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Valdeir Pereira Lima

Climate change and distribution of useful native plant species in Brazil

Florianópolis

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Climate change and distribution of useful native plant species in Brazil

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To my lovely wife – Jéssica Lima, for supporting me during this journey and difficult times

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“In the darkness something was happening at last. A voice had begun to sing. It was very far away and Digory found it hard to decide from what direction it was coming. Sometimes it seemed to come from all directions at once. Sometimes he almost thought it was coming out of the earth beneath them. Its lower notes were deep enough to be the voice of the earth herself. There were no words. There was hardly even a tune. But it was, beyond comparison, the most beautiful noise he had ever heard. It was so beautiful he could hardly bear it.”

Clive Staples Lewis

The Chronicles of Narnia: The Magician’s nephew

PREFACE

The basis for this thesis originally stemmed from my passion for understanding how species are distributed in space and time. It all started in mid 2017, when I sent the first email to Professor Dr. Ilyas Siddique, talking about the possibility of evaluating the impact of climate change on the distribution of native species in the Atlantic Forest. Although this topic is not his expertise, he agreed and gave me all the support for its success. After applying for the Graduate Program in Plant Genetic Resources (PPG-RGV/UFSC) and future approval, I began to delve deeper into the subject through reading numerous articles, as well as contacting other researchers working on the topic. After several discussions together with Professor Dr. Fernando Joner, I decided to focus on potential species for use in agroforestry systems, thus addressing a conservation perspective through sustainable use.

I began the modelling and future projections using a single species – *Plinia edulis* (Cambucá), given the urgent need to assess this rare and threatened tree species from Brazilian Atlantic Rainforest, as well as discuss its incorporation into productive ecological systems (Chapter 2). With astonishing results, the article was immediately accepted for publication in the journal *Austral Ecology*. In the following year, this study was awarded the Prize for Valorization of the Biodiversity of Santa Catarina by the Scientific and Technological Research Foundation of Santa Catarina State (FAPESC) in the Roberto Miguel Klein category, which focuses on studies involving the ecology and biodiversity of native plants.

Working in partnership with the Dutch museum of natural history – Naturalis Biodiversity Center (NBC), the Department of Ecology from the University of São Paulo (USP), the Netherlands Biodiversity Information Facility (NLBIF) and the Faculty of Forestry and Environmental Management from The University of New Brunswick (UNB), I modelled 135 species prioritized in the book *Plants for the Future – Southern Region*, as most of those species can potentially be incorporated into agroecological systems and consequently benefit local communities. Thus, several new ideas emerged such as the preliminary conservation status of each species using the IUCN Red List of Threatened Species criteria (Chapter 3), the identification of species with similar climatic niche requirements, that can be grouped for mixed cropping under different climate conditions and mapping areas of high conservation value (Chapter 4).

RESUMO

Compreender antecipadamente os impactos das mudanças climáticas globais na distribuição das espécies pode ter várias implicações para a conservação. Assim, investigações sobre espécies nativas de interesse agroflorestal no Brasil são extremamente necessárias para compreender com precisão esses impactos e, conseqüentemente, informar os tomadores de decisão. Foram aplicadas abordagens tais como a modelagem de nicho ecológico, métricas de similaridade de nicho e análises macroecológicas para (1) avaliar o impacto das mudanças climáticas globais na distribuição de *Plinia edulis* e a eficácia das unidades de conservação (UCs) brasileiras para a conservação desta espécie, (2) quantificar as mudanças potenciais na área bioclimática de habitat (ABH) de 135 espécies nativas de interesse agroflorestal da flora brasileira usando diferentes cenários de mudanças climáticas, (3) avaliar o estado de conservação preliminar dessas espécies usando os critérios da Lista Vermelha de Espécies Ameaçadas da IUCN, (4) identificar espécies com exigências climáticas semelhantes, que podem ser agrupadas para cultivo misto sob diferentes condições climáticas, e (5) mapear áreas atuais e futuras de alto valor de conservação. Foi observado que *P. edulis* cresce e reproduz potencialmente nas regiões sul, sudeste e nordeste do Brasil, especialmente dentro da Mata Atlântica brasileira. No entanto, os modelos futuros projetados predizem uma redução significativa (36-46%) na adequação ambiental dessa espécie em todos os cenários avaliados. Além disso, as áreas de *P. edulis* não estão adequadamente protegidas pelas UCs. Quantificando as mudanças sobre a distribuição de espécies nativas de interesse agroflorestal priorizadas pela iniciativa do Ministério do Meio Ambiente – Plantas para o Futuro (Região Sul), foi observado um declínio médio entre 38,5-56,3% nas ABHs no cenário de não dispersão e entre 22,3-41,9% no cenário de dispersão total. Além disso, foi observado que apenas 4,3% das espécies estudadas poderiam ser qualificadas como ameaçadas sob os critérios B1 e B2 da Lista Vermelha da IUCN. No entanto, ao considerar a perda quantitativa de habitat prevista devido às mudanças climáticas (critério A3c), as porcentagens aumentaram entre 68,8-84,4% no cenário de não dispersão e entre 40,7-64,4% no cenário de dispersão total. Foram identificados diversos grupos de espécies com alta similaridade climática que podem ser bem combinadas em sistemas de cultivos mistos nas condições climáticas atuais e futuros. Ademais, foi observado que as mudanças climáticas podem modificar a associação espacial desses grupos de espécies sob diferentes cenários climáticos futuros, causando uma mudança média negativa na similaridade climática entre 9.5–13.7% no cenário SSP2-4.5 e entre 9.5–10.5% no cenário SSP5-8.5 para 2041–2060 e 2061–2080, respectivamente.

Finalmente, foi verificado que as áreas de alto valor de conservação sob condições climáticas atuais e futuras variaram para diferentes usos de plantas. Os resultados fornecem um arcabouço para uma estratégia de conservação através do uso sustentável. Assim, tomadores de decisão, organizações conservacionistas e agricultores devem agir de forma a evitar perdas futuras, usando as informações fornecidas nesta tese para promover diferentes intervenções, uma vez que essas espécies em particular podem ser conservadas em áreas urbanas e periurbanas.

Palavras-chave: Biogeografia, biologia das mudanças globais, cultivos mistos, espécies promissoras, mata Atlântica, modelagem de nicho ecológico, pampa, perda de biodiversidade, policulturas.

ABSTRACT

Understanding the impacts of global climate change on the distribution of species in advance might have several implications for conservation. Thus, investigations on potential native agroforestry plant species in Brazil are critically needed to accurately predict these impacts, and consequently inform decision-makers. Here, I applied ecological niche modelling, niche similarity metrics and macro-ecological analyses to (1) assess the impact of global climate change on the distribution of *Plinia edulis*, and the efficacy of Brazilian Protected Areas (PAs) for conservation of this species, (2) quantify potential changes in bioclimatic area of habitat of 135 native potential agroforestry species from the Brazilian flora using different climate change scenarios, (3) assess the preliminary conservation status of these species using the IUCN Red List of Threatened Species criteria, (4) identify species with similar climatic requirements, that can be grouped for mixed cropping under different climate conditions, and (5) map current and future areas of high conservation value. I found that *P. edulis* may currently grow and reproduce in the southern, southeastern and northeastern regions of Brazil specially within the Brazilian Atlantic Rainforest. However, projected future models predict a significant reduction (36-46%) in the environmental suitability across all scenarios evaluated. Additionally, *P. edulis* ranges are not adequately safeguarded by Pas. Furthermore, quantifying potential changes in species' bioclimatic area of habitat (BAH) of native potential agroforestry species prioritized by the Brazilian Ministry of the Environment initiative – Plants for the Future (Southern Region), I noticed that future climate is predicted to trigger a mean decline in BAH between 38.5-56.3% under the non-dispersal scenario and between 22.3-41.9% under the full dispersal scenario. In addition, we found that only 4.3% of the studied species could be threatened under the IUCN Red List criteria B1 and B2. However, when considering the predicted quantitative habitat loss due to climate change (A3c criterion) the percentages increased between 68.8-84.4% under the non-dispersal scenario and between 40.7-64.4% under the full dispersal scenario. I identified multiple groups of species with high climatic similarity that can be combined well in mixed cropping systems under current and future climatic conditions. Then, I observed that climate change is predicted to modify the spatial association of these groups under different future climate scenarios, causing a mean negative change in climatic similarity between 9.5–13.7% under the SSP2-4.5 scenario and between 9.5–10.5% under the SSP5-8.5 scenario for 2041–2060 and 2061–2080, respectively. Finally, I showed that areas of high conservation value for conservation under current and future climate conditions shifted for different plant uses and scenarios. The findings provide a

framework for a conservation strategy through sustainable use. Thus, policymakers, conservation organizations, and farmers should act in such a manner to avoid future losses, using information provided in this thesis to promote different interventions once these particular species can potentially be conserved even in urban and peri-urban areas.

Keywords: Atlantic Forest, biodiversity loss, biogeography, ecological niche modelling, global change biology, mixed cropping, promising species, pampa, polycultures.

RESUMO EXPANDIDO

Introdução

Compreender antecipadamente os impactos das mudanças climáticas globais na distribuição das espécies pode ter várias implicações para a conservação. Assim, investigações sobre espécies nativas de interesse agroflorestal no Brasil são extremamente necessárias para compreender com precisão esses impactos e, conseqüentemente, informar os tomadores de decisão.

Objetivos

- (1) Avaliar o impacto das mudanças climáticas globais na distribuição de *Plinia edulis* e a eficácia das unidades de conservação (UCs) brasileiras para a conservação desta espécie;
- (2) Quantificar as mudanças potenciais na área bioclimática de habitat (ABH) de 135 espécies nativas de interesse agroflorestal da flora brasileira usando diferentes cenários de mudanças climáticas;
- (3) Acessar o estado de conservação preliminar dessas espécies usando os critérios da Lista Vermelha de Espécies Ameaçadas da IUCN;
- (4) Identificar espécies com exigências climáticas semelhantes, que podem ser agrupadas para cultivo misto sob diferentes condições climáticas;
- (5) Mapear áreas atuais e futuras de alto valor de conservação. Foi observado que *P. edulis* cresce e reproduz potencialmente nas regiões sul, sudeste e nordeste do Brasil, especialmente dentro da Mata Atlântica brasileira.

Material e métodos

Os habitats potenciais atuais e futuros para as espécies foram estimados usando MaxEnt, um algoritmo de aprendizado de máquina usado para estimar a distribuição de probabilidade das espécies. Seguindo as diretrizes para usar as categorias e critérios da lista vermelha da IUCN versão 14, a área geográfica (critérios B1a+B2a) foi calculada usando o pacote R 'ConR'. Ademais, foi avaliada a perda quantitativa prevista de habitat devido às mudanças climáticas acessando o declínio na qualidade do habitat (critério A3c), suspeito de ser atendido no futuro, para qualificar se uma determinada espécie estaria em uma categoria de ameaça. A fim de selecionar espécies para sistemas agroflorestais biodiversos, foi

quantificado a sobreposição de nicho (Spearman's ρ) entre os modelos presentes e futuros em diferentes cenários, utilizando a função 'raster.cor.matrix' implementada no pacote R 'ENMTools'. Por fim, para priorizar áreas de alto valor para uso e conservação, foi utilizado o software Zonation v. 4.0.

Resultados e Discussão

Os modelos futuros projetados predizem uma redução significativa (36-46%) na adequação ambiental dessa espécie em todos os cenários avaliados. Além disso, as áreas de *P. edulis* não estão adequadamente protegidas pelas UCs. Quantificando as mudanças sobre a distribuição de espécies nativas de interesse agroflorestal priorizadas pela iniciativa do Ministério do Meio Ambiente – Plantas para o Futuro (Região Sul), foi observado um declínio médio entre 38,5-56,3% nas ABHs no cenário de não dispersão e entre 22,3-41,9% no cenário de dispersão total. Além disso, foi observado que apenas 4,3% das espécies estudadas poderiam ser qualificadas como ameaçadas sob os critérios B1 e B2 da Lista Vermelha da IUCN. No entanto, ao considerar a perda quantitativa de habitat prevista devido às mudanças climáticas (critério A3c), as porcentagens aumentaram entre 68,8-84,4% no cenário de não dispersão e entre 40,7-64,4% no cenário de dispersão total. Foram identificados diversos grupos de espécies com alta similaridade climática que podem ser bem combinadas em sistemas de cultivos mistos nas condições climáticas atuais e futuros. Ademais, foi observado que as mudanças climáticas podem modificar a associação espacial desses grupos de espécies sob diferentes cenários climáticos futuros, causando uma mudança média negativa na similaridade climática entre 9.5–13.7% no cenário SSP2-4.5 e entre 9.5–10.5% no cenário SSP5-8.5 para 2041–2060 e 2061–2080, respectivamente. Finalmente, foi verificado que as áreas de alto valor de conservação sob condições climáticas atuais e futuras variaram para diferentes usos de plantas. Os resultados fornecem um arcabouço para uma estratégia de conservação através do uso sustentável. Assim, tomadores de decisão, organizações conservacionistas e agricultores devem agir de forma a evitar perdas futuras, usando as informações fornecidas nesta tese para promover diferentes intervenções, uma vez que essas espécies em particular podem ser conservadas em áreas urbanas e periurbanas.

Palavras-chave: Biogeografia, biologia das mudanças globais, cultivos mistos, espécies promissoras, mata Atlântica, modelagem de nicho ecológico, pampa, perda de biodiversidade, policulturas.

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Chapter 1

General introduction and thesis outline

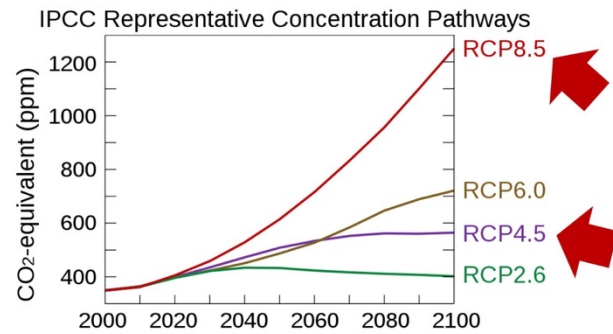
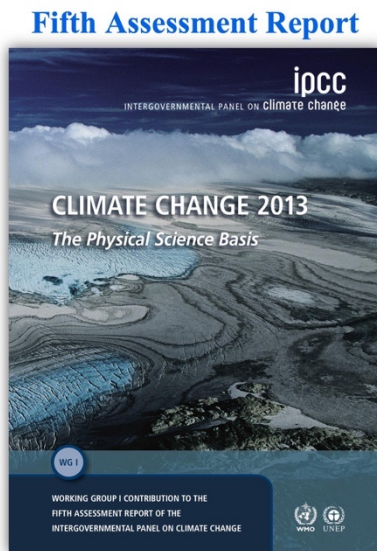


Araucaria forest in Bom Jardim da Serra, Santa Catarina, Brazil by Valdeir P. Lima

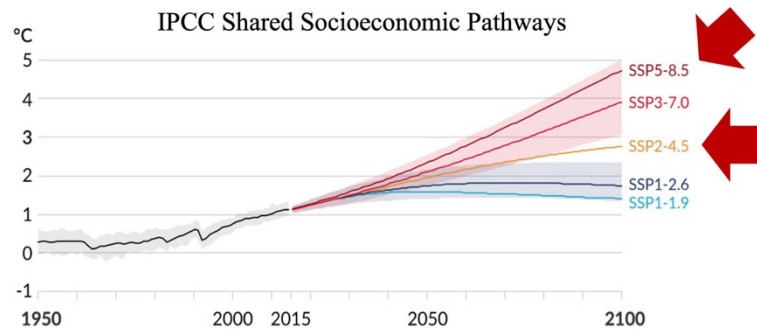
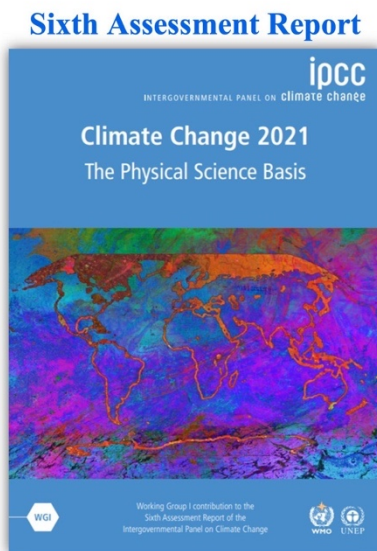
General introduction

Successful conservation strategies for biological resources rely on a straightforward understanding of the distribution of the target species (Guo et al., 2017; IPBES, 2019). Earth's biodiversity is decreasing at an unprecedented rate and consequently impacting human well-being (Díaz et al., 2018; Pimm, Jenkins, & Li, 2018; Waldron et al., 2017). Climate change is one of the most important drivers affecting species distribution and causing biodiversity loss throughout the 21st century (Lima, Marchioro, Joner, ter Steege, & Siddique, 2020; Marchioro, Lima, & Sales, 2020; Peterson et al., 2012; Zwiener et al., 2017). The United Nations Intergovernmental Panel on Climate Change (IPCC) estimates that if Earth's average temperature rises between 2 °C and 3 °C, about 20 to 30% of all terrestrial biodiversity will be at high risk of extinction by the end of the century (IPCC, 2014). In the last century, land and ocean temperature showed a warming of approximately 1.0 °C (IPBES, 2019), which may increase another 1.0 °C to 5.7 °C by 2100, if we do not reduce greenhouse gas emissions (IPCC, 2021). Considering the potential climate change scenarios with additional temperature increases, both widespread species and narrow-ranged endemic species will likely suffer irreparable consequences with regard to their distribution range and abundance (Warren et al., 2013). The IPCC assesses scientific, technical and socioeconomic information concerning climate change, disclosing these results through series of reports (Figure 1).

Climate affects species in different ways such as range shifts, relative abundance changes, habitat fragmentation, risk of extinction for endangered species and microhabitat use (Bates, Mächler, Bolker, & Walker, 2015; Guo, Li, Zhao, & Nawaz, 2019). Although, species can respond to climate change by acclimatization, evolutionary adaptations or even changes in distribution (Peterson et al., 2011), plant species have low acclimatization capacity, since they are adapted to seasonal temperature variations (Corlett, 2011; Feeley, Rehm, & Machovina, 2012). The redistribution of species as one of the consequences of climate change can result in discordant species range shifts, which may affect biotic interactions generating impacts at the community level (Cahill et al., 2013; Pecl et al., 2017; Sorte, Williams, & Carlton, 2010). Knowing that ecological goods and services rely on the ecosystem health, climate-driven changes on biodiversity might have several impacts on economic development, ecosystem health and, as a consequence, on human well-being (Díaz et al., 2018; Pecl et al., 2017).



Scenario	Mean and likely range (2046-2065)	Mean and likely range (208-2100)
RCP2.6	1.0 (0.4 to 1.6)	1.0 (0.3 to 1.7)
RCP4.5	1.4 (0.9 to 2.0)	1.8 (1.1 to 2.6)
RCP6.0	1.3 (0.8 to 1.8)	2.2 (1.4 to 3.1)
RCP8.5	2.0 (1.4 to 2.6)	3.7 (2.6 to 4.8)



Scenario	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Figure 1. Global climate change scenarios based on the Fifth and Sixth Assessment Report (IPCC, 2013, 2021). Red arrows indicate the scenarios used in this thesis.

Brazil is the world’s most biodiversity-rich country, represented by 33,161 known species of vascular plants (Ulloa Ulloa et al., 2017), and harbors some of the largest remnants of tropical old-growth forests (Myers, Mittermeier, Mittermeier, Fonseca, & Kent, 2000). A large number of native plant species have untapped socioeconomic potential and can potentially be incorporated into the Brazilian agricultural industry (Coradin, Siminski, & Reis, 2011). Potential agroforestry plant species are those that benefit both people's livelihoods and ecological systems (Nair, 1993). These species are often characterized for its multiple uses (i.e. condiment, fibre, food, forage, medicinal, ornamental and timber species), different

harvest times and potential for market adoption (Cerda et al., 2014; Florencia Montagnini, 2017). Agroforestry systems can play a pivotal role in mitigating the effects of climate change as they sequester more atmospheric carbon than conventional farming (De Stefano & Jacobson, 2017; Somarriba et al., 2013). Brazil has great potential to increase agroforestry areas and, consequently, boost multiple regulatory ecosystem services (IPBES, 2019; Schuler et al., 2022; Torres, Tiwari, & Atkinson, 2021). In this sense, conservation approaches that seek sustainable use of biodiversity and engaging local communities are urgent as Brazil's environmental legislation and governance of important ecosystem services are currently at risk (Abessa, Famá, & Buruaem, 2019; Levis et al., 2020; Vieira et al., 2018).

Understanding the impacts of climate change on species distribution in advance might have several implications for conservation. Protected areas (PAs) are considered the cornerstone of biodiversity conservation (Coetzee, Gaston, & Chown, 2014; Dinerstein et al., 2017; Huang, Shao, & Liu, 2019). Numerous near-term and long-term targets have been suggested in order to establish PAs worldwide. To illustrate, the Convention on Biological Diversity's Aichi Biodiversity Target 11 included to protect 17% of terrestrial land and inland water areas by 2020. Other inspirational target is the protection of Half-Earth in order to ensure sufficient natural habitats (Dinerstein et al., 2017; Wilson, 2016). Current PAs cover 17.9 million km² of the Earth's land surface (Pimm et al., 2018). Although PAs are fundamental for the conservation of sensitive species (García Márquez et al., 2017), some studies have demonstrated that a large number of species geographic ranges have not been fully conserved (Fonseca & Venticinque, 2018; Oliveira et al., 2017) and therefore, greater effectiveness needs to be sought. For instance, Oliveira et al., (2017) quantified conservation gaps in the Brazilian PAs and noticed that about 71% of them presented a very low density of species in all Brazilian biomes.

Besides PAs, Conservation-by-Use system is another conservation approach characterized by the human being presence as an integral part of the process, promoting species. This approach depends primarily on the valuation of the cultural aspects of a given region and economic value (Reis et al., 2018). Historically, human presence influenced outstandingly the composition and structure of the forest formations, which are evidenced in the landscape (Levis et al., 2018; Reis et al., 2018). For example, the Amazonian forests have been managed by people communities for millennia, thus causing subtle changes in the natural environment and persistent throughout history (Levis et al., 2018). Removal of non-useful plants, protection of useful plants, attraction of animal dispersers, transport of plants,

selection of certain phenotypes, fire management, planting of certain species and soil improvements are comprehensible evidences of management practices performed by human communities in the Amazon mentioned by Levis et al. (2018). Araucaria forests in the Brazilian Atlantic forest of southern Brazil is another example of domesticated landscapes. Reis et al. (2018) noted that the species *Ilex paraguariensis* St. Hilaire (Aquifoliaceae), *Araucaria angustifolia* (Bertol.) Kuntze (Araucariaceae) and *Bromelia antiacantha* Bertol. (Bromeliaceae) have been intentionally promoted through protection, transplant and selection processes. They found high levels of genetic diversity among the species studied on agricultural properties, which did not differ significantly from those obtained in PAs (Reis et al., 2018). Hence, practices of management system conducted by humans produce landscapes with fragments of productive forests, and consequently favor the species conservation.

Ecological niche models (ENMs), also known as Species distribution models (SDMs) have become the most used tool to evaluate species vulnerability (Elith et al., 2006; Franklin, 2010; Gomes, Vieira, Salomão, & ter Steege, 2019; Guisan & Zimmermann, 2000; Guo et al., 2019). The ENM method evaluates the presence or presence/absence of the species under different climatic variables, resulting in maps of environmental suitability, which provide information about possible environments where species may or may not occur (Guisan & Thuiller, 2005a; Raes & Aguirre-Gutiérrez, 2018). ENMs have multiple applications such as the evaluation of the impact of land use on biodiversity, the effects of climate change on the distribution of organisms, tests for evolutionary and biogeographical hypotheses, use for the improvement of fauna and flora atlases and the determination of priority areas for conservation (Amaral, Munhoz, Walter, Aguirre-Gutiérrez, & Raes, 2017; Guisan & Zimmermann, 2000). Although ENMs have several advantages to assess the distribution of species in different scenarios (Guisan & Thuiller, 2005a), there are uncertainties regarding its use such as the absence of observations of their presuppositions in some cases, the lack of knowledge about the uncertainties of the models and the difficulty in knowing the adaptive and dispersal capacity of the species, which are key aspects of biology (Schwartz, 2012; S. J. Sinclair, White, & Newell, 2010).

Thesis outline

Investigations on distributions of potential native agroforestry plant species in Brazil are critically needed to accurately predict the impacts of climate change, and consequently inform decision-makers. The aim of my thesis is to assess the impacts of global climate

change on the distribution of potential native agroforestry plant species in Brazil. This thesis contains a total of five chapters. In **Chapter 1**, I provide a general introduction and the thesis outline. In **Chapter 2**, I assess the impact of global climate change on the distribution of *Plinia edulis*, a rare and useful species and the efficacy of Brazilian Protected Areas network for conservation of this species. In **Chapter 3**, I quantify potential changes in BAH of 135 native potential agroforestry species from the Brazilian flora using two climate change scenarios (SSP2-4.5 and SSP5-8.5) and two dispersal (non-dispersal and full dispersal) scenarios for 2041-2060 and 2061-2080 and assess the preliminary conservation status of each species using the IUCN Red List of Threatened Species criteria. In **Chapter 4**, I identify species with similar climatic requirements, that can be grouped for mixed cropping under different climate conditions, and map current and future areas of high conservation value using two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) to assess mid-term and long-term future climate impacts for the following time periods: 2041-2060 and 2061-2080. In **Chapter 5**, I synthesize the findings of this thesis and highlight some actions to ameliorate the impacts of climate change on the studied species in Brazil.

Chapter 2

Extinction threat to neglected *Plinia edulis* exacerbated by climate change, yet likely mitigated by conservation through sustainable use

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Plinia edulis in Rio do Sul, Santa Catarina, Brazil by Eder Favretto

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Abstract

Forecasting the impacts of climate change on species distribution has several implications for conservation. *Plinia edulis* is a rare and threatened tree species from Brazilian Atlantic Rainforest. In this study, we assessed the impact of global climate change on the distribution of *P. edulis*. Additionally, we evaluated the efficacy of the Brazilian Protected network to conserve this species. Ecological niche models were built using the maximum entropy method based on occurrence records and environmental predictors. Models predicted a reduction of climatically suitable areas for *P. edulis* in all evaluated scenarios in the coming years. Furthermore, we observed that Brazilian Protected Areas (PAs) are ineffective to conserve this species. Given the fact that *P. edulis* is a promising tree species rarely found within Brazilian PAs and threatened by global climate change, we strongly recommend the cultivation of this multipurpose species in agroforestry systems, landscaping and homegardens in order to promote its conservation through sustainable use.

Keywords: biogeography; biodiversity loss; ecological niche modelling; promising species

Introduction

Climate change is one of the most important drivers affecting species distribution, causing biodiversity loss throughout the 21st century (Ashraf et al., 2018; Boria, Olson, Goodman, & Anderson, 2014; Guo et al., 2019; Huang et al., 2019; Peterson, Papeş, & Soberón, 2015; Warren et al., 2013). The strong dependence of the distribution of species on climate explains the changes in the patterns of species distributions observed in the past years (Ashraf et al., 2017; Inoue & Berg, 2017). Climate change affects species in different ways such as range shifts, changes in relative abundance, fragmentation of subpopulations, increased risk of extinction and changes in habitat use (Guo et al., 2019). Although species may respond to climate change by acclimatization, evolutionary adaptation or shifts in distribution (Peterson et al., 2012), wild plants in tropical regions have low acclimatization capacity to long-term warming (Corlett, 2011; Feeley et al., 2012). In this context, strategies such as the delimitation of priority areas for species conservation should consider the risks related to the loss of suitable areas in a changing climate.

The Brazilian Atlantic Rainforest is one of world's most threatened biodiversity hotspots (Myers et al., 2000). The forest cover of this biome has been reduced to less than 20% of its original size (Magnago et al., 2015; Rodrigues, Villa, & Neri, 2019), and currently is distributed mainly in small fragments of less than 50 ha (Ribeiro et al., 2011). Furthermore, the current PA network is insufficient to ensure the long-term survival of this tropical forest. Despite the fact that the isolation of these rainforest fragments compromises their role in biodiversity conservation, they are still the principal reservoirs of biodiversity in anthropogenic landscapes (Pereira, Oliveira, & Torezan, 2013). Accordingly, urgent actions and well-structured goals are required in order to conserve, restore and mitigate this rich and endangered tropical forest in a changing climate.

Plinia edulis (Vell.) Sobral (Myrtaceae), popularly known as “cambucá”, is a rare and endemic tree species from the Brazilian Atlantic Rainforest (Caiafa & Martins, 2010; Sobral, Proença, Souza, Mazine, & Lucas, 2012; Souza, 2009), categorized as vulnerable (VU) by the red list of threatened species of the National Centre for Flora Conservation (CNCFlora, 2019; Martinelli & Moraes, 2013). Recently, *P. edulis* was identified as a species of high biological value and conservation priority by Souza et al., (2018) based on the criteria: distribution, extinction risk, harvesting risk, local use and economic use. *P. edulis* has a restricted geographical distribution, occurring from Rio de Janeiro to Rio Grande do Sul (Sobral et al.,

2012) and a very small population density (Caiafa & Martins, 2010), with approximately only ten thousand individuals estimated to be surviving in the wild (CNCFlora, 2019; Martinelli & Moraes, 2013). This species has not been found within protected areas (PAs) (Martinelli & Moraes, 2013), emphasizing the concern about its conservation status. On the other hand, records of *P. edulis* growing in rural gardens are quite frequent in a recent past. As demonstrated by Souza et al. (2018), however, few informants claim to keep the species on their land. Therefore, it is noticeable that the species is becoming increasingly scarce. It is estimated that in the next 30 years, populations of *P. edulis* may suffer a population decline over 10% without considering climate change effects. Moreover, this species occurs in areas with high anthropogenic pressures that have already lost more than 80% of their original habitats (CNCFlora, 2019; Martinelli & Moraes, 2013). This suggests that *P. edulis* could be categorized as critically endangered rather than vulnerable due to its significant population size reduction (loss \geq 80%) by IUCN standards (IUCN Standards and Petitions Committee, 2019). In such context, global climate change puts additional pressure on the survival this wild-harvested species.

Ecological niche modelling (ENM) is commonly used to make inferences about species distributions (Alamgir, Ahmed, & Turton, 2015; Ashraf et al., 2017; Gomes et al., 2018; Guisan & Thuiller, 2005b; Guisan & Zimmermann, 2000; Guo et al., 2019; Marchioro & Krechmer, 2018; Peng et al., 2019; Raes & Aguirre-Gutiérrez, 2018; Rodrigues, Silva, Eisenlohr, & Schaefer, 2015). ENM evaluates the presence or presence/absence of the species under different environmental variables, resulting in maps of environmental suitability, which provide information about possible areas where species may or may not occur (Gomes et al., 2018; Guisan & Thuiller, 2005b; Guisan & Zimmermann, 2000; Raes & Aguirre-Gutiérrez, 2018). ENM has multiple applications such as the evaluation of the impact of land use on biodiversity, the effects of climate change on the distribution of organisms, tests for evolutionary and biogeographical hypotheses, use for the improvement of fauna and flora atlases and the determination of priority areas for conservation (Amaral et al., 2017; Guisan & Zimmermann, 2000). Here, using ENM, we assess the impact of global climate change on the distribution of *P. edulis* a rare and useful species and the efficacy of Brazilian PA network for conservation of this species.

Material and Methods

Species and climatic data

The occurrence records for *P. edulis* were obtained from the literature, the Global Biodiversity Information Facility (<http://www.gbif.org>) and SpeciesLink (<http://splink.cria.org.br>). We thoroughly checked the distribution records of *P. edulis* in the “Flora do Brasil” (<http://floradobrasil.jbrj.gov.br>) and excluded those that did not correspond to the original distribution. An envelope with 19 environmental predictors obtained in Worldclim version 1.4 (<http://worldclim.org>) with a resolution of 30 arc-sec was used to characterize the climatic niche of the species.

Modelling procedures

Niche models were built using the MaxEnt v.3.4.1k (Phillips, Anderson, & Schapire, 2006), a machine-learning algorithm used to estimate species’ probability distribution based on occurrence records and environmental predictors (Hijmans & Elith, 2011; Phillips et al., 2006). This algorithm is a presence-based method, having a better performance compared to other algorithms, even when few occurrences are available (Elith, Kearney, & Phillips, 2010; Gomes et al., 2018; Muñoz-Pajares et al., 2018; Peng et al., 2019; Proosdij, Sosef, Wieringa, & Raes, 2016).

To diminish spatial autocorrelation and thus improve the performance of the models (Boria et al., 2014; Fourcade, Besnard, & Secondi, 2018), we filtered the occurrence records over a distance of 20km (Zwiener et al., 2017). This procedure was performed through the package spThin version 0.1.0.1 (Aiello-Lammens, Boria, Radosavljevic, Vilela, & Anderson, 2015) in R version 3.6.0 (R Core Team, 2021).

Selecting the correct predictors is a pivotal step in building parsimonious models. Several studies have shown that *a priori* selection of variables and the exclusion of highly correlated variables are important steps in the development of less complex models (Fourcade et al., 2018; West et al., 2015). Firstly, we selected the following climatic variables based on their biological significance: annual mean temperature (Bio1), temperature seasonality (Bio4), maximum temperature of warmest month (Bio5), minimum temperature of coldest month (Bio6), temperature annual range (Bio7), annual precipitation (Bio12), precipitation of wettest month (Bio13), precipitation of driest month (Bio14), and precipitation seasonality (Bio15)

(Elith et al., 2010; Marchioro & Krechmer, 2018). Secondly, we examined the correlation structure of the selected climatic variables through the variance inflation factor (VIF). VIFs measure how much the variance of an estimated regression coefficient increases if their predictors are correlated. Values of VIFs above 5 were excluded (O'Brien, 2007). This statistical procedure was performed in the R version 3.6.0 (R Core Team, 2021).

The MaxEnt algorithm allows us to build models with different settings such as feature classes and regularization multiplier values (Merow, Smith, & Silander, 2013). In order to select a less complex model with high predictive capacity (Morales, Fernández, & Baca-gonzález, 2017; Radosavljevic & Anderson, 2014), we built fifteen models with different combinations (H-1, H-3, H-5, L-1, L-3, L-5, LQ-1, LQ-3, LQ-5, LQH-1, LQH-3, LQH-5 and LQHPT-1, LQHPT-3, LQHPT-5). Finally, we selected the best fit model based on the corrected Akaike Information Criterion (AICc) run in ENM Tools v 1.3. The models with the best fit are characterized by the lower AICc values (Warren & Seifert, 2011).

The model with the best fit was built using 75% of the records for training and 25% for model testing and replicated run-type set as bootstrap with 100 replicates. Additionally, response curves for each variable were created and a jack-knife analysis was carried out to measure the importance of the variables. The models were evaluated through True Skill Statistic (TSS) (Allouche, Tsoar, & Kadmon, 2006) and Area Under the Curve (AUC) (Fielding & Bell, 1997). TSS values range from -1 to +1, where +1 indicates perfect predictions and values of 0 or less indicate unsatisfactory performance. AUC ranges from 0 to 1, where values from 0.5 to 0.7 indicate poor performance, 0.7 to 0.9 indicate moderate performance and above 0.9 indicate high performance (Peng et al., 2019; Peterson et al., 2012). Additionally, we tested the model's deviation from random expectation using corrected null models with 99 runs and 95% confidence interval as proposed by Raes and ter Steege (2007) using the 'dismo' package (Hijmans, Phillips, Leathwick, & Elith, 2017).

Projection for future climatic conditions and centroid analysis

We projected the final model to 2050 and 2070 based on two different scenarios (RCP 4.5 and RCP 8.5). In order to reduce the uncertainties related to future conditions, we averaged projections based on five global climate models: BCC-CSM1-1 (Beijing Climate Center Climate System Model), CCSM4 (Community Climate System Model), HadGEM2-ES (Met Office Unified Model), MIROC5 (Model for Interdisciplinary Research on Climate)

and MRI-CGCM2.3.2 (Meteorological Research Institute, Japan). To quantify the future distribution shifts, we created binary maps using the maximum training sensitivity plus specificity threshold. This threshold presents high performance for identifying suitable areas for conservation (Bean, Stafford, & Brashares, 2012; Loiselle et al., 2003; Meyer, Pie, & Passos, 2014). Using the binary maps, we calculated the percentage of distribution shift compared to current distribution, as well as the magnitude and direction of this change through a centroid analysis. These analyses were performed using the SDM toolbox 2.0 (Brown, 2014).

Geospatial analysis

Maps of the Brazilian PAs, obtained from the Brazilian Institute of Geography and Statistics (<https://www.ibge.gov.br>) were intersected with the climatically suitable areas for *P. edulis* in order to quantify the percentage of the species distribution range that falls within PAs.

Results

Species data, model evaluation and variables

We compiled 87 occurrence records for *P. edulis* and after spatial filtering this number was reduced to 40 occurrences. The final selected model gave satisfactory results with values of AUC higher than 0.90 (AUC test 0.93 and training AUC 0.95). Similarly, the True Skill Statistics test demonstrated an excellent performance of the models (TSS = 0.88). The model was significantly different from random expectation when using bias corrected null models (AUC = 0.78, $P < 0.05$). The model with the best fit, based on the AIC, was LQHPT-5. The mean annual temperature (59.4%) and the driest month (21.5%) were the variables that contributed most to the climatic suitability for *P. edulis* (Appendix S1, S2 and S3).

Current and future distribution and centroids

The potential distribution of *P. edulis* in the current climatic scenario suggested that the species may currently grow and reproduce in the southern, southeastern and northeastern regions of Brazil in areas where the Brazilian Atlantic Rainforest occurs (Fig. 1). When the model was projected to the predicted future climatic conditions, a significant reduction in the suitability was estimated in all scenarios (Table 1 and Fig. 1). Reductions by more than 36% in environmental suitability were estimated for the scenarios RCP 4.5 and RCP 8.5 in 2050

and RCP 4.5 in 2070. The most alarming scenario is the RCP 8.5 in 2070, with estimates of loss in the climatic suitability of approximately 46%. Most of the unsuitable areas predicted for the RCP 4.5 and RCP 8.5 scenarios in 2050 are located in the northeastern and southeastern regions. For scenarios RCP 4.5 and RCP 8.5 in 2070, they are located in the southeastern and southern regions. In addition, our centroid analysis indicated that these changes in distribution occur in a southward direction (Fig. 1).

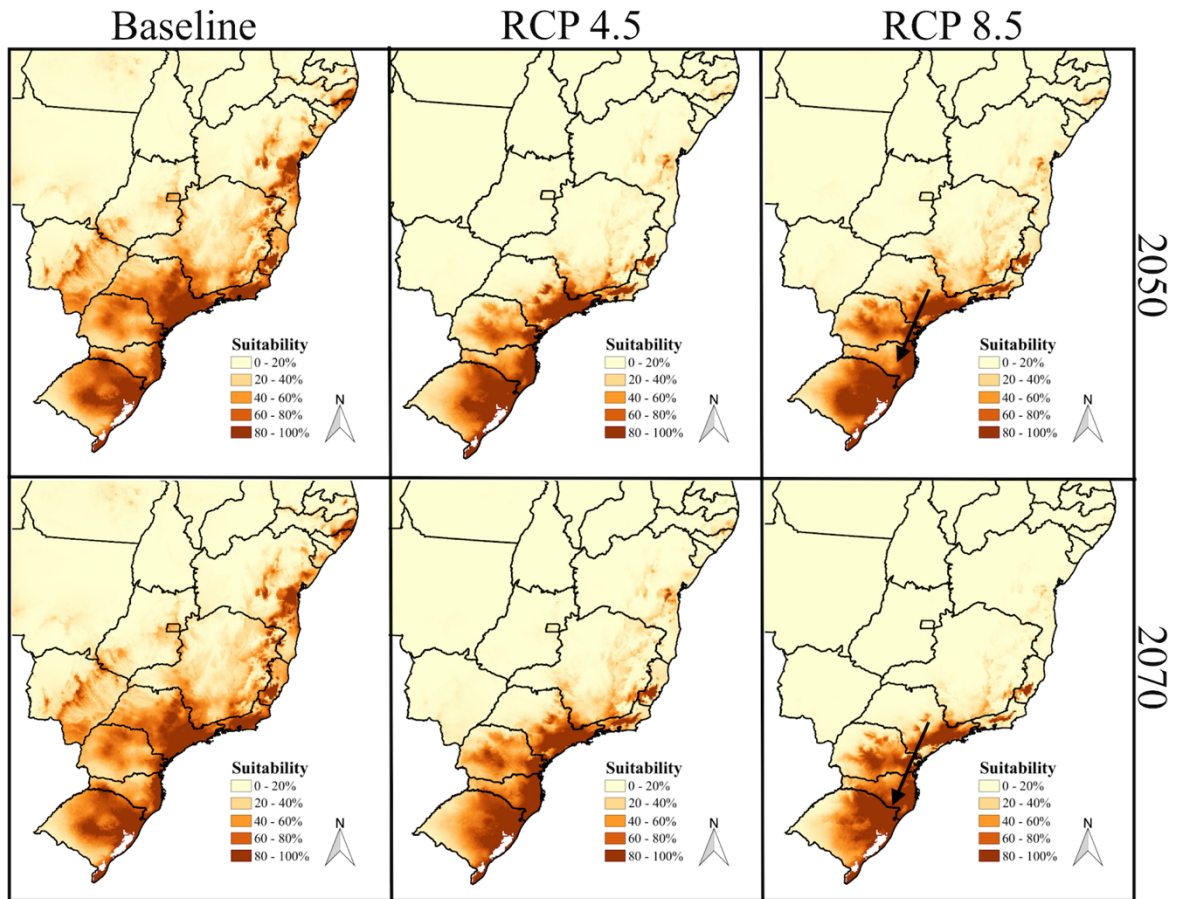


Figure. 1 Current and future climatic suitability for *P. edulis* in the Brazilian Atlantic Rainforest. The vector indicates the direction and magnitude of the changes in species core distribution.

Table 1 Distribution changes in Km² of *P. edulis* in two different years and climate scenarios (RCP)

Year	Scenario	Expansion	Contraction	No change	% of change ¹
2050	RCP 4.5	41,424.39	237,810.45	293,819.47	-36.9
	RCP 8.5	69,682.10	265,156.63	266,473.30	-36.7
2070	RCP 4.5	68,871.85	260,902.78	270,727.15	-36.1
	RCP 8.5	71,403.90	318,127.19	213,502.74	-46.4

¹Negative values indicate area loss.

Efficacy of protected areas

The current Brazilian PA network of federal, state and municipal PAs protects only 13.7% of the climatically suitable areas for *P. edulis*. Assuming that no new PAs will be created, and that current ones will not be deactivated, we estimated that PAs will not be able to protect species suitable ranges in the future, with suitable range percentages varying from 1.7% (RCP 4.5/2050) to 17.8% (RCP 4.5/2070) (Table 2).

Table 2 Percentage of *P. edulis* suitable ranges within Brazilian PAs

Year	Scenario	Suitable range (%)
	Baseline	13.7
2050	RCP 4.5	1.7
	RCP 8.5	6.4
2070	RCP 4.5	17.8
	RCP 8.5	16.0

Discussion

P. edulis populations have already experienced a sharp decline over the last years primarily due to changes in land use. In addition to this driver, climate change will potentially intensify the risk of loss of these populations in the coming years. The models predicted a significant loss in suitable areas for *P. edulis* in all scenarios evaluated over the coming decades. Furthermore, we observed that Brazilian PAs are ineffective to safeguard the species within its current and likely future ranges.

Several studies have predicted how climate change affects the distribution of species in different regions and ecosystems around the world (Alamgir et al., 2015; Ashraf et al., 2017; Guo et al., 2019, 2017; Morin et al., 2018; Newbold, 2018). The Brazilian Atlantic Rainforest is one of the most threatened ecosystems in the world. This ecosystem is characterized by a great diversity of endemic species and at the same time is under diverse anthropogenic pressures (Myers et al., 2000). Rare species, such as *P. edulis*, are likely vulnerable because they have a more restricted geographic distribution, compared to other species (Caiafa & Martins, 2010; Martinelli & Moraes, 2013). Besides the loss of habitat, which is the primary factor in declining biodiversity (Pimm et al., 2014), we project that *P.*

edulis will lose about 50% of its climatically suitable areas in the next few decades. Thus, based on our findings, we note the importance of developing conservation strategies for the species in both short and long term in the Brazilian Atlantic Rainforest.

In the case of *P. edulis*, a promising, yet, thus far, neglected approach is to promote its conservation through cultivation and sustainable use outside protected areas, motivated by its range of economic potentials for food, medicine and ornament (Azevedo et al., 2016; Carvalho, Ishikawa, & Gouvêa, 2012; Rosa et al., 2018; Souza et al., 2018). Several of the potential economic uses of *P. edulis* are not likely to exert significant extractive pressure on the population because they do not consume its propagules (seeds), nor do they exploit excessive portions of the plant biomass. Particularly if cultivated close to frequent human activity and depulped without damaging the seed, the utilization of its highly appreciated fruit pulp for human consumption (Martinelli & Moraes, 2013) or fruit peel for nutraceutical and gastroprotective compounds (Rosa et al. 2018) can substantially improve an integrated production of seedlings because seeds accumulate as ‘waste product’ from pulp processing facilities, a phenomenon also documented for another Atlantic Forest species, *Euterpe edulis* Mart. (Arecaceae) (Mauricio Sedrez Reis, Fantini, Nodari, Guerra, & Reis, 2000). Aqueous extract of leaves of *P. edulis* have antioxidant and cytotoxic activities and, through the evaluation using MCF-7 breast cancer cells, it was suggested that this species is a potential chemo-preventive as well as a possible candidate for the development of antineoplastic drugs (Carvalho et al., 2012). Other promising uses such as medicinal uses of leaves as anti-inflammatory and pain relief compounds (Azevedo et al., 2016), or landscaping and ornamental uses do not jeopardize the completion of the reproductive cycle (Filgueiras & Peixoto, 2005).

Under the projected climate change scenarios, several conservation strategies for biological species have been suggested over the last few years. PAs are considered the keystone of biodiversity conservation (Coetzee et al., 2014; Dinerstein et al., 2017; Huang et al., 2019; Pimm et al., 2018; Saraiva, Santos, Overbeck, Giehl, & Jarenkow, 2018). Numerous short-term and long-term targets have been suggested in order to establish PAs worldwide. To illustrate, the Convention on Biological Diversity’s Aichi Biodiversity Target 11 includes a target to protect 17% of terrestrial land and inland water areas by 2020 (Barnes, 2015). Another inspirational target is the protection of Half-Earth in order to ensure sufficient natural habitats (Dinerstein et al., 2017; Wilson, 2016). Current PAs cover 17.9 million km² of the Earth’s land surface (Pimm et al., 2018). Yet, our study highlights that Brazilian PAs are not

sufficient to safeguard most of the climatically suitable range of *P. edulis*, demonstrating a concern with its conservation under both present and future conditions. This is likely the case for many, if not most, Atlantic forest endemics, given the loss of 80% of forest cover in the region. Lately experts have questioned whether PAs are truly protecting geographic ranges of species around the world (Oliveira et al., 2017; Saraiva et al., 2018). For instance, Oliveira et al. (2017) quantified conservation gaps in the Brazilian PAs and noticed that PAs are failing to safeguard the majority of endemic species. Furthermore, (Saraiva et al., 2018) observed that the evolutionary history and the beta diversity of angiosperms from Brazilian Atlantic Rainforest were not protected by the current PA network.

The results provided by ENM should be assessed with care, because of uncertainties, associated with projections across time and space. Even though environmental niche models have shown to accurately assess the distribution of species in different scenarios of climate change (Ashraf et al., 2017; Gomes et al., 2018, 2019), there are uncertainties regarding to the modeling approach and future climate projections. For our modeling approach we used Maxent, arguably the most accepted algorithm worldwide, outperforming several commonly presence-only models (Elith et al., 2006). Although some studies claim that the use of more algorithms improves model accuracy (Araujo & New, 2007), others argue that consensus forecasting will not always outperform models built with single algorithm (Crimmins, Dobrowski, & Mynsberge, 2013; Grenouillet, Buisson, Casajus, & Lek, 2011). For the future climate projections, we employed an ensemble of five different GCMs as used in recent studies (Gomes et al., 2019; Marchioro & Krechemer, 2018).

We have shown that the threatened Atlantic Rainforest tree *P. edulis* is not adequately protected by PAs within its range. In future climatic scenarios its potential range is likely to contract even further, resulting in a bleak picture for its conservation in PAs. However, its cultural history and growing evidence of a wide range of potential economic uses suggest that its multipurpose utilization is unlikely to substantially trade off with its conservation. Public policy and private initiatives should put forward the utilization of this species in agroforestry systems, landscaping and homegardens in order to promote its conservation through sustainable use.

Supplementary information

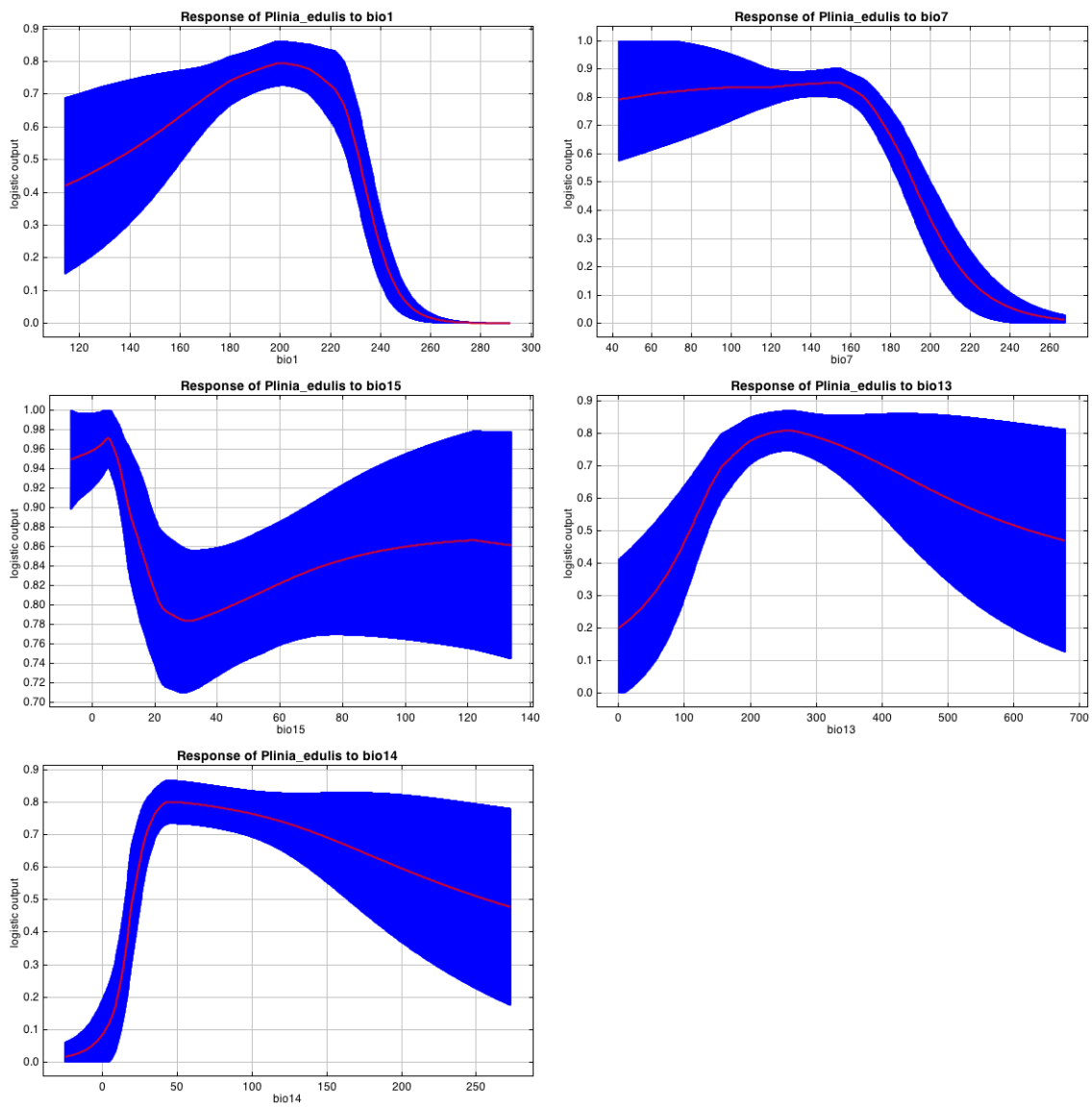
Appendix S1. Model selection based on AICc for *P. edulis* in the Brazilian Atlantic Rainforest.

Feature classes	Regularization	AICc	BIC	Δ AICc
LQHPT	5	735.52	741.44	0
LQ	1	742.28	749.37	-7
LQH	5	745.36	752.70	-10
LQHPT	3	746.36	750.40	-11
LQ	3	746.83	751.87	-11
LQ	5	752.40	756.40	-17
L	3	758.22	763.26	-23
L	1	758.57	765.18	-23
L	5	761.26	765.26	-26
H	3	771.87	764.79	-36
LQH	3	787.14	769.73	-52
LQH	1	965.11	777.44	-230
LQHPT	1	1019.12	775.04	-284
H	1	1445.59	792.26	-710

Appendix S2 Analysis of variable contributions for *P. edulis*.

Variable	Percent contribution	Permutation importance
Annual Mean Temperature	59.4	60.6
Precipitation of Driest Month	21.5	23.5
Temperature Annual Range	13.4	8.9
Precipitation Seasonality	3.3	3.9
Precipitation of Wettest Month	2.4	3.1

Appendix S3 Variable response curves



Chapter 3

Climate change threatens native potential agroforestry plant species in Brazil

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Plinia peruviana in Jaú, São Paulo, Brazil by Victoria Guaratti

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Abstract

Climate change is one of the main drivers of species extinction in the 21st-century. Here, we aim to (1) quantify potential changes in species' bioclimatic area of habitat (BAH) of 135 native potential agroforestry species from the Brazilian flora, using two different climate change scenarios (SSP2-4.5 and SSP5-8.5) and dispersal scenarios, where species have no ability to disperse and reach new areas (non-dispersal) and where species can migrate within the estimated BAH (full dispersal) for 2041-2060 and 2061-2080. We then (2) assess the preliminary conservation status of each species based on IUCN criteria. Current and future potential habitats for species were predicted using MaxEnt, a machine-learning algorithm used to estimate species' probability distribution. Future climate is predicted to trigger a mean decline in BAH between 38.5-56.3% under the non-dispersal scenario and between 22.3-41.9% under the full dispersal scenario for 135 native potential agroforestry species. Additionally, we found that only 4.3% of the studied species could be threatened under the IUCN Red List criteria B1 and B2. However, when considering the predicted quantitative habitat loss due to climate change (A3c criterion) the percentages increased between 68.8-84.4% under the non-dispersal scenario and between 40.7-64.4% under the full dispersal scenario. To lessen such threats, we argue that encouraging the use of these species in rural and peri-urban agroecosystems are promising, complementary strategies for their long-term conservation.

Keywords: Atlantic Forest, biodiversity loss, conservation biogeography, global change biology, ecological niche modeling, pampa.

Introduction

Hundreds of species are unquestionably promising for future human welfare (Antonelli, Smith, & Simmonds, 2019), yet a large number of these species may potentially be threatened by impacts of climate change in the coming decades. Climate change is one of the important drivers affecting species survival, causing global biodiversity loss (Chen, Hill, Ohlemuller, Roy, & Thomas, 2011; IPBES, 2019; Pecl et al., 2017; Warren et al., 2013). Climate change affects species in different ways, such as altering the suitability of current habitat of species, resulting in accelerated extinction rates (Chen et al., 2011; Destro, Fernandes, Andrade, De Marco, & Terribile, 2019; Travis et al., 2013). The United Nations Intergovernmental Panel on Climate Change (IPCC) estimates that if Earth's average temperature rises between 2 °C and 3 °C, about 20 to 30% of all terrestrial biodiversity will be at high risk of extinction by the end of the century (IPCC, 2014). In the last century, land and ocean temperature showed a warming of approximately 1.0 °C (IPBES, 2019), which may increase another 1.4 °C to 5.0 °C by 2100, if we do not reduce greenhouse gas emissions (IPCC, 2019). The latest IPCC special report reinforces the importance of keeping the temperature increase below 1.5 °C, in order to keep negative effects on natural resources, ecosystem functioning, food security and biodiversity to a minimum (IPCC, 2018). Considering the potential climate change scenarios with additional temperature increases, both widespread species and narrow-ranged endemic species will likely suffer irreparable consequences with regard to their distribution range and abundance (Warren et al., 2013).

Brazil is the world's most biodiversity-rich country, with 33,161 known species of vascular plants (Ulloa Ulloa et al., 2017), and harboring some of the largest remnants of tropical old-growth forests (Myers et al., 2000). Despite the large number of native plant species, many of which with major untapped socioeconomic potential, the Brazilian agricultural industry exploits only a few, and largely, exotic crops (Coradin et al., 2011). Agroforestry species are those that have the function of simultaneously benefiting people's livelihoods and the ecological systems while showing great potential for multi-species intercropping (Nair, 1993). These species are often characterized by their multiple uses, different harvest seasons and potential for market adoption (Cerda et al., 2014; Florencia Montagnini, 2017; Sinclair, 1999; Somarriba, 1992). Several useful native Brazilian plant species are potentially suitable for pasture production, silviculture, orchards, bioenergy, green manuring, as well as in integrated, biodiverse, multifunctional agroforestry (Coradin et al., 2011; Siddique, Dionísio, & Simões-Ramos, 2017). Besides enhancing biodiversity and

promoting the socio-economic development of local communities (Jose, 2012; Reppin, Kuyah, de Neergaard, Oelofse, & Rosenstock, 2020; Santos, Crouzeilles, & Sansevero, 2019; Sistla et al., 2016), agroforestry systems can play a pivotal role in mitigating the effects of climate change: they sequester more atmospheric carbon than conventional farming (De Stefano & Jacobson, 2017; Marconi & Armengot, 2020; Somarriba et al., 2013). Although agroforestry practices can ameliorate the impacts of climate change in Brazil, these agroecological systems are also vulnerable (Gomes et al., 2020). Considering the rapidly increasing human demand for plant products, native plant species from megadiverse countries undoubtedly represent a reservoir of genetic diversity, providing beneficial alleles for crop improvement and higher adaptive potential to face global changes (Coradin et al., 2011; Kofsky, Zhang, & Song, 2018). Changes in land use may not be the main driver impacting these species as they are widely distributed among the neotropics and are easily found along streets and city squares across Brazil, some almost ruderal, regenerating in open areas of cities (Coradin et al., 2011; Lorenzi, 2016). The future impact of climate change on species distributions should be taken into account for setting conservation priorities, as well as for promoting species conservation through their sustainable use (Zwiener et al., 2017).

Spatial and temporal changes of species' suitable habitat can be predicted with ecological niche models (ENMs), the most widely used tool to assess species vulnerability to changing climatic conditions (Gomes et al., 2018; Guisan & Thuiller, 2005b; Raes & Aguirre-Gutiérrez, 2018). Besides that, modeled habitats based on climatic variables allow us to consider the impacts of climate change on the species' area of habitat, which is the habitat available to a particular species within its range (Brooks et al., 2019). Here, to consider those impacts, we modeled the species' bioclimatic area of habitat (BAH). Species dispersal is pivotal to the survival of species in the face of rapid climate change (Soberon & Peterson, 2005). Thus, to better understand species responses, this central process that determines the potential spread of a population needs to be addressed in conservation assessments (Travis et al., 2013). Although several studies have sought to better understand the impact of climate change on the distribution of plant species with narrow-ranged distribution or threatened with extinction, we note that no study has yet focused on species of agroforestry interest in Brazil, which generally have widespread distribution. These species are promising for conservation-by-use, an approach used by people communities for millennia in different ecosystems in Brazil (Levis et al., 2017; Reis et al., 2018).

Here, we apply an ENM approach to (1) quantify potential changes in BAH of 135 native potential agroforestry species from the Brazilian flora using two climate change scenarios (SSP2-4.5 and SSP5-8.5) and two dispersal (non-dispersal and full dispersal) scenarios for 2041-2060 and 2061-2080. We then (2) assess the preliminary conservation status of each species using IUCN Red List of Threatened Species criteria (IUCN Standards and Petitions Committee, 2019).

Results

Model performance

We evaluated the model performance through a null-model for significance testing of presence-only ENMs and retained 135 significant ENMs, corresponding to 97.1% of all species. Overall, final models showed high accuracy, indicated by AUC values ranging from 0.850 ± 0.139 to 0.985 ± 0.058 , demonstrating a clear ability to distinguish suitable from unsuitable habitats. We detected no spurious correlations through inspection of species-response-curves.

Impacts on species BAH

Under the non-dispersal scenario, the average decline in BAH was predicted to be between 38.5% (SSP2-4.5) and 43.5% SSP5-8.5 by 2041-2060 and between 43.4% (SSP2-4.5) and 56.3% (SSP5-8.5) by 2061-2080. For the full dispersal scenario, however, the average decline of BAH was predicted to be between 22.3% (SSP2-4.5) and 29.7% (SSP5-8.5) by 2041-2060 and between 27.4% (SSP2-4.5) and 41.9% (SSP5-8.5) by 2061-2080 (Supplementary Table S1). Although the majority of species predicted BAH losses over different scenarios, some are predicted to experience BAH gains (Fig 1., Table 1, Supplementary Table S1). We noticed that some species were predicted to lose their entire BAH by 2041-2060 and 2061-2080, such as the medicinal species *Cunila microcephala* in the non-dispersal scenario and the forage species *Ornithopus micranthus*, in all scenarios, except for the SSP5-8.5 (2061-2080) in the non-dispersal scenario and SSP2-4.5 and SSP5-8.5 (2061-2080) in the full dispersal scenario. Species with the greatest increase in BAH were the forage species *Indigofera sabulicola* with an increase of 388%, the ornamental species *Epidendrum fulgens* (263%), and the forage species *Echinochloa polystachya* (259%) in the SSP5-8.5 for 2061-2080 considering the full dispersal scenario (Table 1, Supplementary Table S1).

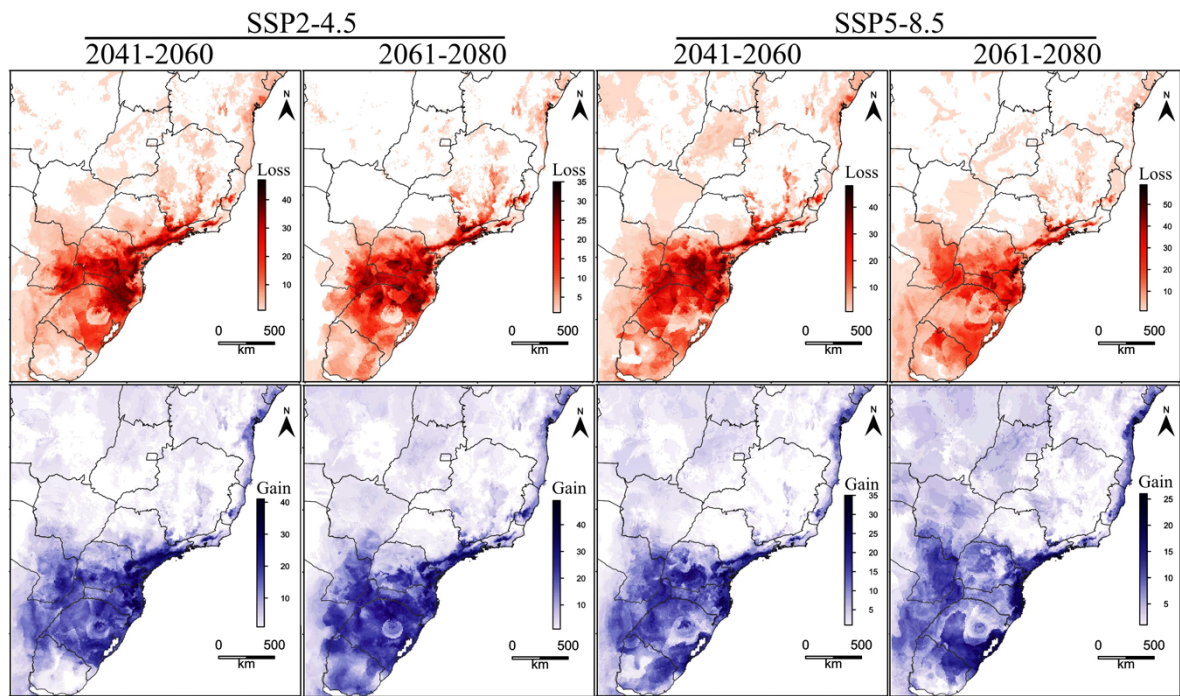


Figure 1. Loss (red) and gain (blue) of BAH for 135 native potential agroforestry plant species in Brazil, obtained by stacking ENM binary predictions, based on different climate scenarios and years. Legend indicates the number of species. Maps created with custom R script. Version R 4.1.1 (<https://www.R-project.org/>). Base map source (Brazilian states shapefile) obtained from the Brazilian Institute of Geography and Statistics (<https://www.ibge.gov.br/>).

Looking at specific groups by their main use, we estimate loss of BAH ranging from 2,9% (*Tropaeolum pentaphyllum*) to 76.5% (*Pimenta pseudocaryophyllus*) for aromatic species; 6.1% (*Geonoma gamiova*) to 58.8% (*Gynerium sagittatum*) for fibrous species; 7.1% (*Acca sellowiana*) to 91.8% (*Annona crassiflora*) for food species; 2.5% (*Stylosanthes leiocarpa*) to 100% (*O. micranthus*) for forage species from Fabaceae family; 1.6% (*Paspalum modestum*) to 95.9% (*Paspalum jesuiticum*) for forage species from Poaceae family; 4.5% (*Mikania laevigata*) to 100% (*C. microcephala*) for medicinal species; 2,3% (*Aspilia montevidensis*) to 99.6% (*Dyckia distachya*) for ornamental species; and 1.1% (*Hyeronima alchorneoides*) 88,4% (*Peltophorum dubium*) for medicinal species (Table 1, Supplementary Table S1). The species *Araucaria angustifolia*, which has already been traditionally combined in agroecological practices in southern Brazil is predicted to reduce up to 66% of its BAH under SSP5-8.5 by 2061-2080 in both dispersal scenarios (Fig. 2, Supplementary Table S1).

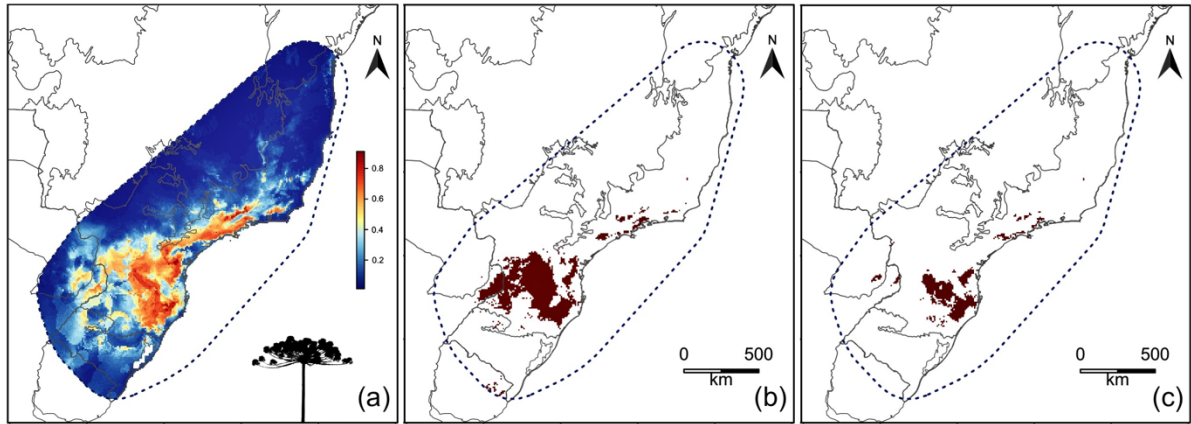


Figure 2. Decline of BAH by climate change for *A. angustifolia*, a species traditionally combined with other agricultural crops from Atlantic Forest. **a)** Current habitat suitability. Blue to red indicates the increase of suitability **b-c)** Future suitable habitats based on SSP2-4.5 and SSP5-8.5 scenarios for 2061-2080. Wine red colour indicates the remaining BAH. Estimated BAH is surrounded by dotted lines in royal blue colour. Maps created with custom R script. Version R 4.1.1 (<https://www.R-project.org/>). Base map source (Terrestrial biomes shapefile) obtained from the Brazilian Ministry of the Environment (<https://www.gov.br/mma/>).

Table 1. Future range changes for 135 native potential agroforestry plant species in Brazil under two dispersal scenarios.

	NON-DISPERSAL				FULL DISPERSAL			
	2041-2060		2061-2080		2041-2060		2061-2080	
Aromatic species	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
<i>Capsicum flexuosum</i>	-36.1	-47.7	-39.2	-60.1	-33.7	-35.8	-38.0	-57.1
<i>Pimenta pseudocaryophyllus</i>	-45.3	-51.7	-52.9	-77.6	-38.9	-47.6	-44.8	-76.5
<i>Schinus terebinthifolia</i>	-28.6	-33.6	-30.6	-47.0	-12.7	-14.7	-16.6	-31.3
<i>Tropaeolum pentaphyllum</i>	-30.9	-29.9	-34.1	-39.2	-2.9	3.1	0.1	-14.1
Fibrous species								
<i>Coleataenia prionitis</i>	-17.9	-38.5	-33.6	-52.1	50.6	26.1	54.4	32.7
<i>Geonoma gamiova</i>	-6.1	-6.6	-17.5	-35.2	56.1	86.1	25.0	28.8
<i>Gynerium sagittatum</i>	-43.5	-47.8	-48.1	-58.8	-32.0	-34.2	-34.8	-42.0
<i>Philodendron corcovadense</i>	-35.4	-38.1	-40.9	-45.1	-7.6	1.1	-12.5	14.5
<i>Schoenoplectus californicus</i>	-27.5	-32.8	-32.4	-51.0	-22.8	-28.4	-25.9	-47.9
Food species								
<i>Acca sellowiana</i>	-22.6	-28.7	-34.6	-39.4	-7.1	-20.1	-10.3	-13.4
<i>Annona crassiflora</i>	-68.2	-82.9	-76.3	-91.8	-61.0	-77.9	-71.5	-89.1
<i>Araucaria angustifolia</i>	-46.2	-52.9	-52.7	-66.6	-46.1	-52.9	-52.6	-66.5
<i>Butia eriospatha</i>	-67.7	-77.3	-67.8	-87.4	-45.2	-50.4	-52.7	-64.3

<i>Campomanesia xanthocarpa</i>	-38.9	-32.1	-36.6	-47.8	-35.5	-25.8	-35.2	-43.3
<i>Eugenia involucrata</i>	-42.4	-44.5	-45.6	-61.8	-39.9	-40.4	-43.6	-59.7
<i>Eugenia pyriformis</i>	-34.2	-60.1	-53.4	-60.9	-17.6	-38.9	-42.1	-48.8
<i>Eugenia uniflora</i>	-39.4	-43.8	-42.8	-56.2	-9.6	-8.0	-16.6	-33.8
<i>Euterpe edulis</i>	-50.1	-52.7	-58.0	-69.7	-19.9	-19.9	-20.3	-33.7
<i>Opuntia elata</i>	-12.0	-58.6	-57.8	-47.9	45.8	-28.7	-26.2	12.3
<i>Passiflora actinia</i>	-46.5	-44.3	-41.6	-49.4	-37.3	-21.6	-33.6	-26.2
<i>Physalis pubescens</i>	-43.2	-48.1	-47.1	-61.9	-41.4	-46.0	-45.5	-59.2
<i>Plinia peruviana</i>	-79.6	-87.3	-76.0	-88.3	-56.9	-68.0	-60.2	-64.2
<i>Psidium cattleianum</i>	-26.5	-31.9	-37.4	-46.1	-10.2	-20.7	-26.6	-34.0
<i>Vasconcellea quercifolia</i>	-42.1	-51.5	-52.8	-50.3	-26.3	-43.0	-44.5	-34.8
Forage species (Fabaceae)								
<i>Adesmia bicolor</i>	-64.5	-69.0	-74.1	-80.1	-48.2	-58.5	-48.6	-76.0
<i>Adesmia latifolia</i>	-68.3	-47.2	-51.8	-52.9	40.8	39.3	13.8	23.5
<i>Adesmia tristis</i>	-94.4	-97.0	-98.0	-99.2	-94.4	-96.9	-98.0	-99.2
<i>Desmodium adscendens</i>	-15.7	-14.4	-18.5	-16.3	76.6	122.9	91.9	190.9
<i>Desmodium barbatum</i>	-17.0	-17.5	-19.8	-24.1	25.0	29.0	30.8	29.0
<i>Desmodium incanum</i>	-27.7	-29.9	-31.9	-41.9	-21.5	-24.5	-27.6	-37.7
<i>Desmodium subsericeum</i>	-59.1	-70.8	-65.1	-77.5	-44.4	-63.7	-55.7	-68.7
<i>Indigofera sabulicola</i>	0.3	0.3	0.5	0.0	183.7	218.4	191.0	387.7
<i>Leptospron adenanthum</i>	-10.5	-11.8	-12.6	-10.3	62.7	79.6	74.6	119.2
<i>Macropitium psammodes</i>	-20.9	-30.3	-32.3	-12.9	115.3	123.1	115.5	227.9
<i>Ornithopus micranthus</i>	-100.0	-100.0	-100.0	-95.1	-100.0	-100.0	-95.1	-95.1
<i>Stylosanthes leiocarpa</i>	-37.6	-36.2	-37.2	-30.7	-21.8	-2.5	-14.8	19.4
<i>Trifolium polymorphum</i>	-47.1	-48.8	-67.6	-81.8	2.6	2.3	-5.0	-48.1
<i>Trifolium riograndense</i>	-91.1	-75.5	-95.3	-86.4	-91.1	-75.2	-95.3	-86.4
<i>Vigna luteola</i>	-16.9	-23.1	-21.7	-26.2	0.5	-4.7	-5.8	-11.8
Forage species (Poaceae)								
<i>Axonopus compressus</i>	-36.4	-34.8	-37.5	-55.2	-23.8	-19.7	-22.6	-42.0
<i>Axonopus fissifolius</i>	-24.6	-26.5	-28.0	-34.0	98.5	143.3	121.8	182.7
<i>Axonopus obtusifolius</i>	-53.4	-57.9	-59.1	-76.0	0.2	-3.6	-7.1	-34.3
<i>Bothriochloa laguroides</i>	-54.8	-50.9	-60.6	-77.3	-38.6	-23.8	-37.6	-65.5
<i>Bromus auleticus</i>	-81.0	-82.3	-69.7	-88.5	-79.2	-80.3	-52.3	-83.6
<i>Bromus catharticus</i>	-35.8	-44.3	-40.7	-49.6	-33.2	-41.5	-36.2	-45.8
<i>Dichantherium sabulorum</i>	-35.4	-38.2	-45.1	-62.9	-34.4	-33.9	-44.0	-60.3
<i>Echinochloa polystachya</i>	-7.6	-8.3	-9.8	-10.8	174.3	210.0	187.5	259.4
<i>Hemarthria altissima</i>	-11.4	-7.0	-4.6	-8.4	60.2	47.2	73.2	116.0
<i>Ischaemum minus</i>	-29.9	-40.9	-47.1	-6.0	42.2	36.8	22.6	141.5
<i>Mnesithea seloana</i>	-41.1	-49.9	-64.4	-72.4	36.3	28.6	30.0	23.3
<i>Nassella neesiana</i>	-30.7	-31.9	-34.4	-46.3	-26.3	-29.4	-21.2	-45.4
<i>Paspalum alnum</i>	-2.0	-18.8	-14.4	-16.9	93.1	48.4	54.3	63.5
<i>Paspalum denticulatum</i>	-22.9	-31.1	-31.2	-43.5	-1.8	0.6	7.8	-17.9

<i>Paspalum dilatatum</i>	-26.1	-26.3	-27.8	-45.8	-25.6	-26.0	-27.2	-45.7
<i>Paspalum glaucescens</i>	-59.0	-42.0	-55.2	-61.0	-36.7	5.7	-37.8	-41.9
<i>Paspalum guenoarum</i>	-24.1	-28.3	-31.4	-42.3	-11.9	-14.6	-17.8	-28.1
<i>Paspalum jesuiticum</i>	-69.4	-74.1	-81.2	-95.9	-69.4	-74.1	-81.2	-95.9
<i>Paspalum lepton</i>	-5.6	-6.6	-12.3	-5.4	117.6	111.5	137.9	127.1
<i>Paspalum modestum</i>	0.3	-4.1	-1.6	-4.2	110.6	99.8	102.6	143.0
<i>Paspalum notatum</i>	-26.0	-27.1	-28.0	-42.0	-25.2	-26.0	-26.9	-40.6
<i>Paspalum pumilum</i>	-41.8	-39.3	-39.7	-50.2	-41.0	-34.7	-38.5	-47.9
<i>Paspalum regnellii</i>	-16.8	-37.4	-29.0	-40.4	40.4	17.0	7.5	20.1
<i>Poa lanigera</i>	-30.2	-28.6	-30.3	-46.7	-3.2	-9.1	4.1	-25.3
<i>Schizachyrium tenerum</i>	-49.8	-51.2	-53.4	-68.9	-46.3	-46.2	-50.0	-64.3
Medicinal species								
<i>Achyrocline satureioides</i>	-45.7	-48.0	-47.8	-59.1	-45.0	-47.0	-47.3	-57.4
<i>Baccharis articulata</i>	-48.8	-53.2	-50.9	-58.7	-44.2	-43.7	-45.1	-53.3
<i>Baccharis crispa</i>	-39.2	-45.4	-44.7	-57.8	-38.2	-42.7	-43.1	-56.6
<i>Baccharis dracunculifolia</i>	-42.9	-52.8	-51.6	-64.5	-37.4	-44.7	-45.6	-58.4
<i>Bauhinia forficata</i>	-42.5	-44.9	-43.4	-55.3	-33.0	-32.4	-33.1	-45.1
<i>Bromelia antiacantha</i>	-28.2	-29.1	-26.0	-23.4	26.5	34.6	26.9	27.0
<i>Casearia sylvestris</i>	-37.1	-38.3	-39.0	-50.4	-7.3	-7.5	-6.8	1.7
<i>Cecropia glaziovii</i>	-42.6	-51.8	-55.4	-69.1	-21.7	-41.0	-40.3	-54.2
<i>Copaifera trapezifolia</i>	-19.3	-22.3	-25.1	-39.6	20.1	9.5	15.0	-17.5
<i>Croton celtidifolius</i>	-35.0	-54.2	-44.0	-81.6	-32.8	-53.3	-40.6	-81.4
<i>Cunila microcephala</i>	-100.0	-100.0	-100.0	-100.0	-42.4	-33.1	-48.3	-88.1
<i>Drimys brasiliensis</i>	-73.8	-76.9	-77.9	-91.7	-73.8	-76.9	-77.9	-91.7
<i>Echinodorus grandiflorus</i>	-20.0	-28.5	-26.8	-36.5	-17.4	-23.9	-23.3	-31.4
<i>Equisetum giganteum</i>	-36.2	-39.8	-38.1	-48.7	-31.0	-34.8	-31.8	-40.7
<i>Hypericum caprifoliatum</i>	-5.5	-11.2	-12.8	-19.9	29.6	7.2	2.6	5.1
<i>Ilex paraguariensis</i>	-40.0	-41.2	-46.3	-57.8	-38.8	-37.3	-44.9	-57.6
<i>Jodina rhombifolia</i>	-57.5	-58.4	-59.5	-62.2	-51.5	-52.5	-53.0	-50.9
<i>Mikania glomerata</i>	-41.7	-37.1	-47.6	-56.9	-12.9	-6.0	-18.8	-24.4
<i>Mikania laevigata</i>	-27.4	-23.0	-26.5	-32.8	-12.8	3.2	-14.4	-4.5
<i>Monteverdia ilicifolia</i>	-23.7	-36.8	-37.5	-41.5	-18.9	-30.5	-33.2	-36.5
<i>Ocimum carnosum</i>	-17.3	-41.1	-36.1	-35.7	-10.3	-34.4	-30.0	-29.4
<i>Piper umbellatum</i>	-43.7	-50.4	-48.9	-63.7	-37.6	-42.2	-45.0	-54.4
<i>Plantago australis</i>	-38.5	-42.0	-40.6	-53.3	-34.0	-37.3	-35.1	-46.1
<i>Sambucus australis</i>	-32.5	-37.8	-38.0	-39.5	-26.3	-34.1	-29.6	-32.7
<i>Smilax campestris</i>	-44.7	-45.7	-47.0	-62.2	-37.6	-36.2	-41.4	-54.9
<i>Solanum mauritanium</i>	-43.5	-45.2	-48.8	-61.0	-39.1	-39.2	-45.9	-58.3
<i>Solanum paniculatum</i>	-42.6	-54.0	-46.9	-62.0	-26.4	-38.2	-30.5	-30.1
<i>Sorocea bonplandii</i>	-43.8	-56.4	-52.3	-68.1	-21.1	-39.5	-21.9	-58.3
<i>Trichilia catigua</i>	-38.5	-66.0	-56.5	-79.4	-8.5	-34.9	-23.5	-51.8
<i>Varronia curassavica</i>	-29.1	-33.2	-32.5	-36.5	65.3	122.4	83.6	229.5

<i>Wilbrandia ebracteata</i>	-36.3	-28.6	-23.2	-60.5	28.2	20.5	42.3	-33.6
<i>Zollernia ilicifolia</i>	-38.8	-42.5	-42.4	-57.4	-14.1	-6.6	-15.0	-36.1
Ornamental species								
<i>Ananas bracteatus</i>	-44.6	-46.6	-46.0	-60.2	-37.3	-37.7	-39.5	-52.7
<i>Aspilia montevidensis</i>	-27.5	-28.9	-35.6	-27.6	-2.3	9.9	-10.8	13.4
<i>Calliandra tweedii</i>	-32.7	-42.9	-42.4	-52.5	-27.8	-33.9	-38.1	-44.5
<i>Cortaderia selloana</i>	-35.0	-44.0	-39.2	-57.7	-30.1	-39.4	-31.6	-52.6
<i>Dyckia distachya</i>	-44.7	-99.6	-71.8	-91.7	159.0	-36.8	44.4	21.4
<i>Epidendrum fulgens</i>	-18.1	-19.0	-37.5	-3.7	30.3	123.1	14.2	264.0
<i>Fuchsia regia</i>	-51.2	-56.4	-56.9	-79.9	-49.7	-54.9	-55.6	-79.3
<i>Gomesa flexuosa</i>	-38.1	-40.6	-39.2	-60.5	-23.0	-31.4	-24.6	-52.4
<i>Handroanthus chrysotrichus</i>	-38.5	-43.2	-45.3	-60.5	-14.9	-25.0	-21.0	-40.7
<i>Heliconia farinosa</i>	-13.7	-15.5	-12.6	-20.6	27.7	64.1	71.9	29.1
<i>Jacaranda puberula</i>	-40.2	-49.4	-50.1	-63.7	-27.0	-36.9	-36.2	-52.5
<i>Parodia ottonis</i>	-63.9	-56.0	-72.6	-82.5	-51.8	-42.4	-68.5	-76.6
<i>Petunia integrifolia</i>	-4.2	-5.6	-12.7	-12.2	7.3	1.2	-10.1	-4.9
<i>Pyrostegia venusta</i>	-49.3	-46.6	-46.3	-48.9	-12.0	22.2	8.4	70.5
<i>Rumohra adiantiformis</i>	-34.9	-38.3	-41.6	-52.2	-34.6	-36.6	-41.5	-51.8
<i>Syagrus romanzoffiana</i>	-61.0	-62.4	-61.8	-75.5	-27.3	-30.0	-21.7	-56.0
<i>Tibouchina sellowiana</i>	-41.8	-53.9	-50.3	-74.5	-9.1	-39.6	-35.0	-69.8
<i>Trichocline catharinensis</i>	-54.1	-85.6	-83.3	-89.0	-53.0	-71.2	-83.3	-86.7
<i>Verbena rigida</i>	-47.5	-68.4	-67.0	-69.3	-32.6	-50.8	-49.8	-66.2
Timber species								
<i>Apuleia leiocarpa</i>	-56.0	-61.0	-60.6	-75.3	-52.8	-57.0	-57.8	-71.1
<i>Aspidosperma polyneuron</i>	-49.7	-57.1	-47.7	-63.6	34.7	41.4	29.4	155.9
<i>Ateleia glazioviana</i>	-28.3	-15.3	-36.7	-17.0	17.3	39.2	-11.5	27.4
<i>Balfourodendron riedelianum</i>	-29.0	-52.7	-37.7	-51.6	-24.2	-47.3	-31.1	-46.0
<i>Cabralea canjerana</i>	-42.4	-52.0	-50.9	-61.6	-40.4	-48.1	-48.5	-57.1
<i>Calophyllum brasiliense</i>	-39.8	-41.2	-43.3	-40.7	104.5	137.5	125.3	183.0
<i>Cedrela fissilis</i>	-48.4	-54.1	-52.8	-67.1	-47.8	-52.6	-52.5	-66.3
<i>Colubrina glandulosa</i>	-60.7	-59.6	-54.9	-74.7	-52.3	-49.9	-45.3	-69.8
<i>Cordia trichotoma</i>	-54.0	-59.9	-58.4	-72.6	-41.5	-45.2	-44.8	-57.6
<i>Enterolobium contortisiliquum</i>	-46.8	-63.3	-55.7	-74.8	-23.9	-44.9	-32.0	-49.3
<i>Handroanthus heptaphyllus</i>	-26.4	-30.7	-38.3	-58.2	28.0	25.7	7.3	-12.4
<i>Hyeronima alchorneoides</i>	-34.8	-38.2	-36.3	-45.4	-1.1	13.7	9.7	32.6
<i>Miconia cinnamomifolia</i>	-8.9	-15.5	-14.6	-27.0	27.9	12.4	15.0	-13.0
<i>Mimosa scabrella</i>	-44.8	-61.5	-61.2	-83.5	-44.8	-61.4	-61.2	-83.5
<i>Nectandra lanceolata</i>	-40.2	-52.1	-49.7	-60.8	-34.6	-47.3	-44.9	-56.9
<i>Ocotea puberula</i>	-38.2	-39.7	-39.7	-55.4	-34.0	-33.3	-35.4	-50.8
<i>Parapiptadenia rigida</i>	-38.4	-48.3	-44.5	-56.5	-20.9	-17.1	-26.8	-33.5
<i>Peltophorum dubium</i>	-76.5	-79.4	-74.8	-88.4	-58.3	-61.5	-49.8	-68.9
<i>Piptocarpha angustifolia</i>	-41.7	-65.7	-69.9	-72.2	-9.2	-47.3	-59.5	-56.3

<i>Schizolobium parahyba</i>	-38.6	-36.0	-36.7	-52.2	-24.1	-11.1	-15.9	-39.1
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IUCN Red list preliminary assessment

Assessing the geographic range (B1a + B2a criteria), we found that only 4.3% of the native species was qualified for a Threat category (Supplementary Table S2). However, when considering the predicted quantitative habitat loss due to climate change (A3c criterion) the percentages increased. We observed that 68.8% (SSP2-4.5/2041-2060) to 84.4% (SSP5-8.5/2061-2080) under the non-dispersal scenario (Fig. 3a, Supplementary Table S1) and 40.7% (SSP2-4.5/2041-2060) to 64.4% (SSP5-8.5/2061-2080) under the full dispersal scenario of the species could be qualified as threatened according to IUCN Red List criteria (Fig. 3b, Supplementary Table S1). The highest proportions of species were qualified as vulnerable with 49.6% (SSP2-4.5/2041-2060), 40.7% (SSP5-8.5/2041-2060) and 46.6% (SSP2-4.5/2061-2080) under the non-dispersal scenario and 30.3% (SSP2-4.5/2041-2060), 35.5% (SSP5-8.5/2041-2060) and 34.8% (SSP2-4.5/2061-2080) under the full dispersal scenario. The exception was the SSP5-8.5 (2061-2080) scenario, where the largest proportion was qualified as endangered in both the non-dispersal scenario (48.1%) and full dispersal scenario (31.8%) (Fig. 3a, Fig. 3b). Approximately 96% of the species have not yet been accessed by the IUCN and are currently Not Evaluated (NE). Here, we show that 86% of these species are predicted to change from Not Evaluated to a threat category, Vulnerable (VU), Endangered (EN) and Critically Endangered (CR), in all major uses and based on different climate change scenarios (Fig. 4, Table 2, Supplementary Figures S1). All species groups changed from 50% to 100% of their species to the Vulnerable category. Timber species had the highest percentage of their species (84.2%) changing to the Endangered category and, the forage species belonging to the Fabaceae family had the highest (55.6%) changing to the Critically Endangered category.

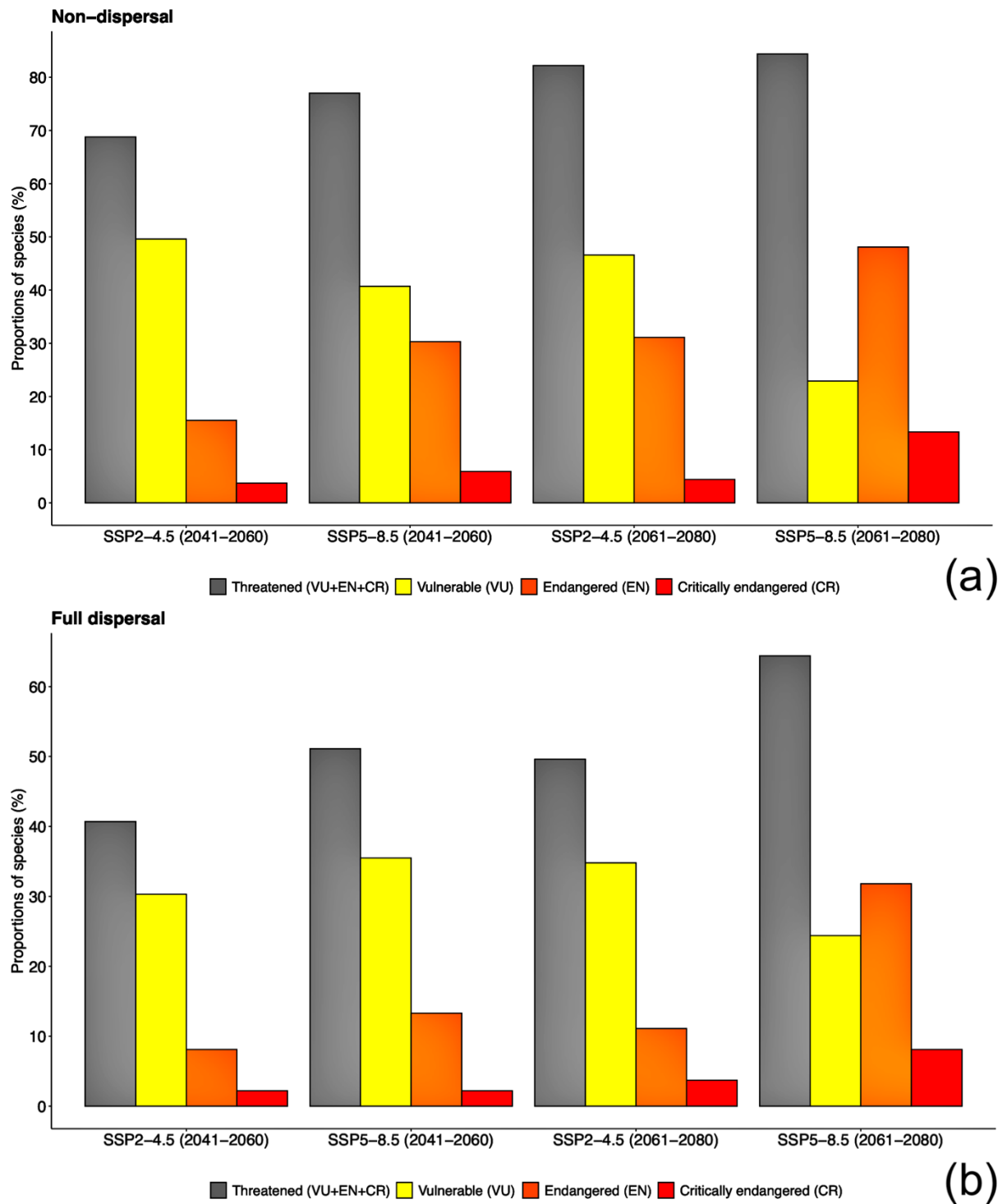


Figure 3. Percentage of Brazilian agroforestry plant species potentially qualified in a threat categories VU+EN+CR, and in separate categories Vulnerable (VU), Endangered (EN) and Critically Endangered (CR), under two different climate change scenarios (SSP2-4.5 and SSP5-8.5) for the following time periods: 2041-2060 and 2061-2080, assuming two dispersal scenarios: **a)** non-dispersal and **b)** full dispersal.

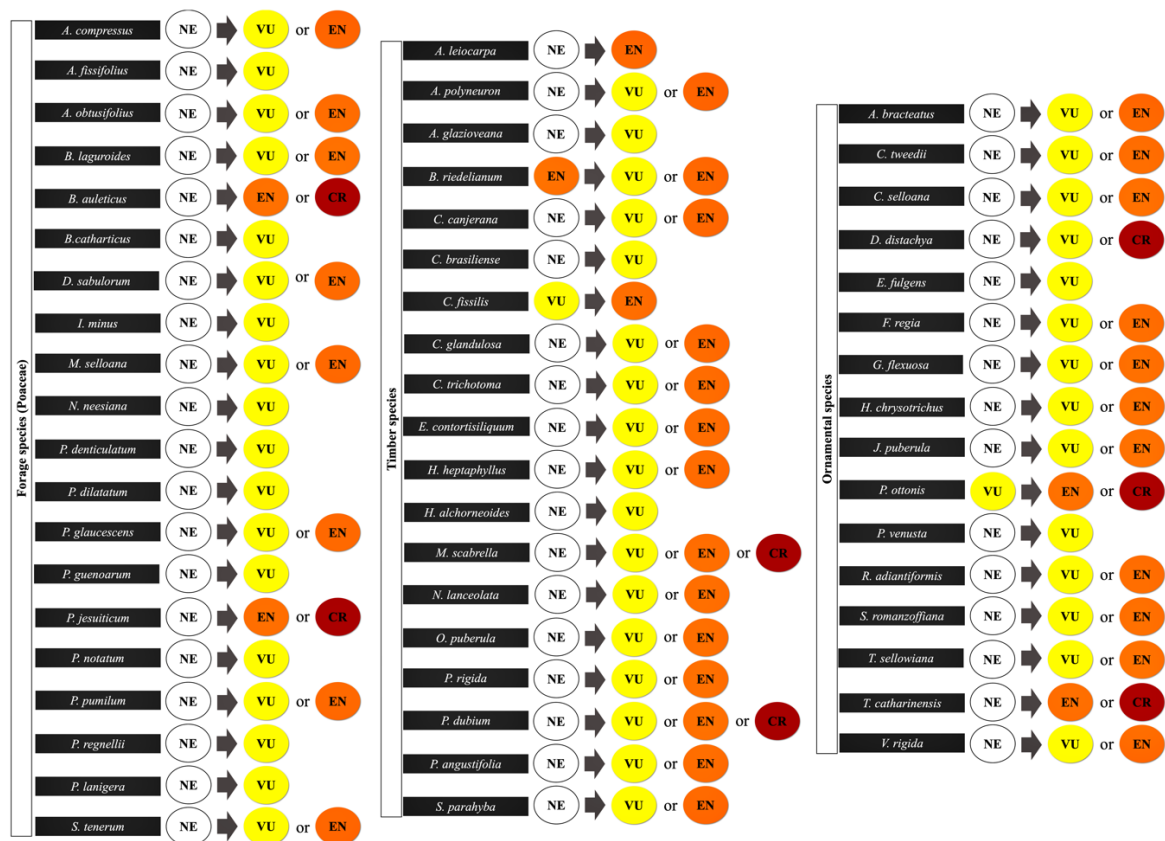


Figure 4. Native potential agroforestry plant species changing from a current assessed IUCN category or Not Evaluated (NE) to a threat category, Vulnerable (VU), Endangered (EN) and Critically Endangered (CR), based on different major uses due to climate change.

Table 2. Number and percentage of species changing from Not Evaluated to a threat category, Vulnerable (VU), Endangered (EN) and Critically Endangered (CR), in all major uses and in at least one climate change scenario.

Main use	VU		EN		CR	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
Aromatic species	4	100.0	2	50.0	-	-
Fibrous species	4	100.0	2	50.0	-	-
Food species	12	80.0	11	73.3	3	20.0
Forage species (Fabaceae)	6	66.7	5	55.6	5	55.6
Forage species (Poaceae)	10	50.0	9	45.0	2	10.0
Medicinal species	27	93.1	20	69.0	3	10.3
Ornamental species	14	87.5	12	75.0	3	18.8
Timber species	17	89.5	16	84.2	2	10.5

Discussion

Climate change is an important driver of species extinction (IPBES, 2019; Pecl et al., 2017; Somarriba et al., 2013). We found that future climate change was predicted to cause a decline in BAH between 38.5-56.3% under the non-dispersal scenario and between 22.3-41.9% under the full dispersal scenario in 135 Brazilian native species. Several studies forecasted the impacts of climate change on species distribution by using ENMs worldwide (Gomes et al., 2019; Guo et al., 2017; Rodrigues et al., 2015; Wilson, Walters, Mayle, Lingner, & Vibrans, 2019), and consequently on ecosystem functionality (Cámara-Leret et al., 2019; Pecl et al., 2017). The worst-case scenario (SSP5-8.5) showed the highest average decline in BAH in both non-dispersal (56.3%) and full dispersal (41.9%), when compared to the stabilization scenario (SSP2-4.5) and in 2061-2080, showing that species tend to be more threatened in this scenario and year, as demonstrated in other studies conducted with Brazilian species (Esser, Saraiva, & Jarenkow, 2019; Lima et al., 2020). Our study evaluated widespread plant species, such as *Axonopus fissifolius*, occurring in all Brazilian phytogeographic domains and species with a narrow-ranged distribution, such as *Adesmia bicolor* from South Brazilian grasslands (Pampa). We noticed that both narrow-ranged and widespread species may be impacted by climate change. For instance, the narrow-ranged species *O. micranthus*, used in annual forage crops, is predicted to lose up to 100% of its suitable habitat in most climate change scenarios. Our models also suggested that the widespread Brazilian peppertree (*Schinus terebinthifolia*) may lose up to 47% of its original habitats. These results need to be interpreted with caution, since all species that were predicted to lose 100% of BAH have small sample sizes ($n < 50$, Supplementary Table S1), which is one of the main determinants of model accuracy (Santini, Benítez-López, Maiorano, Čengić, & Huijbregts, 2021). Some species tend to be favored by certain climate change scenarios under full dispersal scenario (Raes et al., 2014; Vaz & Nabout, 2016), such as here the medicinal species *Varronia curassavica*, with an increase of BAH up to 230%; the ornamental species *Epidendrum fulgens* up to 264% and the forage species *Indigofera sabulicola* up to 387%. Although some species were predicted to expand their range, this does not guarantee the survival of these species, since other drivers, such as the capability of poor dispersal species to cope with climate change (Sánchez-Fernández et al., 2016), deforestation (de Lima et al., 2015; Gomes et al., 2019) and other land-use changes threaten Brazilian ecosystems and the survival of their associated species (Ribeiro et al., 2011).

Rapid range changes of species may, in turn, impact material, non-material and regulating contributions of nature to people (Cámara-Leret et al., 2019; Chen et al., 2011; Díaz et al., 2018; Siddique et al., 2021). The global productivity of farms may be negatively affected by climate change throughout most of the tropics (Harvey et al., 2014). Smallholders and traditional Brazilian communities such as the *caíçaras*, *quilombolas* and indigenous peoples make use of these species in agroforestry practices (Coradin et al., 2011), a land use management system that increases carbon sequestration in biomass and soils (Marconi & Armengot, 2020; Schneidewind et al., 2019). These systems improve people's livelihoods by simultaneously providing income, food security, fuel, medicine, forage, and/or other goods and services. Moreover, increased tree cover due to agroforestry may help to mitigate climate change (Díaz et al., 2018; Dinesh, Campbell, Bonilla-findji, & Richards, 2017; Reppin et al., 2020). Here we present evidence of how currently suitable areas for cultivation of these species may become unsuitable in the future. This may lead to a severe decline in people's livelihoods and regional food security (Lin, Perfecto, & Vandermeer, 2008; Reppin et al., 2020). Moreover, under climate shifts species survival is likely to be threatened by biogeographic barriers such as an agricultural or otherwise ecologically degraded landscape matrix which would prevent species migration to climatically more suitable areas (Perfecto, John Vandermeer, & Angus Wright, 2019).

The outcomes of climate change predicted by biogeographical and ecological studies have been neglected and have barely been integrated into conservation planning (Hannah et al., 2020; Zwiener et al., 2017). Prioritization of conservation efforts is often based on a species' extinction risk (Zizka et al., 2020). Determining whether a taxon is threatened with extinction depends on biological indicators, such as rapid population decline, and qualifying species in a threat category may assist in decision making (IUCN Standards and Petitions Committee, 2019). Our analyses highlight that 68.8% to 84.4% (non-dispersal) and 40.7% to 64.4% (full dispersal) of our species of interest may become threatened. Additionally, species already threatened according to the IUCN red list; *A. angustifolia* (CR), *Butia eriospatha* (VU), *Balfourodendron riedelianum* (EN), *Cedrela fissilis* (VU) and *Parodia ottonis* (VU) will remain listed as such as a result of climate change. In assessing Amazonian tree species, Gomes et al. (2019) found that 43-46% of trees species should be listed as threatened according to IUCN A2, A4, B1 and D2 criteria for RCP 2.6 and RCP 8.5 respectively. Similarly, Zizka *et al.* (2020), analyzing the conservation status of species of Bromeliaceae based on the geographic range in the Americas, showed that a total of 81% of bromeliad

species are possibly threatened according to IUCN red list criteria. These authors observed that the medicinal species *Bromelia antiacantha* is possibly not threatened (LC or NT) in the current scenario, which agrees with our full dispersal scenario results that show that the BAH of this species may remain stable under all future climate change scenarios as well. Elias et al. (Elias, Lima, & Santos, 2019) assessed the conservation status of eleven palm species through A2, A4 and B2 criteria in the state of Santa Catarina (Atlantic Forest) and qualified *Euterpe edulis* and *G. gamiova* as Vulnerable and *Butia catarinensis* and *Butia eriospatha* as Endangered. According to our findings, *E. edulis* may be categorized as Endangered for showing a decline in BAH of over 50% in all climate change scenarios when assuming species have no dispersal. However, when we considered the full dispersal scenario, we noted that although there are declines in BAH in all climate change scenarios, only in the SSP5-8.5 for 2061-2080 this species might be qualified as Vulnerable. For *G. gamiova* we observed a similar result (Vulnerable) exclusively in the SSP5-8.5 for 2061-2080 assuming no dispersal. On the other hand, assuming the full dispersal scenario, we noted an increase in BAH of up to 86% in the SSP5-8.5 for 2041-2060 for all climate change scenarios. Our results are equally consistent with the assessment of these authors for *B. catarinensis* and *B. eriospatha*. We still recorded an alarming scenario for *B. eriospatha*, qualifying the species as Critically endangered because of a decline of BAH declines over 87% (non-dispersal) under the worst-case scenario SSP5-8.5 for 2061-2080. Thus, given the large number of agroforestry species at risk of extinction, and the low number of species assessed by the IUCN Red List, we emphasize an urgent need for updates of the official list of threatened species, to provide a more precise indicator for threatened plant species conservation planning in Brazil. Despite all legal implications for threatened species in Brazil, agroforestry systems can act as an alternative to overcome part of the conflicts between conventional agricultural production and the conservation of natural resources, as can be seen in the new forest code (Law 12.651/2012), which provides explicit provisions for sustainable agroforestry. Additionally, a specific Law (12.854/2013) promotes forest recovery activities and the implementation of agroforestry systems (Siminski, dos Santos, & Wendt, 2016).

It is well known that deforestation is a primary driver leading species to extinction (IPBES, 2019; Pimm et al., 2014). However, climate change is expected to overtake this driver in a few decades (Gomes et al., 2019). The majority of the species prioritized in the “Plants for the future initiative”, found mainly in the Atlantic Forest have great potential to be conserved through sustainable practices, particularly by smallholders and traditional

communities (Coradin et al., 2011). The Atlantic Forest remains endangered as a result of continued deforestation and the future of this forest relies on well-structured conservation plans based on reliable information (Brancalion et al., 2019; Crouzeilles et al., 2019; de Lima et al., 2015). The Atlantic Forest cover has been reduced to less than 20% of its original size (Magnago et al., 2015; Rodrigues et al., 2019), distributed mainly in small and disturbed fragments of less than 50 hectares (de Lima et al., 2020; Ribeiro et al., 2011). Thus, most of the endemic species in the Atlantic Forest biome could already be qualified as critically endangered according to IUCN criteria (IUCN Standards and Petitions Committee, 2019). On the other hand, despite our predicted catastrophic scenarios for native Atlantic Forest species, we observe that species such as Bracatinga (*M. scabrella*), Brazilian peppertree (*Schinus terebinthifolia*) and Peruvian groundcherry (*Physalis peruviana*), are distributed across the neotropics and easily found along streets and city squares all over Brazil. Many of these are pioneers, some almost ruderal, regenerating easily in open city areas (Coradin et al., 2011; Lorenzi, 2016). Many of these forest species have endured over 500 years of deforestation, and still remain abundant in the Atlantic Forest even after losing approximately 80% of their natural habitat (Lorenzi, 2016; Ribeiro et al., 2011; Rodrigues et al., 2019). Hence, we note the need for studies that address species response to global changes to better understand the resilience potential of these species.

Protecting people's livelihoods in a rapidly changing climate may be one of the great challenges of the 21st century. Although it is not shared by all of the scientific community, as discussed by Loreau (Loreau, 2014), species with economic value seem to have advantages for conservation over those with non-economic value as can be seen in long-term human activities such as protection, transport and planting of useful species and removal of non-useful species by local communities (Berkes & Folke, 2000; Reis et al., 2018; Zechini et al., 2018). Indeed, socioeconomic underutilization of plant resources may in some cases even jeopardize socioecological synergies of tropical forest resilience (Siddique et al., 2021). All species analyzed here have a great potential to be conserved through a conservation-by-use approach, because of their different uses that do not necessarily jeopardize reproduction and persistence. They play an important role among local communities (Cámara-Leret et al., 2019; Fernandes & Piovezana, 2015; Levis et al., 2017; Lima et al., 2020; Machado Mello & Peroni, 2015) and farmers' livelihoods (Reis et al., 2018; Zechini et al., 2018). Searching for evidence of conservation among species with economic and cultural values, Reis *et al.* (Reis et al., 2018) noticed that the species *Ilex paraguariensis*, *A. angustifolia* and *B. antiacantha* were

intentionally favored through protection, transplantation and selection by farmers. Furthermore, Donazzolo *et al.* (Donazzolo, Stefenon, Guerra, & Nodari, 2020) noted that management of *Acca sellowiana* populations, retained high level of genetic diversity and tended to increase the species genetic variability. We argue that adopting measures, such as the establishment of new agroforestry systems to increase carbon sequestration, the selection of varieties capable of withstanding new climates and the improvement of habitat connectivity to facilitate species migration/dispersal should be a strategy for short-term and long-term conservation and people's livelihoods.

ENMs are widely used to forecast the distribution of species across geographic space and time. Building meaningful models to estimate the future distribution of species for an uncertain future requires very specific decisions and interpretations with extreme caution (Santini *et al.*, 2021; Thuiller, Guéguen, Renaud, Karger, & Zimmermann, 2019; Zurell *et al.*, 2020). Several uncertainties and complexities are related to our study. Modeling a large number of species can make the species-specific selection of predictors methodologically and practically complex (Thuiller *et al.*, 2019; Warren, Matzke, & Iglesias, 2020). To mitigate this, we selected the most suitable environmental predictors for different plant growth forms. Model performance evaluation is a key step for ENM studies and probably the most problematic one owing to its complexity (Warren *et al.*, 2020). The random cross-validation approach is the most common practice, adopted by modelers to evaluate model performance, where datasets are split into k folds, using one part to test the model and the remaining ($k-1$ folds) to calibrate the model (Araujo & New, 2007; Leroy *et al.*, 2018). To reduce the over-optimistic nature of cross-validation, we applied a null-model for significance testing of presence-only ENMs (Raes & ter Steege, 2007). Binarization of continuous probabilities output is commonly employed by modelers to quantify species range changes and build species richness over time (Newbold, 2018). Nevertheless, Santini *et al.* (Santini *et al.*, 2021) recently concluded that this practice reduces the predictive probability of models. Although we binarized ENMs outputs to quantify the climate change impacts, we applied a threshold highly indicated for conservation purposes for showing high performance in the identification of suitable areas and commonly used (Bean *et al.*, 2012; Lima *et al.*, 2020; Loiselle *et al.*, 2003; Meyer *et al.*, 2014). We assumed that the species are at equilibrium with the environment (Araújo & Pearson, 2005) and occurrence records were sampled randomly (Guillera-Arroita *et al.*, 2015). Furthermore, we included no biotic interactions (Bascompte, García, Ortega, Rezende, & Pironon, 2019; Soberon & Peterson, 2005), adaptations and

evolution (Hoffmann & Sgrò, 2011) into our modeling approach. For dispersal (Guisan & Thuiller, 2005b; Soberon & Peterson, 2005), we considered two scenarios (non-dispersal and full dispersal), but we limited the full dispersal scenario to species BAH, since we understand that plant dispersal rates over 0.1 km/year might not occur for vascular and non-vascular plants (Hannah et al., 2020; Thuiller et al., 2008; R. Warren et al., 2013) or over 100 km for Brazilian tree species as result of climate change (Gomes et al., 2019; Mayle, 2000). Although humans fundamentally affect dispersal and alter landscapes by transporting individuals (Bullock et al., 2018; Levis et al., 2018; Ordonez, 2014), we did not include human-mediated dispersal data in our models due to the lack of information related to human migrations as well as for each specific species. Another limitation of our study is to restrict our analysis to the estimated BAH of species, which may mask some macroecological patterns, yet adopting this conservative approach allows us to observe more concise species responses and diminish model overfitting (Gomes et al., 2018, 2019; Mendes, Velazco, Andrade, & De Marco, 2020).

In summary, we showed that future climate will likely trigger a decline in BAH between 38.5-56.3% under the non-dispersal scenario and between 22.3-41.9% under the full dispersal scenario of several native potential agroforestry species from the Brazilian flora. Additionally, we found that only 4.3% of the studied species could be threatened under the IUCN criteria B1 and B2. However, when considering the IUCN criterion A3, 68.8-84.4% (non-dispersal) and 40.7-64.4% (full dispersal) of our species of interest could be qualified as threatened. Although accessing genetic material with quality for native species might be difficult and the scenarios used here estimate considerable losses for 2041-2060 and 2061-2080, we argue that actions such as the promotion of these species in agroecosystems are promising alternatives to increase their population sizes. We urge that public policies involving farmers and local communities be adopted, as practices and management systems implemented by them have proven to maintain landscapes with productive forest fragments, and consequently favors species and forest conservation. Lastly, we highly recommend the development of scientific research towards biotechnological applications to select promising genotypes for a changing global climate.

Methods

Study area and target species

The study area includes the Atlantic Forest and Pampa grasslands in Eastern South America. We modelled 139 native potential agroforestry plant species (i.e. aromatic, fibre, food, forage, medicinal, ornamental and timber species) prioritized by the Brazilian Ministry of the Environment initiative “*Native species of the Brazilian flora of current and potential economic value - Plants for the Future - Southern Region*” (*Espécies Nativas da Flora Brasileira de Valor Econômico Atual e Potencial – Plantas para o futuro – Região Sul*). This initiative seeks to promote the sustainable use of Brazilian native plant species often used in different regions of the country (Coradin et al., 2011). In addition to contributing to the country's commitments under the Convention on Biological Diversity (CBD) and International Treaty on Plant Genetic Resources for Food and Agriculture, particularly with regard to promoting the sustainable use of biodiversity components (Coradin et al., 2011), these species provide food security for local communities and have commercial value in national and foreign markets. In spite of the fact that not all species have already been found in current agricultural systems or been managed by farmers, they all have one or multiple uses and can be combined in mixed cropping. Some species such as *A. angustifolia* (Zechini et al., 2018), *A. sellowiana* (Donazzolo et al., 2020), *E. edulis* (Favreto, Mello, & de Moura Baptista, 2010), *Ilex paraguariensis* (Siminski et al., 2016), and *Mimosa scabrella* (Silva, Machado, Galvão, & Filho, 2016) have already traditionally been combined with other agricultural crops in managed landscapes in southern Brazil. All taxonomic authorities and species common names are listed in Supplementary Table S3.

Species occurrence data

Occurrence data for the 139 species evaluated here was downloaded from the Global Biodiversity Information Facility (<https://doi.org/10.15468/dl.vjezvb>) (GBIF, 2022). We collected a total of 28,860 unique records. The sample size for species ranged from 12 (*Ornithopus micrantus*) to 5464 (*Casearia sylvestris*). We standardized botanical names using the R package ‘flora’ (G. Carvalho, 2017), which uses the nomenclature accepted by the Brazilian Flora 2020 project (<http://floradobrasil.jbrj.gov.br/>). To avoid modeling truncated niches, we extracted all records from an extent, defined by latitudes 60°S-15°N and longitudes 90°-30°W (Raes, 2012). We checked the geographical consistencies of all records using the cleaning pipeline proposed by Gomes *et al.* (Gomes et al., 2018). Firstly, we removed all occurrences outside the Neotropics. Then, we removed all records with missing latitude and longitude, using the function ‘cleancoordinates’ from the R package ‘CoordinateCleaner’ (Zizka et al., 2019). Finally, we estimated the kernel density for each

species in order to remove spatial outliers using the density function from the R package ‘stats’ (R Core Team, 2021). As geographic sampling biases are common among biological collections (Daru et al., 2018; U. Oliveira et al., 2016), which can lead to over-representation of environmental conditions, we spatially filtered the species occurrence data over a distance of 20km using the R package ‘spThin’ in order to diminish spatial autocorrelation (Aiello-Lammens et al., 2015). We did not model species for which there were less than ten records, as models fit with few data may not be reliable (Beaumont et al., 2016; Proosdij et al., 2016).

Environmental predictors

We obtained 19 bioclimatic variables from the Worldclim version 2.1. (<http://worldclim.org>) at a resolution of 5 arc-minutes (roughly 10 km at the equator), to characterize the species climatic requirements (Fick & Hijmans, 2017). These environmental variables represent the time period of 1970-2000. Predictors were selected (1) *a priori* based on their biological significance for different plant growth forms (Fourcade et al., 2018) (Supplementary Table S4). These predictors are critical in determining the distribution limits of a wide range of plant growth forms and are highly related to plant physiological responses (Austin & Van Niel, 2011; Woodward, 1987). We then (2) checked for multicollinearity by examining the correlation structure of the predictor variables through the variance inflation factor (VIF) for epiphyte, fern, graminoid, herb, hydrophyte, lithophyte, shrub, tree and vine species (IUCN, 2020). This measure evaluates how much the variance of an estimated regression coefficient increases if their predictors are correlated (Dormann et al., 2013). We kept only predictors with VIF values below 5 (Fremout et al., 2020). The VIFs were checked using the function ‘vifstep’ in the R package ‘usdm’ (Naimi, 2015). The retained predictors are shown in Supplementary Table S5.

Modeling approach

We used bioclimatic habitat suitability to assess the potential impacts of climate change on species’ BAH and inform IUCN Red List assessments (Syfert et al., 2014). To delimit BAH, we incorporated a 100 km buffer around species extent of occurrence (EOO), as we understand that plant dispersal rates over 0.1 km/year might not occur for vascular and non-vascular plants (Hannah et al., 2020; Thuiller et al., 2008; Warren et al., 2013), and adopting a conservative approach reduces model overfitting (Gomes et al., 2018, 2019; Mendes et al., 2020). EOOs were quantified by drawing a minimum convex polygon (MCP)

around known species records as recommend by IUCN (IUCN Standards and Petitions Committee, 2019). Current and future potential habitats for species were predicted using MaxEnt v.3.4.1k, a machine-learning algorithm used to estimate species' probability distribution (Phillips et al., 2006). MaxEnt is the presence-based method widely used for having high performance when compared to other available algorithms (Elith et al., 2010; Gomes et al., 2018; Muñoz-Pajares et al., 2018; Peng et al., 2019; Proosdij et al., 2016). ENMs were fitted using the following parameters in the MaxEnt: bootstrap method with 100 replicates, 500 maximum iterations, 10,000 points of background, and Cloglog output format. We only kept linear and quadratic features to avoid overfitting of the models and as recommended by Merow *et al.* because of the absence of a biological justification with the variables used (Boucher-Lalonde, Morin, & Currie, 2012; Merow et al., 2013). Furthermore, we inspected species-response-curves to avoid spurious calibrations, following the evaluation strip method proposed by Elith *et al.* (Elith, Ferrier, Huettmann, & Leathwick, 2005). This method investigates the effect of one variable at a time, keeping the others constant at their mean values (Elith et al., 2005). To assess robustness and alert policy-makers for the uncertainties typically associated with these methods, each ENM was tested against a bias corrected null-model as proposed by Raes and ter Steege (Raes & ter Steege, 2007). The AUC values of the ENMs built with n occurrence records were tested against the upper AUC values of the lower quantile of 95% of the AUC values obtained from 100 x n points drawn and predicted randomly. Only significant ENMs were projected to future climatic conditions.

Future projections

The climate projections were carried out according to the Sixth Assessment Report (AR6) of the IPCC, using two Shared Socioeconomic Pathways (SSPs) as reference (SSP2-4.5 and SSP5-8.5). SSPs are projections of future climates, based on different socioeconomic assumptions such as population, technological, and economic growth. The SSP2-4.5 (2041-2060) is a stabilization scenario, assuming global temperature increases ranging from 2.1 to 4.3 °C and mean warming of 3.0 °C. The SSP5-8.5 (2061-2080) represents the worst-case scenario, assuming absence of climate change policies, with global temperatures continue to rise throughout the 21st century, with estimates ranging from 3.8 to 7.4 °C and mean warming of 5.0 °C (IPCC, 2019). We averaged eight different global climate models: BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6 and MRI-ESM2-0 to take into account the uncertainties related to future climate conditions (Araujo & New, 2007). The fitted consensus ENMs were projected to these two datasets to

obtain predicted future maps of habitat suitability for each species.

To map changes in future ranges of species, we converted the continuous habitat suitability into binaries using the maximum training sensitivity plus specificity threshold (Bean et al., 2012; Jiménez-Valverde & Lobo, 2007). This threshold is indicated for conservation purposes for its high performance in the identification of suitable areas (Bean et al., 2012; Lima et al., 2020; Loiselle et al., 2003; Meyer et al., 2014). To assess whether species will face a decline or expansion in BAH under future climate conditions, we quantified the difference between the relative number of pixels occupied in current and future BAHs. We assumed that species have no dispersal capacity and full dispersal capacity for 2041-2060 and 2061-2080 timeframes. In the first scenario, species do not have the ability to disperse and reach new areas (pixels) in future climate scenarios. In the second, species can migrate within the estimated BAH of each species. Here, to ensure transparency and reproducibility for reporting ENMs, we adhered to the ODMAP (Overview, Data, Model, Assessment, Prediction) protocol v1.0. (Supplementary Table S6), as proposed by Zurell *et al.* (Zurell et al., 2020). All analyses were conducted within R environment version R 4.1.1 (R Core Team, 2021).

IUCN Red list preliminary assessment

The IUCN Red List assessments provide important information related to species status, trends and threats for the establishment of conservation planning and improvement of decision-making (Betts et al., 2020; IUCN Standards and Petitions Committee, 2019; ter Steege et al., 2015). Criterion B is linked to the geographic range and has two sub-criteria (B1 and B2), which are based on the extent of occurrence (EOO) and B2 on the area of occupancy (AOO), respectively (IUCN Standards and Petitions Committee, 2019). Further, three other conditions (a, b, and c) describe aspects of the biology and potential decline of the taxon in response to threats (IUCN Standards and Petitions Committee, 2019). At least one sub-criterion and two conditions must be met to qualify a given species as threatened (IUCN Standards and Petitions Committee, 2019). Following the guidelines for using the IUCN Red List Categories and Criteria version 14, we calculated the geographic range (B1a + B2a criteria) using the R package ‘ConR’ (Dauby et al., 2017). Additionally, we evaluated predicted quantitative habitat loss due to climate change by assessing the decline in habitat quality (A3c criterion), suspected to be met in the future, to qualify whether a particular species would be in a threat category (IUCN Standards and Petitions Committee, 2019). The

classification of threat includes: Vulnerable (VU), Endangered (EN) and Critically Endangered (CR). To qualify a species as Vulnerable, qualitative habitat loss must be $\geq 30\%$, Endangered $\geq 50\%$ and Critically Endangered $\geq 80\%$. These categories are related to the risk of extinction of species in the wild (IUCN Standards and Petitions Committee, 2019).

Online supplementary information for “Climate change threatens native potential agroforestry plant species in Brazil”

Table S1. Number of unique records, species future range changes and species qualified for the IUCN threatened category (VU, EN, CR) based on A3 criterion under two dispersal scenarios (Non-dispersal and full dispersal).

	Records	NON-DISPERSAL							
		2041-2060				2061-2080			
		SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
	Change	IUCN	Change	IUCN	Change	IUCN	Change	IUCN	
Aromatic species									
<i>Capsicum flexuosum</i>	353	-36.1	VU	-47.7	VU	-39.2	VU	-60.1	EN
<i>Pimenta pseudocaryophyllus</i>	544	-45.3	VU	-51.7	EN	-52.9	EN	-77.6	EN
<i>Schinus terebinthifolia</i>	1714	-28.6		-33.6	VU	-30.6	VU	-47.0	VU
<i>Tropaeolum pentaphyllum</i>	98	-30.9	VU	-29.9		-34.1	VU	-39.2	VU
Fibrous species									
<i>Coleataenia prionitis</i>	301	-17.9		-38.5	VU	-33.6	VU	-52.1	EN
<i>Geonoma gamiova</i>	114	-6.1		-6.6		-17.5		-35.2	VU
<i>Gynerium sagittatum</i>	363	-43.5	VU	-47.8	VU	-48.1	VU	-58.8	EN
<i>Philodendron corcovadense</i>	53	-35.4	VU	-38.1	VU	-40.9	VU	-45.1	VU
<i>Schoenoplectus californicus</i>	414	-27.5		-32.8	VU	-32.4	VU	-51.0	EN
Food species									
<i>Acca sellowiana</i>	262	-22.6		-28.7		-34.6	VU	-39.4	VU
<i>Annona crassiflora</i>	318	-68.2	EN	-82.9	CR	-76.3	EN	-91.8	CR
<i>Araucaria angustifolia</i>	226	-46.2	VU	-52.9	EN	-52.7	EN	-66.6	EN
<i>Butia catarinensis</i>	37	0.0		0.0		0.0		0.0	
<i>Butia eriospatha</i>	38	-67.7	EN	-77.3	EN	-67.8	EN	-87.4	CR
<i>Campomanesia xanthocarpa</i>	579	-38.9	VU	-32.1	VU	-36.6	VU	-47.8	VU
<i>Eugenia involucrata</i>	599	-42.4	VU	-44.5	VU	-45.6	VU	-61.8	EN
<i>Eugenia pyriformis</i>	600	-34.2	VU	-60.1	EN	-53.4	EN	-60.9	EN
<i>Eugenia uniflora</i>	381	-39.4	VU	-43.8	VU	-42.8	VU	-56.2	EN
<i>Euterpe edulis</i>	392	-50.1	EN	-52.7	EN	-58.0	EN	-69.7	EN
<i>Opuntia elata</i>	58	-12.0		-58.6	EN	-57.8	EN	-47.9	VU
<i>Passiflora actinia</i>	119	-46.5	VU	-44.3	VU	-41.6	VU	-49.4	VU
<i>Physalis pubescens</i>	588	-43.2	VU	-48.1	VU	-47.1	VU	-61.9	EN
<i>Plinia peruviana</i>	48	-79.6	EN	-87.3	CR	-76.0	EN	-88.3	CR
<i>Psidium cattleianum</i>	576	-26.5		-31.9	VU	-37.4	VU	-46.1	VU
<i>Vasconcellea quercifolia</i>	600	-42.1	VU	-51.5	EN	-52.8	EN	-50.3	EN
Forage species (Fabaceae)									
<i>Adesmia bicolor</i>	98	-64.5	EN	-69.0	EN	-74.1	EN	-80.1	CR
<i>Adesmia latifolia</i>	38	-68.3	EN	-47.2	VU	-51.8	EN	-52.9	EN
<i>Adesmia securigerifolia</i>	27	0.0		0.0		0.0		0.0	
<i>Adesmia tristis</i>	51	-94.4	CR	-97.0	CR	-98.0	CR	-99.2	CR
<i>Desmodium adscendens</i>	1282	-15.7		-14.4		-18.5		-16.3	
<i>Desmodium barbatum</i>	1708	-17.0		-17.5		-19.8		-24.1	
<i>Desmodium incanum</i>	1627	-27.7		-29.9		-31.9	VU	-41.9	VU
<i>Desmodium subsericeum</i>	137	-59.1	EN	-70.8	EN	-65.1	EN	-77.5	EN
<i>Indigofera sabulicola</i>	80	0.3		0.3		0.5		0.0	
<i>Leptospron adenanthum</i>	477	-10.5		-11.8		-12.6		-10.3	
<i>Macroptilium psammodes</i>	47	-20.9		-30.3	VU	-32.3	VU	-12.9	
<i>Ornithopus micranthus</i>	12	-100.0	CR	-100.0	CR	-100.0	CR	-95.1	CR
<i>Stylosanthes leiocarpa</i>	105	-37.6	VU	-36.2	VU	-37.2	VU	-30.7	VU
<i>Trifolium polymorphum</i>	103	-47.1	VU	-48.8	VU	-67.6	EN	-81.8	CR
<i>Trifolium riograndense</i>	29	-91.1	CR	-75.5	EN	-95.3	CR	-86.4	CR
<i>Vigna luteola</i>	515	-16.9		-23.1		-21.7		-26.2	

Forage species (Poaceae)									
<i>Axonopus compressus</i>	1022	-36.4	VU	-34.8	VU	-37.5	VU	-55.2	EN
<i>Axonopus fissifolius</i>	588	-24.6		-26.5		-28.0		-34.0	VU
<i>Axonopus obtusifolius</i>	61	-53.4	EN	-57.9	EN	-59.1	EN	-76.0	EN
<i>Bothriochloa laguroides</i>	214	-54.8	EN	-50.9	EN	-60.6	EN	-77.3	EN
<i>Bromus auleticus</i>	165	-81.0	CR	-82.3	CR	-69.7	EN	-88.5	CR
<i>Bromus catharticus</i>	597	-35.8	VU	-44.3	VU	-40.7	VU	-49.6	VU
<i>Dichantheium sabulorum</i>	103	-35.4	VU	-38.2	VU	-45.1	VU	-62.9	EN
<i>Echinochloa polystachya</i>	499	-7.6		-8.3		-9.8		-10.8	
<i>Hemarthria altissima</i>	149	-11.4		-7.0		-4.6		-8.4	
<i>Ischaemum minus</i>	37	-29.9		-40.9	VU	-47.1	VU	-6.0	
<i>Mnesithea seloana</i>	76	-41.1	VU	-49.9	VU	-64.4	EN	-72.4	EN
<i>Nassella neesiana</i>	503	-30.7	VU	-31.9	VU	-34.4	VU	-46.3	VU
<i>Paspalum alnum</i>	178	-2.0		-18.8		-14.4		-16.9	
<i>Paspalum denticulatum</i>	261	-22.9		-31.1	VU	-31.2	VU	-43.5	VU
<i>Paspalum dilatatum</i>	335	-26.1		-26.3		-27.8		-45.8	VU
<i>Paspalum glaucescens</i>	161	-59.0	EN	-42.0	VU	-55.2	EN	-61.0	EN
<i>Paspalum guenoarum</i>	205	-24.1		-28.3		-31.4	VU	-42.3	VU
<i>Paspalum jesuiticum</i>	38	-69.4	EN	-74.1	EN	-81.2	CR	-95.9	CR
<i>Paspalum leptum</i>	199	-5.6		-6.6		-12.3		-5.4	
<i>Paspalum modestum</i>	41	0.3		-4.1		-1.6		-4.2	
<i>Paspalum notatum</i>	595	-26.0		-27.1		-28.0		-42.0	VU
<i>Paspalum pumilum</i>	195	-41.8	VU	-39.3	VU	-39.7	VU	-50.2	EN
<i>Paspalum regnellii</i>	116	-16.8		-37.4	VU	-29.0		-40.4	VU
<i>Paspalum rhodopedum</i>	30	0.0		0.0		0.0		0.0	
<i>Poa lanigera</i>	159	-30.2	VU	-28.6		-30.3	VU	-46.7	VU
<i>Schizachyrium tenerum</i>	428	-49.8	VU	-51.2	EN	-53.4	EN	-68.9	EN
Medicinal species									
<i>Achyrocline satureioides</i>	1352	-45.7	VU	-48.0	VU	-47.8	VU	-59.1	EN
<i>Baccharis articulata</i>	512	-48.8	VU	-53.2	EN	-50.9	EN	-58.7	EN
<i>Baccharis crispa</i>	589	-39.2	VU	-45.4	VU	-44.7	VU	-57.8	EN
<i>Baccharis dracunculifolia</i>	1216	-42.9	VU	-52.8	EN	-51.6	EN	-64.5	EN
<i>Bauhinia forficata</i>	1002	-42.5	VU	-44.9	VU	-43.4	VU	-55.3	EN
<i>Bromelia antiacantha</i>	66	-28.2		-29.1		-26.0		-23.4	
<i>Casearia sylvestris</i>	5464	-37.1	VU	-38.3	VU	-39.0	VU	-50.4	EN
<i>Cecropia glaziovii</i>	180	-42.6	VU	-51.8	EN	-55.4	EN	-69.1	EN
<i>Copaifera trapezifolia</i>	135	-19.3		-22.3		-25.1		-39.6	VU
<i>Croton celtidifolius</i>	191	-35.0	VU	-54.2	EN	-44.0	VU	-81.6	CR
<i>Cunila microcephala</i>	21	-100.0	CR	-100.0	CR	-100.0	CR	-100.0	CR
<i>Drimys brasiliensis</i>	600	-73.8	EN	-76.9	EN	-77.9	EN	-91.7	CR
<i>Echinodorus grandiflorus</i>	294	-20.0		-28.5		-26.8		-36.5	VU
<i>Equisetum giganteum</i>	595	-36.2	VU	-39.8	VU	-38.1	VU	-48.7	VU
<i>Hypericum caprifoliatum</i>	83	-5.5		-11.2		-12.8		-19.9	
<i>Ilex paraguariensis</i>	1040	-40.0	VU	-41.2	VU	-46.3	VU	-57.8	EN
<i>Jodina rhombifolia</i>	83	-57.5	EN	-58.4	EN	-59.5	EN	-62.2	EN
<i>Mikania glomerata</i>	285	-41.7	VU	-37.1	VU	-47.6	VU	-56.9	EN
<i>Mikania laevigata</i>	161	-27.4		-23.0		-26.5		-32.8	VU
<i>Monteverdia ilicifolia</i>	500	-23.7		-36.8	VU	-37.5	VU	-41.5	VU
<i>Ocimum carnosum</i>	570	-17.3		-41.1	VU	-36.1	VU	-35.7	VU
<i>Piper umbellatum</i>	595	-43.7	VU	-50.4	EN	-48.9	VU	-63.7	EN
<i>Plantago australis</i>	1047	-38.5	VU	-42.0	VU	-40.6	VU	-53.3	EN
<i>Sambucus australis</i>	180	-32.5	VU	-37.8	VU	-38.0	VU	-39.5	VU
<i>Smilax campestris</i>	554	-44.7	VU	-45.7	VU	-47.0	VU	-62.2	EN
<i>Solanum mauritianum</i>	523	-43.5	VU	-45.2	VU	-48.8	VU	-61.0	EN
<i>Solanum paniculatum</i>	1898	-42.6	VU	-54.0	EN	-46.9	VU	-62.0	EN
<i>Sorocea bonplandii</i>	600	-43.8	VU	-56.4	EN	-52.3	EN	-68.1	EN
<i>Trichilia catigua</i>	1077	-38.5	VU	-66.0	EN	-56.5	EN	-79.4	EN
<i>Varronia curassavica</i>	1684	-29.1		-33.2	VU	-32.5	VU	-36.5	VU
<i>Wilbrandia ebracteata</i>	151	-36.3	VU	-28.6		-23.2		-60.5	EN

<i>Zollernia ilicifolia</i>	235	-38.8	VU	-42.5	VU	-42.4	VU	-57.4	EN
Ornamental species									
<i>Ananas bracteatus</i>	67	-44.6	VU	-46.6	VU	-46.0	VU	-60.2	EN
<i>Aspilia montevidensis</i>	276	-27.5		-28.9		-35.6	VU	-27.6	
<i>Calliandra tweedii</i>	221	-32.7	VU	-42.9	VU	-42.4	VU	-52.5	EN
<i>Cortaderia selloana</i>	257	-35.0	VU	-44.0	VU	-39.2	VU	-57.7	EN
<i>Dyckia distachya</i>	43	-44.7	VU	-99.6	CR	-71.8	EN	-91.7	CR
<i>Epidendrum fulgens</i>	85	-18.1		-19.0		-37.5	VU	-3.7	
<i>Fuchsia regia</i>	499	-51.2	EN	-56.4	EN	-56.9	EN	-79.9	EN
<i>Gomesa flexuosa</i>	179	-38.1	VU	-40.6	VU	-39.2	VU	-60.5	EN
<i>Handroanthus chrysotrichus</i>	307	-38.5	VU	-43.2	VU	-45.3	VU	-60.5	EN
<i>Heliconia farinosa</i>	199	-13.7		-15.5		-12.6		-20.6	
<i>Jacaranda puberula</i>	506	-40.2	VU	-49.4	VU	-50.1	EN	-63.7	EN
<i>Parodia ottonis</i>	149	-63.9	EN	-56.0	EN	-72.6	EN	-82.5	CR
<i>Petunia integrifolia</i>	361	-4.2		-5.6		-12.7		-12.2	
<i>Pyrostegia venusta</i>	1523	-49.3	VU	-46.6	VU	-46.3	VU	-48.9	VU
<i>Rumohra adiantiformis</i>	576	-34.9	VU	-38.3	VU	-41.6	VU	-52.2	EN
<i>Sinningia leucotricha</i>	14	0.0		0.0		0.0		0.0	
<i>Syagrus romanzoffiana</i>	229	-61.0	EN	-62.4	EN	-61.8	EN	-75.5	EN
<i>Tibouchina sellowiana</i>	365	-41.8	VU	-53.9	EN	-50.3	EN	-74.5	EN
<i>Trichocline catharinensis</i>	127	-54.1	EN	-85.6	CR	-83.3	CR	-89.0	CR
<i>Verbena rigida</i>	381	-47.5	VU	-68.4	EN	-67.0	EN	-69.3	EN
Timber species									
<i>Apuleia leiocarpa</i>	923	-56.0	EN	-61.0	EN	-60.6	EN	-75.3	EN
<i>Aspidosperma polyneuron</i>	599	-49.7	VU	-57.1	EN	-47.7	VU	-63.6	EN
<i>Ateleia glazioveana</i>	92	-28.3		-15.3		-36.7	VU	-17.0	
<i>Balfourodendron riedelianum</i>	342	-29.0		-52.7	EN	-37.7	VU	-51.6	EN
<i>Cabrlea canjerana</i>	1306	-42.4	VU	-52.0	EN	-50.9	EN	-61.6	EN
<i>Calophyllum brasiliense</i>	1633	-39.8	VU	-41.2	VU	-43.3	VU	-40.7	VU
<i>Cedrela fissilis</i>	935	-48.4	VU	-54.1	EN	-52.8	EN	-67.1	EN
<i>Colubrina glandulosa</i>	364	-60.7	EN	-59.6	EN	-54.9	EN	-74.7	EN
<i>Cordia trichotoma</i>	975	-54.0	EN	-59.9	EN	-58.4	EN	-72.6	EN
<i>Enterolobium contortisiliquum</i>	598	-46.8	VU	-63.3	EN	-55.7	EN	-74.8	EN
<i>Handroanthus heptaphyllus</i>	389	-26.4		-30.7	VU	-38.3	VU	-58.2	EN
<i>Hyeronima alchorneoides</i>	196	-34.8	VU	-38.2	VU	-36.3	VU	-45.4	VU
<i>Miconia cinnamomifolia</i>	480	-8.9		-15.5		-14.6		-27.0	
<i>Mimosa scabrella</i>	318	-44.8	VU	-61.5	EN	-61.2	EN	-83.5	CR
<i>Nectandra lanceolata</i>	542	-40.2	VU	-52.1	EN	-49.7	VU	-60.8	EN
<i>Ocotea puberula</i>	1399	-38.2	VU	-39.7	VU	-39.7	VU	-55.4	EN
<i>Parapiptadenia rigida</i>	594	-38.4	VU	-48.3	VU	-44.5	VU	-56.5	EN
<i>Peltophorum dubium</i>	596	-76.5	EN	-79.4	EN	-74.8	EN	-88.4	CR
<i>Piptocarpha angustifolia</i>	71	-41.7	VU	-65.7	EN	-69.9	EN	-72.2	EN
<i>Schizolobium parahyba</i>	325	-38.6	VU	-36.0	VU	-36.7	VU	-52.2	EN
Median range change (%)		-38.5		-43.5		-43.4		-56.3	

	FULL DISPERSAL							
	2041-2060				2061-2080			
	SSP2-4.5		SSP5-8.5		SSP2-4.5		SSP5-8.5	
	Change	IUCN	Change	IUCN	Change	IUCN	Change	IUCN
Aromatic species								
<i>Capsicum flexuosum</i>	-33.7	VU	-35.8	VU	-38.0	VU	-57.1	EN
<i>Pimenta pseudocaryophyllus</i>	-38.9	VU	-47.6	VU	-44.8	VU	-76.5	EN
<i>Schinus terebinthifolia</i>	-12.7		-14.7		-16.6		-31.3	VU
<i>Tropaeolum pentaphyllum</i>	-2.9		3.1		0.1		-14.1	
Fibrous species								
<i>Coleataenia prionitis</i>	50.6		26.1		54.4		32.7	
<i>Geonoma gamiova</i>	56.1		86.1		25.0		28.8	

<i>Gynerium sagittatum</i>	-32.0	VU	-34.2	VU	-34.8	VU	-42.0	VU
<i>Philodendron corcovadense</i>	-7.6		1.1		-12.5		14.5	
<i>Schoenoplectus californicus</i>	-22.8		-28.4		-25.9		-47.9	VU
Food species								
<i>Acca sellowiana</i>	-7.1		-20.1		-10.3		-13.4	
<i>Annona crassiflora</i>	-61.0	EN	-77.9	EN	-71.5	EN	-89.1	CR
<i>Araucaria angustifolia</i>	-46.1	VU	-52.9	EN	-52.6	EN	-66.5	EN
<i>Butia catarinensis</i>	0.0		0.0		0.0		0.0	
<i>Butia eriospatha</i>	-45.2	VU	-50.4	EN	-52.7	EN	-64.3	EN
<i>Campomanesia xanthocarpa</i>	-35.5	VU	-25.8		-35.2	VU	-43.3	VU
<i>Eugenia involucrata</i>	-39.9	VU	-40.4	VU	-43.6	VU	-59.7	EN
<i>Eugenia pyriformis</i>	-17.6		-38.9	VU	-42.1	VU	-48.8	VU
<i>Eugenia uniflora</i>	-9.6		-8.0		-16.6		-33.8	VU
<i>Euterpe edulis</i>	-19.9		-19.9		-20.3		-33.7	VU
<i>Opuntia elata</i>	45.8		-28.7		-26.2		12.3	
<i>Passiflora actinia</i>	-37.3	VU	-21.6		-33.6	VU	-26.2	
<i>Physalis pubescens</i>	-41.4	VU	-46.0	VU	-45.5	VU	-59.2	EN
<i>Plinia peruviana</i>	-56.9	EN	-68.0	EN	-60.2	EN	-64.2	EN
<i>Psidium cattleianum</i>	-10.2		-20.7		-26.6		-34.0	VU
<i>Vasconcellea quercifolia</i>	-26.3		-43.0	VU	-44.5	VU	-34.8	VU
Forage species (Fabaceae)								
<i>Adesmia bicolor</i>	-48.2	VU	-58.5	EN	-48.6	VU	-76.0	EN
<i>Adesmia latifolia</i>	40.8		39.3		13.8		23.5	
<i>Adesmia securigerifolia</i>	0.0		0.0		0.0		0.0	
<i>Adesmia tristis</i>	-94.4	CR	-96.9	CR	-98.0	CR	-99.2	CR
<i>Desmodium adscendens</i>	76.6		122.9		91.9		190.9	
<i>Desmodium barbatum</i>	25.0		29.0		30.8		29.0	
<i>Desmodium incanum</i>	-21.5		-24.5		-27.6		-37.7	VU
<i>Desmodium subsericeum</i>	-44.4	VU	-63.7	EN	-55.7	EN	-68.7	EN
<i>Indigofera sabulicola</i>	183.7		218.4		191.0		387.7	
<i>Leptospron adenanthum</i>	62.7		79.6		74.6		119.2	
<i>Macroptilium psammodes</i>	115.3		123.1		115.5		227.9	
<i>Ornithopus micranthus</i>	-100.0	CR	-100.0	CR	-95.1	CR	-95.1	CR
<i>Stylosanthes leiocarpa</i>	-21.8		-2.5		-14.8		19.4	
<i>Trifolium polymorphum</i>	2.6		2.3		-5.0		-48.1	VU
<i>Trifolium riograndense</i>	-91.1	CR	-75.2	EN	-95.3	CR	-86.4	CR
<i>Vigna luteola</i>	0.5		-4.7		-5.8		-11.8	
Forage species (Poaceae)								
<i>Axonopus compressus</i>	-23.8		-19.7		-22.6		-42.0	VU
<i>Axonopus fissifolius</i>	98.5		143.3		121.8		182.7	
<i>Axonopus obtusifolius</i>	0.2		-3.6		-7.1		-34.3	VU
<i>Bothriochloa laguroides</i>	-38.6	VU	-23.8		-37.6	VU	-65.5	EN
<i>Bromus auleticus</i>	-79.2	EN	-80.3	CR	-52.3	EN	-83.6	CR
<i>Bromus catharticus</i>	-33.2	VU	-41.5	VU	-36.2	VU	-45.8	VU
<i>Dichanthelium sabulorum</i>	-34.4	VU	-33.9	VU	-44.0	VU	-60.3	EN
<i>Echinochloa polystachya</i>	174.3		210.0		187.5		259.4	
<i>Hemarthria altissima</i>	60.2		47.2		73.2		116.0	
<i>Ischaemum minus</i>	42.2		36.8		22.6		141.5	
<i>Mnesithea seloana</i>	36.3		28.6		30.0		23.3	
<i>Nassella neesiana</i>	-26.3		-29.4		-21.2		-45.4	VU
<i>Paspalum alnum</i>	93.1		48.4		54.3		63.5	
<i>Paspalum denticulatum</i>	-1.8		0.6		7.8		-17.9	
<i>Paspalum dilatatum</i>	-25.6		-26.0		-27.2		-45.7	VU
<i>Paspalum glaucescens</i>	-36.7	VU	5.7		-37.8	VU	-41.9	VU
<i>Paspalum guenoarum</i>	-11.9		-14.6		-17.8		-28.1	
<i>Paspalum jesuiticum</i>	-69.4	EN	-74.1	EN	-81.2	CR	-95.9	CR
<i>Paspalum leptum</i>	117.6		111.5		137.9		127.1	

<i>Paspalum modestum</i>	110.6		99.8		102.6		143.0	
<i>Paspalum notatum</i>	-25.2		-26.0		-26.9		-40.6	VU
<i>Paspalum pumilum</i>	-41.0	VU	-34.7	VU	-38.5	VU	-47.9	VU
<i>Paspalum regnellii</i>	40.4		17.0		7.5		20.1	
<i>Paspalum rhodopedum</i>	0.0		0.0		0.0		0.0	
<i>Poa lanigera</i>	-3.2		-9.1		4.1		-25.3	
<i>Schizachyrium tenerum</i>	-46.3	VU	-46.2	VU	-50.0	EN	-64.3	EN
Medicinal species								
<i>Achyrocline satureioides</i>	-45.0	VU	-47.0	VU	-47.3	VU	-57.4	EN
<i>Baccharis articulata</i>	-44.2	VU	-43.7	VU	-45.1	VU	-53.3	EN
<i>Baccharis crispa</i>	-38.2	VU	-42.7	VU	-43.1	VU	-56.6	EN
<i>Baccharis dracunculifolia</i>	-37.4	VU	-44.7	VU	-45.6	VU	-58.4	EN
<i>Bauhinia forficata</i>	-33.0	VU	-32.4	VU	-33.1	VU	-45.1	VU
<i>Bromelia antiacantha</i>	26.5		34.6		26.9		27.0	
<i>Casearia sylvestris</i>	-7.3		-7.5		-6.8		1.7	
<i>Cecropia glaziovii</i>	-21.7		-41.0	VU	-40.3	VU	-54.2	EN
<i>Copaifera trapezifolia</i>	20.1		9.5		15.0		-17.5	
<i>Croton celtidifolius</i>	-32.8	VU	-53.3	EN	-40.6	VU	-81.4	CR
<i>Cunila microcephala</i>	-42.4	VU	-33.1	VU	-48.3	VU	-88.1	CR
<i>Drimys brasiliensis</i>	-73.8	EN	-76.9	EN	-77.9	EN	-91.7	CR
<i>Echinodorus grandiflorus</i>	-17.4		-23.9		-23.3		-31.4	VU
<i>Equisetum giganteum</i>	-31.0	VU	-34.8	VU	-31.8	VU	-40.7	VU
<i>Hypericum caprifoliatum</i>	29.6		7.2		2.6		5.1	
<i>Ilex paraguariensis</i>	-38.8	VU	-37.3	VU	-44.9	VU	-57.6	EN
<i>Jodina rhombifolia</i>	-51.5	EN	-52.5	EN	-53.0	EN	-50.9	EN
<i>Mikania glomerata</i>	-12.9		-6.0		-18.8		-24.4	
<i>Mikania laevigata</i>	-12.8		3.2		-14.4		-4.5	
<i>Monteverdia ilicifolia</i>	-18.9		-30.5	VU	-33.2	VU	-36.5	VU
<i>Ocimum carnosum</i>	-10.3		-34.4	VU	-30.0	VU	-29.4	
<i>Piper umbellatum</i>	-37.6	VU	-42.2	VU	-45.0	VU	-54.4	EN
<i>Plantago australis</i>	-34.0	VU	-37.3	VU	-35.1	VU	-46.1	VU
<i>Sambucus australis</i>	-26.3		-34.1	VU	-29.6		-32.7	VU
<i>Smilax campestris</i>	-37.6	VU	-36.2	VU	-41.4	VU	-54.9	EN
<i>Solanum mauritianum</i>	-39.1	VU	-39.2	VU	-45.9	VU	-58.3	EN
<i>Solanum paniculatum</i>	-26.4		-38.2	VU	-30.5	VU	-30.1	VU
<i>Sorocea bonplandii</i>	-21.1		-39.5	VU	-21.9		-58.3	EN
<i>Trichilia catigua</i>	-8.5		-34.9	VU	-23.5		-51.8	EN
<i>Varronia curassavica</i>	65.3		122.4		83.6		229.5	
<i>Wilbrandia ebracteata</i>	28.2		20.5		42.3		-33.6	VU
<i>Zollernia ilicifolia</i>	-14.1		-6.6		-15.0		-36.1	VU
Ornamental species								
<i>Ananas bracteatus</i>	-37.3	VU	-37.7	VU	-39.5	VU	-52.7	EN
<i>Aspilia montevidensis</i>	-2.3		9.9		-10.8		13.4	
<i>Calliandra tweedii</i>	-27.8		-33.9	VU	-38.1	VU	-44.5	VU
<i>Cortaderia selloana</i>	-30.1	VU	-39.4	VU	-31.6	VU	-52.6	EN
<i>Dyckia distachya</i>	159.0		-36.8	VU	44.4		21.4	
<i>Epidendrum fulgens</i>	30.3		123.1		14.2		264.0	
<i>Fuchsia regia</i>	-49.7	VU	-54.9	EN	-55.6	EN	-79.3	EN
<i>Gomesa flexuosa</i>	-23.0		-31.4	VU	-24.6		-52.4	EN
<i>Handroanthus chrysotrichus</i>	-14.9		-25.0		-21.0		-40.7	VU
<i>Heliconia farinosa</i>	27.7		64.1		71.9		29.1	
<i>Jacaranda puberula</i>	-27.0		-36.9	VU	-36.2	VU	-52.5	EN
<i>Parodia ottonis</i>	-51.8	EN	-42.4	VU	-68.5	EN	-76.6	EN
<i>Petunia integrifolia</i>	7.3		1.2		-10.1		-4.9	
<i>Pyrostegia venusta</i>	-12.0		22.2		8.4		70.5	
<i>Rumohra adiantiformis</i>	-34.6	VU	-36.6	VU	-41.5	VU	-51.8	EN
<i>Sinningia leucotricha</i>	0.0		0.0		0.0		0.0	

<i>Syagrus romanzoffiana</i>	-27.3		-30.0	VU	-21.7		-56.0	EN
<i>Tibouchina sellowiana</i>	-9.1		-39.6	VU	-35.0	VU	-69.8	EN
<i>Trichocline catharinensis</i>	-53.0	EN	-71.2	EN	-83.3	CR	-86.7	CR
<i>Verbena rigida</i>	-32.6	VU	-50.8	EN	-49.8	VU	-66.2	EN
Timber species								
<i>Apuleia leiocarpa</i>	-52.8	EN	-57.0	EN	-57.8	EN	-71.1	EN
<i>Aspidosperma polyneuron</i>	34.7		41.4		29.4		155.9	
<i>Ateleia glazioveana</i>	17.3		39.2		-11.5		27.4	
<i>Balfourodendron riedelianum</i>	-24.2		-47.3	VU	-31.1	VU	-46.0	VU
<i>Cabrera canjerana</i>	-40.4	VU	-48.1	VU	-48.5	VU	-57.1	EN
<i>Calophyllum brasiliense</i>	104.5		137.5		125.3		183.0	
<i>Cedrela fissilis</i>	-47.8	VU	-52.6	EN	-52.5	EN	-66.3	EN
<i>Colubrina glandulosa</i>	-52.3	EN	-49.9	VU	-45.3	VU	-69.8	EN
<i>Cordia trichotoma</i>	-41.5	VU	-45.2	VU	-44.8	VU	-57.6	EN
<i>Enterolobium contortisiliquum</i>	-23.9		-44.9	VU	-32.0	VU	-49.3	VU
<i>Handroanthus heptaphyllus</i>	28.0		25.7		7.3		-12.4	
<i>Hyeronima alchorneoides</i>	-1.1		13.7		9.7		32.6	
<i>Miconia cinnamomifolia</i>	27.9		12.4		15.0		-13.0	
<i>Mimosa scabrella</i>	-44.8	VU	-61.4	EN	-61.2	EN	-83.5	CR
<i>Nectandra lanceolata</i>	-34.6	VU	-47.3	VU	-44.9	VU	-56.9	EN
<i>Ocotea puberula</i>	-34.0	VU	-33.3	VU	-35.4	VU	-50.8	EN
<i>Parapiptadenia rigida</i>	-20.9		-17.1		-26.8		-33.5	VU
<i>Peltophorum dubium</i>	-58.3	EN	-61.5	EN	-49.8	VU	-68.9	EN
<i>Piptocarpha angustifolia</i>	-9.2		-47.3	VU	-59.5	EN	-56.3	EN
<i>Schizolobium parahyba</i>	-24.1		-11.1		-15.9		-39.1	VU
Median range change (%)	-22.3		-29.7		-27.4		-41.9	

Table S2. Brazilian agroforestry plant species qualified for the IUCN threatened category (VU, EN, CR) based on B1 and B2 criteria.

Taxa	EOO	AOO	Nbe uniqu ue occ.	Nbe subPop	Nbe loc	Category CriteriaB	Category code	Category AOO	Category EOO
<i>Acca sellowiana</i>	69997 02	344	86	86	86	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Achyrocline satureioides</i>	14540 778	1804	451	451	451	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Adesmia bicolor</i>	78709 0	188	47	47	47	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Adesmia latifolia</i>	67426 7	68	17	17	17	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Adesmia securigerifolia</i>	25323	28	7	7	7	VU	VU B2a	VU	LC or NT
<i>Adesmia tristis</i>	17952 9	84	21	21	21	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ananas bracteatus</i>	88111 71	180	45	45	45	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Annona crassiflora</i>	22561 36	544	136	136	136	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Apuleia leiocarpa</i>	10179 173	1260	315	315	315	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Araucaria angustifolia</i>	89863 6	392	98	98	98	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Aspidosperma polyneuron</i>	68739 55	220	55	55	55	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Aspilia montevidensis</i>	82079 1	404	101	101	101	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ateleia glazioveana</i>	70384 4	128	32	32	32	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT

<i>Axonopus compressus</i>	15420 146	1416	354	354	354	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Axonopus fissifolius</i>	15296 979	1004	251	251	251	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Axonopus obtusifolius</i>	12963 45	104	26	26	26	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Baccharis articulata</i>	27724 73	776	194	194	194	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Baccharis crispa</i>	31762 00	884	221	221	221	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Baccharis dracunculifolia</i>	36026 03	1588	397	397	397	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Balfourodendron riedelianum</i>	28313 17	536	134	134	134	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Bauhinia forficata</i>	56318 69	1460	365	365	365	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Bothriochloa laguroides</i>	15403 63	392	98	98	98	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Bromelia antiacantha</i>	10582 65	172	43	43	43	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Bromus auleticus</i>	14277 00	296	74	74	74	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Bromus catharticus</i>	10922 335	960	240	240	240	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Butia catarinensis</i>	12054	32	8	8	8	VU	VU B1a+B2a	VU	VU
<i>Butia eriospatha</i>	27180 2	88	22	22	22	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Cabralea canjerana</i>	77105 90	1492	373	373	373	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Calliandra tweedii</i>	29241 53	396	99	99	99	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Calophyllum brasiliense</i>	12376 033	1992	498	498	498	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Campomanesia xanthocarpa</i>	16763 37	828	207	207	207	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Capsicum flexuosum</i>	77539 4	456	114	114	114	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Casearia sylvestris</i>	15478 279	10136	3083	1554	2005	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Cecropia glaziovii</i>	10350 36	460	123	96	104	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Cedrela fissilis</i>	70426 50	2000	581	399	452	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Coleataenia prionitis</i>	54835 8	324	81	81	81	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Colubrina glandulosa</i>	11519 147	836	249	158	180	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Copaifera trapezifolia</i>	19172 91	260	79	51	57	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Cordia trichotoma</i>	43926 47	2132	609	431	480	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Cortaderia selloana</i>	10265 083	524	131	131	131	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Croton celtidifolius</i>	22523 77	456	133	90	99	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Cunila microcephala</i>	58542 8	56	14	14	14	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Desmodium adscendens</i>	14067 033	1880	470	470	470	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Desmodium barbatum</i>	13795 118	2584	646	646	646	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Desmodium incanum</i>	16580 945	2644	661	661	661	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Desmodium subsericeum</i>	22973 39	216	54	54	54	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Dichantheium sabulorum</i>	78831 2	196	49	49	49	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Drimys brasiliensis</i>	15805 94	1224	403	185	237	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Dyckia distachya</i>	98578	52	13	13	13	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Echinochloa polystachya</i>	15594 791	784	196	196	196	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT

<i>Echinodorus grandiflorus</i>	12544 057	636	159	159	159	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Enterolobium contortisiliquum</i>	50918 32	1560	446	312	345	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Epidendrum fulgens</i>	10211 2	120	30	30	30	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Equisetum giganteum</i>	11386 476	1028	257	257	257	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Eugenia involucrata</i>	31097 92	1292	380	241	276	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Eugenia pyriformis</i>	23161 04	1304	384	235	277	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Eugenia uniflora</i>	11454 00	820	238	145	171	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Euterpe edulis</i>	19644 85	680	189	133	147	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Fuchsia regia</i>	58546 1	472	118	118	118	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Geonoma gamiova</i>	13617 2	188	47	47	47	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Gomesa flexuosa</i>	12140 29	292	73	73	73	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Gynerium sagittatum</i>	10747 783	624	156	156	156	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Handroanthus chrysotrichus</i>	35897 69	816	222	176	191	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Handroanthus heptaphyllus</i>	51356 59	780	217	167	182	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Heliconia farinosa</i>	12057 73	264	66	66	66	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Hemarthria altissima</i>	30457 31	300	75	75	75	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Hyeronima alchorneoides</i>	11827 263	504	132	109	116	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Hypericum caprifoliatum</i>	76464 3	160	40	40	40	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ilex paraguariensis</i>	30900 76	1764	571	298	364	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Indigofera sabulicola</i>	42937 27	204	51	51	51	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ischaemum minus</i>	19306 4	72	18	18	18	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Jacaranda puberula</i>	24541 18	1172	336	209	256	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Jodina rhombifolia</i>	19131 83	252	65	52	55	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Leptospron adenanthum</i>	15795 072	872	218	218	218	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Macropitilium psammodes</i>	49004 6	100	25	25	25	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Miconia cinnamomifolia</i>	82388 8	904	268	149	183	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Mikania glomerata</i>	18916 32	512	128	128	128	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Mikania laevigata</i>	12846 81	216	54	54	54	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Mimosa scabrella</i>	15235 96	736	210	127	155	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Mnesithea seloana</i>	59558 6	184	46	46	46	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Monteverdia ilicifolia</i>	35803 66	744	186	186	186	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Nassella neesiana</i>	17748 75	640	160	160	160	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Nectandra lanceolata</i>	12927 43	1040	313	203	228	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ocimum carnosum</i>	37176 20	828	207	207	207	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ocotea puberula</i>	20379 903	2696	807	480	569	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Opuntia elata</i>	13043 59	116	29	29	29	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Ornithopus micranthus</i>	65958	32	8	8	8	VU	VU B2a	VU	LC or NT

<i>Parapiptadenia rigida</i>	10771 33	1288	369	212	268	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Parodia ottonis</i>	39927 5	220	55	55	55	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum alnum</i>	61664 1	280	70	70	70	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum denticulatum</i>	11330 69	436	109	109	109	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum dilatatum</i>	94009 47	572	143	143	143	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum glaucescens</i>	16132 96	224	56	56	56	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum guenoarum</i>	29544 03	336	84	84	84	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum jesuiticum</i>	24966 5	40	10	10	10	VU	VU B2a	VU	LC or NT
<i>Paspalum leptum</i>	95363 6	292	73	73	73	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum modestum</i>	26671 3	92	23	23	23	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum notatum</i>	12858 516	992	248	248	248	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum pumilum</i>	73603 25	348	87	87	87	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum regnellii</i>	70996 3	208	52	52	52	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Paspalum rhodopedum</i>	69362	28	7	7	7	VU	VU B2a	VU	LC or NT
<i>Passiflora actinia</i>	29215 8	100	25	25	25	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Peltophorum dubium</i>	29872 64	1412	404	278	314	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Petunia integrifolia</i>	28518 32	580	145	145	145	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Philodendron corcovadense</i>	47913 6	100	25	25	25	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Physalis pubescens</i>	15466 155	1248	312	312	312	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Pimenta pseudocaryophyllus</i>	20319 89	900	302	137	179	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Piper umbellatum</i>	13265 963	1004	251	251	251	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Piptocarpha angustifolia</i>	30743 2	180	50	42	44	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Plantago australis</i>	12035 189	1340	335	335	335	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Plinia peruviana</i>	12754 00	96	27	24	24	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Poa lanigera</i>	11393 17	232	58	58	58	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Psidium cattleianum</i>	17506 04	1340	397	214	274	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Pyrostegia venusta</i>	15031 676	2264	566	566	566	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Rumohra adiantiformis</i>	42748 17	816	204	204	204	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Sambucus australis</i>	35003 44	488	140	107	113	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Schinus terebinthifolia</i>	27259 35	3524	1036	538	699	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Schizachyrium tenerum</i>	11748 537	612	153	153	153	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Schizolobium parahyba</i>	10915 127	780	225	151	169	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Schoenoplectus californicus</i>	10561 705	576	144	144	144	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Sinningia leucotricha</i>	28940	28	7	7	7	VU	VU B2a	VU	LC or NT
<i>Smilax campestris</i>	57851 38	996	249	249	249	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Solanum mauritianum</i>	33565 06	1184	347	238	270	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Solanum paniculatum</i>	40956 90	1884	471	471	471	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT

<i>Sorocea bonplandii</i>	14562 75	1060	299	191	220	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Stylosanthes leiocarpa</i>	22484 71	184	46	46	46	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Syagrus romanzoffiana</i>	23418 28	612	175	130	141	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Tibouchina sellowiana</i>	53633 8	740	213	115	151	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Trichilia catigua</i>	42879 51	1844	576	299	373	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Trichocline catharinensis</i>	13765 2	164	41	41	41	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Trifolium polymorphum</i>	23314 91	240	60	60	60	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Trifolium riograndense</i>	10532 8	84	21	21	21	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Tropaeolum pentaphyllum</i>	23519 73	188	47	47	47	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Varronia curassavica</i>	14436 380	1980	495	495	495	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Vasconcellea quercifolia</i>	25805 12	1004	451	148	188	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Verbena rigida</i>	11443 00	512	128	128	128	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Vigna luteola</i>	16680 952	1020	255	255	255	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Wilbrandia ebracteata</i>	56039 6	180	45	45	45	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT
<i>Zollernia ilicifolia</i>	29387 59	520	148	109	120	LC or NT	LC or NT B1a+B2a	LC or NT	LC or NT

Table S3. Taxonomic authorities and common names for the Brazilian agroforestry plant species prioritized by the Brazilian Ministry of the Environment initiative Native species of the Brazilian flora of current and potential economic value - Plants for the Future - Southern Region.

Aromatic species	Common names
<i>Capsicum flexuosum</i> Sendtn.	Pimenta-braba, pimenta-do-mato, pimenta-silvestre, pimenta-do-morro.
<i>Pimenta pseudocaryophyllus</i> (Gomes) Landrum.	Cravo, pau-cravo, craveiro, louro-cravo, louro, craveiro-do-mato, chá-de-bugre.
<i>Schinus terebinthifolius</i> Raddi.	Aroeira-pimenteira, aroeira-vermelha, aroeira-mansa, aroeira, aroeira-braba, aroeira-branca, aroeira-da-praia, aroeira-do-brejo, aroeira-do-campo, aroeira-de-sabiá, aroeirinha, coração-de-bugre, fruto-de-sabiá, fruto-de-raposa, fruto-de-cutia, araguaraiaba, corneiba, árvore-da-pimenta, cabuí, cambuí, lentisco.
<i>Tropaeolum pentaphyllum</i> Lam.	Crem, batata-crem, crem-de-baraço, crem-trepador, capuchinha, carrapicho, chagas, cinco-chagas, chagas-da-miúda, sapatinho-de-iaia, sapatinho-do-diabo.
Fibrous species	
<i>Coleataenia prionitis</i> (Nees) Soreng	Capim-santa-fé, palha-santa-fé, santa-fé, pii-guiycé, paja-brava
<i>Geonoma gamiova</i> Barb. Rodr.	Guaricana-de-folha-larga, ouricana, gamiova, palheira, palheira-de-folha-larga, aricana, uricana
<i>Gynerium sagittatum</i> (Aubl.) P.Beauv.	Cana-brava, ubá, cana-ubá, parimá, ariná, eguará, eraí, flecha, cana-flecha, flecha-de-urubu, cana-do-rio, canarana, canarana-flecha, cana-amarga, capim-uva, cana-selvagem
<i>Philodendron concovadense</i> Kunth	Cipó-imbé, cipó-preto
<i>Schoenoplectus californicus</i> (C.a.Mey.) Soják	Junco, junco-gigante, piri, tiririca-agulha
Food species	
<i>Acca sellowiana</i> (Berg) Burret	Goiaba serrana, feijoa, goiaba-da-serra, goiaba-verde, pineapple-guava.
<i>Annona crassiflora</i> Mart.	Marolo, araticum-do-cerrado.
<i>Araucaria angustifolia</i> (Bertol.) Kuntze.	Pinheiro, araucária, pinheiro-do-paraná, pinheiro-brasileiro.
<i>Butia catarinensis</i> Noblick & Lorenzi	Butiá, butiá-cabeçudo, butiá-da-praia, butiazeiro, coquinho-azedo.
<i>Butia eriospatha</i> (Mart. Ex Drude) Becc.	Butiá-da-serra, butiá-serrano, butiazeiro-serrano, butiá-vermelho, butiá-peludo.

<i>Campomanesia xanthocarpa</i> (Mart.) O.Berg	Guabiroba, gabiroba, guabirobeira.
<i>Eugenia involucrata</i> Dc.	Cerejeira-do-rio-grande, cerejeira-do-mato, cereja-do-rio-grande, cereja-do-mato.
<i>Eugenia pyriformis</i> Cambess.	Uvaia, uvalha, ubaia, uvaeira, azedinha, pome-azedo.
<i>Eugenia uniflora</i> L.	Pitanga, pitangueira, pitanga-mulata, pitanga-preta.
<i>Euterpe edulis</i> Mart.	Juçara, palmito, palmito-juçara, ripeiro, açai-da-mata-atlântica.
<i>Opuntia elata</i> Salm-Dyck	Arumbeva, arumbé, palmatória, cardo-palmatório, palma.
<i>Passiflora actinia</i> Hook.	Maracujá-do-mato, maracujá-silvestre, maracujá-redondinho.
<i>Physalis pubescens</i> L.	Fisális, joá-de-capote, juá-de-capote, tomate-de-capote, canapu, camapu, bucho-de-rã, bate-testa, juápoca, joá-poca, golden-berry.
<i>Plinia peruviana</i> (Poir.) Govaerts	Jaboticaba, jaboticabeira, brazilian-grape.
<i>Psidium cattleianum</i> Sabine	Araçá, araçá-vermelho, araçá-amarelo, araçazeiro, araçazeiro-da-praia.
<i>Vasconcellea quercifolia</i> A. St. –Hil.	Jaracatiá, mamãozinho, mamoeiro-do-mato, mamute, mamão-brabo, figo-de-índio, coco-de-podre.
Forage species (Fabaceae)	
<i>Adesma bicolor</i> (Poir.) DC.	
<i>Adesmia latifolia</i> (Spreng.) Vogel	
<i>Adesmia securigerifolia</i> Herter	
<i>Adesmia tristis</i> Vogel	
<i>Desmodium adscendens</i> (Sw.) DC.	
<i>Desmodium barbatum</i> (L.) Benth.	
<i>Desmodium incanum</i> DC.	
<i>Desmodium subsericeum</i> Malme	
<i>Indigofera sabulicola</i> Benth.	
<i>Leptospron adenanthum</i> (G.Mey.) A.Delgado	
<i>Macroptilium psammodes</i> (Lindm.) S.I. Drewes & R.A. Palacios.	
<i>Ornithopus micranthus</i> (Benth.) Arechav.	
<i>Stylosanthes leiocarpa</i> Vogel.	
<i>Trifolium polymorphum</i> Poir.	
<i>Trifolium rio-grandense</i> Burkart	
<i>Vigna luteola</i> (JAcq.) Benth.	
Forage species (Poaceae)	
<i>Axonopus compressus</i> (Sw.) P. Beauv.	
<i>Axonopus fissifolius</i> (Raddi) Kuhlm.	
<i>Axonopus obtusifolius</i> (Raddi) Chase	
<i>Bothriochloa laguroides</i> (DC.) Herter	
<i>Bromus auleticus</i> Trin. Ex Nees	
<i>Bromus catharticus</i> Vahl.	
<i>Dichantherium sabulorum</i> (Lam.) Gould & C.A. Clark	
<i>Echinochloa polystachya</i> (kunth) Hitchc.	
<i>Hemarthria altissima</i> (Poir.) Stapf & C.E.Hubb	
<i>Ischaemum minus</i> J.Presl	
<i>Mnesithea selloana</i> (Hack.) de Koning & Sosef	
<i>Nassella neesiana</i> (Trin. & Rupr.) Barkworth	
<i>Paspalum alnum</i> Chase	
<i>Paspalum denticulatum</i> Trin.	
<i>Paspalum dilatatum</i> Poir.	
<i>Paspalum glaucescens</i> Hack.	
<i>Paspalum guenoarum</i> Arechav.	
<i>Paspalum jesuiticum</i> Parodi	
<i>Paspalum leptum</i> Schult.	
<i>Paspalum modestum</i> Mez	
<i>Paspalum notatum</i> Fluggé	
<i>Paspalum pumilum</i> Nees	
<i>Paspalum regnellii</i> Mez	
<i>Paspalum rhodopedum</i> L.B.Sm. & Wassh.	

<i>Poa lanigera</i> Nees	
<i>Schizachyrium tenerum</i> Nees	
Medicinal species	
<i>Achyrocline satureioides</i> (Lam.) DC.	Marcela, macela, macelinha
<i>Baccharis articulata</i> (Lam.) Pers.	Carqueja-doce, carqueja, vassoura
<i>Baccharis crispa</i> Spreng.	Carqueja-verdadeira, carqueja-amarga, vassourinha
<i>Baccharis dracunculifolia</i> DC.	Vassourinha, alecrim-do-campo, alecrim-vassoura
<i>Bauhinia forficata</i> Link	Pata-de-vaca, casco-de-vaca, pata-de-boi, pata-de-touro, unha-de-vaca, unha-de-boi, mororó
<i>Bromelia antiacantha</i> Bertol.	Banana-do-mato, caraguatá, bananinha-de-macaco
<i>Casearia Sylvestris</i> Sw.	Chá-de-bugre, erva-de-bugre, guaçatonga
<i>Cecropia glaziovii</i> Snethl.	Embaúba, embaúva, embaúba-vermelha
<i>Copaifera trapezifolia</i> Hayne.	Pau-óleo, copaíba, copaibeira, capuva, óleo
<i>Croton celtidifolius</i> Baill.	Pau-sangue, sangue-de-dragão, tapicingui
<i>Cunila microcephala</i> Benth.	Poejo, poejinho, poejo-do-banhado
<i>Drimys brasiliensis</i> Miers	Casca-de-anta, cataia, para-tudo, canela-armaga, caátuya
<i>Echinodorus grandiflorus</i> (Charm. & Schltr.) Micheli	Chapéu-de-couro
<i>Equisetum giganteum</i> L.	Cavalinha, rabo-de-cavalo
<i>Hypericum caprifoliatum</i> Cham. & Schldtl	Orelha-de-gato, escadinha, sinapismo, hipérico
<i>Ilex paraguariensis</i> A.St.-Hil.	Erva-mate, chá-verde,
<i>Jodina rhombifolia</i> (Hook. & Arn.) Reissek	Cancorosa-de-três-pontas, iodina, jodina
<i>Mikania glomerata</i> Spreng.	Guaco, guaco-liso, cipó-caatinga, erva-de-cobra
<i>Mikania laevigata</i> Sch.Bip. ex Baker	Guaco cheiroso, guaco
<i>Mimosa scabrella</i> Benth	Bracatinga, abracatinga, bracatinho, paracatinga, anizeiro, mandengo
<i>Ocimum Carnosum</i> (Spreng.) Link & Otto ex Benth.	Alfavaca-anisada, alfavaca-cheiro-de-anis, elixir-paregórico, anis, alfavaquina, alfavaca-preta, erva-das-mulheres
<i>Plantago australis</i> Lam.	Tansagem, tanchagem
<i>Piper umbellatum</i> L.	Pariparoba, pariparova, periparoba, capeba, caena, aguaxima, caapeba, catajé, lençol-de-santa-bárbara, jaguarandi
<i>Sambucus australis</i> Cham. & Schldtl.	Sabugueiro, sabugueiro-do-rio-grande, sabugueiro-do-brasil
<i>Smilax campestris</i> Griseb.	Salsaparrilha, sarsaparrilha, japecanga, japicanga, jupicanga, nhapecanga, zarza, ivapeca
<i>Solanum mauritianum</i> Scop.	Fumo-brabo, cvitinga, couvetinga, tabaqueira, fona-de-porco, bugweed, wild-tobacco, tree-tobacco
<i>Solanum paniculatum</i> L.	Jurubeba, jurubeba-verdadeira, jurubebinha, jurupeba
<i>Sorocea bonplandii</i> (Baill.) W.C.Burger et al., <i>Zollernia ilicifolia</i> (Brongn.) Vogel, <i>Jodona rhombifolia</i> (Hook. & Arn.) Reissek	Falsas-espineira-santas, espineiras-santas
<i>Trichilia catigua</i> A.Juss.	Catiguá, cataguá, catuaba, amarelinho, aroeirinha, angelim-rosa, mangaltô-catinga,
<i>Varronia curassavica</i> Jacq. (Boraginaceae)	Erva-baleeira, salicina, balieira, maria-preta
<i>Wilbrandia ebracteata</i> Cogn.	Taiuiá
<i>Zollernia ilicifolia</i> (Brongn.) Vogel	Coração de negro, ipê boia, laranjeira brava, laranjeira da mata, laranjeira do mato, Maria preta, mocetaiba, mucitaiba, mucitaiba preta, orelha de onça, pau santo
Ornamental species	
<i>Ananas bracteatus</i> (Lindl.) Schult. & Schult.f.	Ananás-ornamental, abacaxi-silvestre, abacaxi-vermelho, abacaxi-ornamental, abacaxi-do-pará, red-pineapple, wild-pineapple
<i>Aspilia montevidensis</i> (Spreng.) Kuntze	Mal-me-quer-do-campo, mal-me-quer-amarelo, margarida-do-campo, aspília
<i>Calliandra tweedii</i> Benth.	Topete-de-cardeal, cardeal, quebra-foice, sarandi, espinho-vermelho, maricá-vermelho, esponjinha, esponjinha-vermelha
<i>Cortaderia selloana</i> (Schult.) Asch.	Capim-dos-pampas, penacho, cana-tinga, palha-de-penacho, pluma-de-capim, bandeira, pluma, tiririca, macega, paina
<i>Dyckia distachya</i> Hassi.	Gravatá, bromélia
<i>Epidendrum fulgens</i> Brongn.	Orquídea-da-praia, epidendro, orquídea-de-restinga
<i>Fuchsia regia</i> (Vell.) Munz	Brinco-de-princesa
<i>Gomesa flexuosa</i> (Lodd.) M.W.Chase & N.H.Williams	Chuva-de-ouro, orquídea-dançarina
<i>Handroanthus chrysotrichus</i> (Mart. Ex DC.) Mattos	Ipê-amarelo, ipê-do-morro, ipê-amarelo-cascudo, ipê-tabaco

<i>Heliconia farinosa</i> Raddi	Caité, caité-banana, bananeirinha-do-mato, helicônia
<i>Jacaranda puberula</i> Cham.	Caroba, caroba-da-mata, carobeira, caroba-roxa, carobinha, jacarandá-branco
<i>Parodia ottonis</i> (Lehm.) N.P.Taylor	Tuna-de-bola, tuninha, mandacaruzinho, tuna-amarela, cactus-bola
<i>Petunia integrifolia</i> (Hook.) Schinz & Thell.	Petúnia-perene
<i>Pyrostegia venusta</i> (Ker Gawl.) Miers	Flor-de-são-joão, cipó-de-são-joão-amarelo
<i>Rumohra adiantiformis</i> (G.Forst.) Ching	Samambaia-preta, samambaia-silvestre, iron-fern, leather-leaf-fern, hojas-de-cuero
<i>Sinningia leucotricha</i> (Hoehne) H.E.Moore	Rainha-do-abismo
<i>Syagrus romanzoffiana</i> (Cham.) Glassman	Jerivá, gerivá, coqueiro-gerivá, coqueiro, coco-de-cachorro, baba-de-boi, coco-de-catarro, coco-de-babão
<i>Tibouchina sellowiana</i> Cogn.	Manacá-da-serra, manacá, quaresmeira, quaresmeira-da-serra, jacatirão
<i>Trichocline catharinensis</i> Cabrera	Cravo-amarelo-do-campo, cravo-amarelo
<i>Verbena rigida</i> Spreng	Erva-aramé, camaradinha, verbena, sand-paper-verbena, vained-verbena, tuberous-vervain, stiff-vervain, veined-verbena
Timber species	
<i>Apuleia leiocarpa</i> (Vogel) J. F. Macbr.	Grápia, guarapiapinha, grapiapinha, garapa.
<i>Aspidosperma polyneuron</i> Mull.Arg.	Peroba-rosa, peroba, peroba-açu
<i>Ateleia glazioviana</i> Baill.	Timbó, timbozinho, cinamomo-bravo
<i>Balfourodendron riedelianum</i> (Engl.) Engl.	Guatambu, pau-marfim, farinha-seca
<i>Cabralea canjerana</i> (Vell.) Mart.	Canjerana, canharana, cajarana
<i>Calophyllum brasiliense</i> Cambess.	Olandi, olandim, landi, landim
<i>Cedrela fissilis</i> Vell.	Cedro, cedro-batata, acaicá
<i>Colubrina glandulosa</i> Perkins	Sobraji, sobrasil, sobraju
<i>Cordia trichotoma</i> (Vell.) Arráb ex Steud.	Louro-pardo, louro-batata, ajui
<i>Enterolobium contortisiliquum</i> (Vell.) Morong	Timbaúba, orelha-de-macaco, tamburé
<i>Handroanthus heptaphyllus</i> Mattos	Ipê-roxo, ipê-rosa, ipê-preto
<i>Hieronyma alchorneoides</i> Allemão	Licurana, aricurana, abacateiro
<i>Miconia cinnamomifolia</i> (DC.) Naudin	Jacatirão-açu, jacatirão, carvalho-vermelho
<i>Mimosa scabrella</i> Benth.	Bracatinga, abracatinga, anizeiro
<i>Nectandra lanceolata</i> Nees	Canela-amarela, canela-branca, canela-louro
<i>Ocotea puberula</i> (Rich.) Nees	Canela-guaicá, amansa-besta, louro-pimenta
<i>Parapiptadenia rigida</i> (Benth.) Brenan	Angico, angico-amarelo, angico-cedro
<i>Peltophorum dubium</i> (Spreng.) Taub.	Canafistula, cássia-amarela, faveira
<i>Piptocarpha angustifolia</i> Dusén ex Malme	Vassorão-branco, vassourão
<i>Schizolobium parahyba</i> (Vel.) S. F. Blake	Guapuruvu, fischeira, pataqueira

Table S4. Most relevant bioclimatic variables selected *a priori* based on different plant growth forms.

Plant Growth Forms	<i>a priori</i>	References
Epiphyte (n=2)	bio1, bio2, bio4, bio6, bio7, bio10, bio12, bio14, bio15, bio18, bio19	(Aguiar-Melo et al., 2019; Kolanowska, Rewicz, & Baranow, 2020; Maciel, Sánchez-Tapia, De Siqueira, & Alves, 2017)
Fern (n=1)	bio1, bio3, bio4, bio7, bio8, bio9, bio10, bio11, bio13, bio18, bio19	(de Gasper, Eisenlohr, & Salino, 2015; de Gasper, Grittz, Russi, Schwartz, & Rodrigues, 2020)
Graminoid (n=27)	bio1, bio2, bio4, bio5, bio8, bio10, bio11, bio12, bio15, bio16	(Albuquerque, Macías-Rodríguez, Búrquez, & Rowe, 2020; Cupertino-Eisenlohr et al., 2017; Karunarathne, Feduzka, & Hojsgaard, 2020)
Herb (n=26)	bio1, bio3, bio4, bio5, bio7, bio8, bio9, bio12, bio13, bio14	(Barros et al., 2015; L. T. A. Vieira et al., 2015)

Hydrophyte (n=2)	bio3, bio4, bio6, bio7, bio8, bio10, bio11, bio12, bio14, bio15, bio18, bio19	(Alahuhta, Heino, & Luoto, 2011; Heneidy, Halmy, Fakhry, & El-Makawy, 2019; Lehtonen, 2009)
Lithophyte (n=1)	bio1, bio4, bio7, bio12, bio15	(Melo & Waechter, 2020)
Shrub (n=17)	bio2, bio4, bio5, bio6, bio8, bio9, bio16, bio17, bio18	(Amaral et al., 2017; K. J. P. Silva & Souza, 2018)
Tree (n=53)	bio1, bio3, bio4, bio5, bio6, bio11, bio12, bio14, bio15, bio16, bio17	(V. H. F. Gomes et al., 2019; Zwiener et al., 2017)
Vine (n=10)	bio1, bio2, bio6, bio7, bio12, bio14, bio17	(Barros, Diniz-Filho, & Freitas, 2018; Teixeira, Mäder, Silva-Arias, Bonatto, & Freitas, 2016)

Table S5. Variance inflation factor values (VIFs) inspected to different plant growth forms using the IUCN Plant Growth Forms Classification Scheme.

Variables	Epiphyte (n=2)	Fern (n=1)	Graminoid (n=27)	Herb (n=26)	Hydrophyte (n=2)	Lithophyte (n=1)	Shrub (n=17)	Tree (n=53)	Vine (n=10)
Annual Mean Temperature (bio1)	1.86	-	-	-	-	1.67	-	-	1.89
Mean Diurnal Range (bio2)	2.16	-	1.92	-	-	-	1.79	-	3.23
Isothermality (bio3)	-	2.80	-	3.11	3.48	-	-	1.90	-
Temperature Seasonality (bio4)	2.72	-	2.82	-	-	-	2.44	-	-
Max Temperature of Warmest Month (bio5)	-	-	-	-	-	-	1.29	1.29	-
Temperature Annual Range (bio7)	-	3.11	-	4.03	3.41	2.08	-	-	4.31
Mean Temperature of Wettest Quarter (bio8)	-	-	-	2.74	-	-	-	-	-
Mean Temperature of Driest Quarter (bio9)	-	-	-	4.66	-	-	-	-	-
Mean Temperature of Warmest Quarter (bio10)	-	1.40	1.33	-	1.28	-	-	-	-
Annual Precipitation (bio12)	-	-	-	-	-	2.30	-	-	3.84
Precipitation of Wettest Month (bio13)	-	4.17	-	2.43	-	-	-	-	-
Precipitation of driest month (bio14)	3.92	-	-	1.41	3.72	-	-	2.69	2.57
Precipitation Seasonality (bio15)	2.47	-	1.56	-	2.22	1.22	-	2.15	-
Precipitation of Wettest Quarter (bio16)	-	-	2.67	-	-	-	3.40	2.32	-
Precipitation of Driest Quarter (bio17)	-	-	-	-	-	-	2.33	-	-
Precipitation of Warmest Quarter (bio18)	2.17	1.57	-	-	1.85	-	2.04	-	-
Precipitation of Coldest Quarter (bio19)	2.19	2.21	-	-	2.13	-	-	-	-

Table S6. ODMAP (Overview, Data, Model, Assessment, Prediction) protocol for ecological niche models

Climate change threatens Brazilian agroforestry plant species

– ODMAP Protocol –

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2021-06-01

Overview

Authorship

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Model objective

Model objective: Forecast and transfer

Target output: Continuous habitat suitability and binary maps of potential presence for each species

Focal Taxon

Focal Taxon: Brazilian agroforestry native plant species

Location

Location: Brazil, mainly areas covering the Atlantic Forest and Pampa grasslands

Scale of Analysis

Spatial extent (lon/lat): 65° W - 33° W, 3° S - 34° S

Temporal extent/time period: Current data for 1970-2000 and future for 2041-2060 and 2061-2080

Boundary: Political

Biodiversity data

Observation type: field survey

Response data type: presence-only

Predictors

Predictor types: climatic

Hypotheses

Hypotheses: Species BAHs are affected by climate change. We quantify potential changes in BAH for 139 native agroforestry species from the Brazilian flora using two different climate change scenarios (SSP2-4.5 and SSP5-8.5) for 2041-2060 and for 2061-2080.

Assumptions

We assume that (1) the species are at equilibrium with the environment, (2) have stable niches, (3) occurrence records sampled randomly, (4) predictors are free of errors and (5) habitat suitability as a proxy of species BAH.

Algorithms

Modelling techniques: MaxEnt v.3.4.1k

Model complexity: We only kept linear and quadratic features to avoid overfitting of the models and as recommended by Merow *et al.* because of the absence of a biological justification with the variables used (Boucher-Lalonde *et al.*, 2012; Merow *et al.*, 2013).

Workflow

Current and future potential habitats for species were predicted using MaxEnt v.3.4.1k. To assess robustness and alert policy-makers for the uncertainties typically associated with these methods, each ENM was tested against a bias corrected null-model as proposed by Raes and ter Steege (Raes & ter Steege, 2007). The climate projections were carried out according to the Sixth Assessment Report (AR6) of the IPCC, using two Shared Socioeconomic Pathways (SSPs) as reference (SSP2-4.5 and SSP5-8.5). We averaged eight different global climate models: BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR,

MIROC-ES2L, MIROC6 and MRI-ESM2-0 to take into account the uncertainties related to future climate conditions (Araujo & New, 2007).

Software

All modelling and tests were carried out within the R environment (R Core Team, 2021), using the R packages ‘dismo’ (Hijmans et al., 2017), ‘flora’ (G. Carvalho, 2017), ‘rgdal’ (Bivand, Keitt, & Rowlingson, 2016), ‘rgeos’ (Bivand & Rundel, 2019), ‘rJava’ (Urbanek, 2019), ‘raster’ (Hijmans, 2019), ‘sf’ (Pebesma, 2018) and ‘usdm’ (Naimi, 2015).

Code availability: Available on request

Data availability: Datasets generated are available from GBIF:

<https://doi.org/10.15468/dl.vjezvb>

Data

Biodiversity data

Taxon names: Taxon names are listed in the Supplementary Information.

Taxonomic reference system: We standardized botanical names using the R package ‘flora’, which uses the nomenclature accepted by the Brazilian Flora 2020 project (<http://floradobrasil.jbrj.gov.br/>).

Ecological level: species

Data sources: All species occurrence data was obtained from the online database of the Global Biodiversity Information Facility (<https://doi.org/10.15468/dl.vjezvb>)

Sampling design: We extracted all records from the following extent -90, -25, -70, 20 to avoid modelling truncated niches

Sample size: The sample size for species ranged from 12 (*Ornithopus micrantus*) to 5464 (*Casearia sylvestris*).

Background data: We drew 10,000 points of background for each species’ BAH independently.

Data partitioning

Model performance was assessed using a bias corrected null-model as proposed by Raes and ter Steege.

Predictor variables

Annual Mean Temperature (bio1), Mean Diurnal Range (bio2), Isothermality (bio3), Temperature Seasonality (bio4), Max Temperature of Warmest Month (bio5), Temperature Annual Range (bio7), Mean Temperature of Wettest Quarter (bio8), Mean Temperature of Driest Quarter (bio9), Mean Temperature of Warmest Quarter (bio10), Annual Precipitation (bio12), Precipitation of Wettest Month (bio13), Precipitation of driest month (bio14), Precipitation Seasonality (bio15), Precipitation of Wettest Quarter (bio16), Precipitation of Driest Quarter (bio17), Precipitation of Warmest Quarter (bio18) and Precipitation of Coldest Quarter (bio19)

Data sources: Worldclim version 2.1. (<http://worldclim.org>)

Spatial extent: -90, -25, -70, 20

Spatial resolution: The raw resolution of the climate data was 5 arc-minutes

Coordinate reference system: WGS 1984

Temporal extent: Temporal extent of raw data was 1970-2000

Transfer data

Data sources: Worldclim version 2.1.

(<https://www.worldclim.org/data/cmip6/cmip6climate.html>)

Spatial extent: -90, -25, -70, 20

Spatial resolution: The raw resolution of the future climate data was 5 arc-minutes

Temporal extent: 2041-2060 and 2061-2080

Models and scenarios: We averaged eight different global climate models: BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6 and MRI-ESM2-0

Quantification of Novelty: As transferring models across time can lead to spurious extrapolations and consequently unrealistic predicted ENMs, we adopted a conservative approach by fitting the models to the estimated species BAHs.

Model

Multicollinearity

Multicollinearity: We checked for multicollinearity by examining the correlation structure of the predictor variables through the variance inflation factor (VIF). We kept only predictors with VIF values below 5 (Fremout et al., 2020). The VIFs were checked using the function ‘vifstep’ in the R package ‘usdm’ (Naimi, 2015).

Model settings

ENMs were fitted using the following parameters in the MaxEnt: bootstrap method with 100 replicates, 500 maximum iterations, 10,000 points of background, and Cloglog output format. We only kept linear and quadratic features to avoid overfitting of the models and as recommended by Merow *et al.* because of the absence of a biological justification with the variables used (Boucher-Lalonde et al., 2012; Merow et al., 2013).

Model estimates

We computed variable importance of evaluation runs.

Analysis and Correction of non-independence

None

Threshold selection

To map changes in future ranges of species, we converted the continuous habitat suitability into binaries using the maximum training sensitivity plus specificity threshold (Bean et al., 2012; Jiménez-Valverde & Lobo, 2007).

Assessment

Performance statistics

Model performance was assessed using a bias corrected null-model as proposed by Raes and ter Steege.

Plausibility check

Response shapes: we inspected species-response-curves to avoid spurious calibrations, following the evaluation strip method proposed by Elith *et al.*(Elith et al., 2005).

Prediction

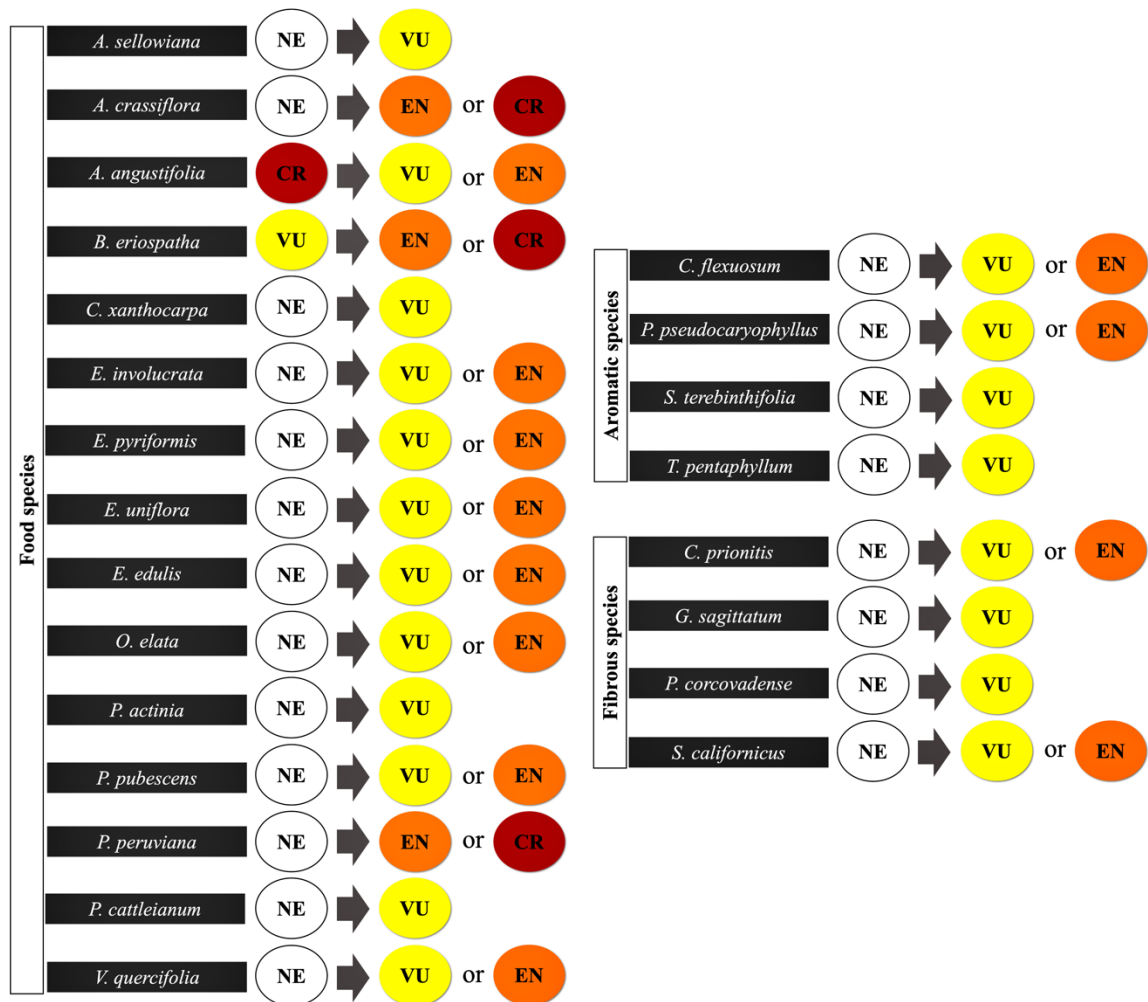
Prediction output

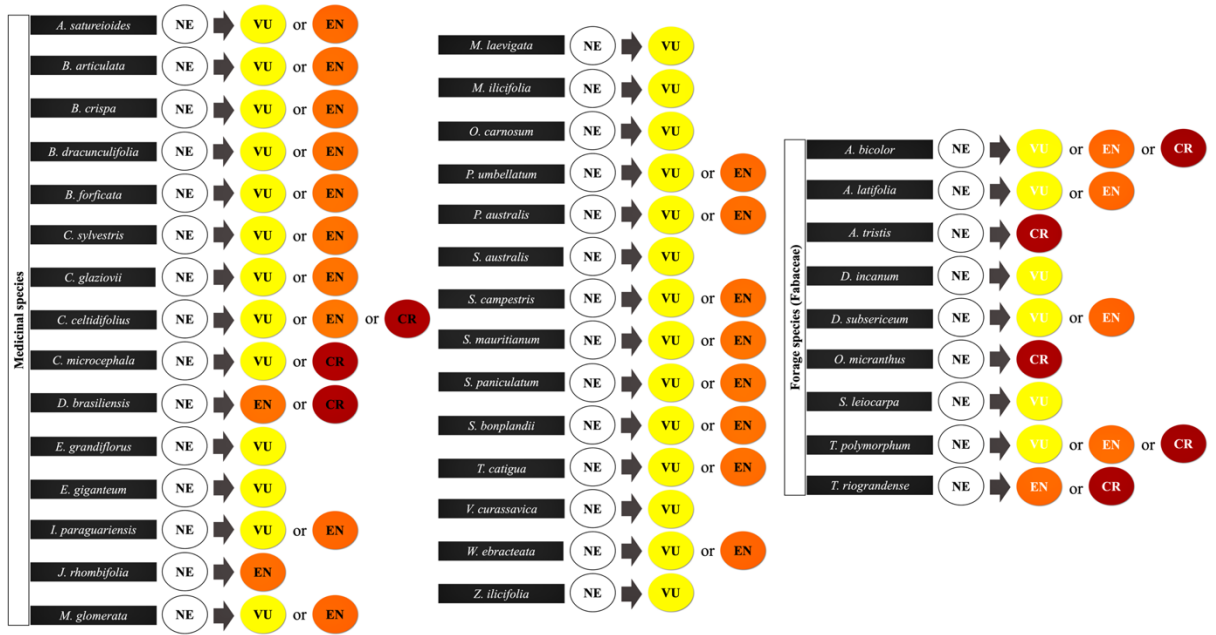
Prediction unit: Continuous habitat suitability and binary maps of potential presence for each species.

Uncertainty quantification

Scenario uncertainty: For future climate change predictions, we averaged eight global climate change models.

Figure S1. Potential native agroforestry plant species changing from a current assessed IUCN category or Not Evaluated (NE) to a threat category, Vulnerable (VU), Endangered (EN) and Critically Endangered (CR), based on different major uses due to climate change.





Chapter 4

Planning conservation for potential native agroforestry plant species under climate change in Brazil

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Schizolobium parahyba in Florianópolis, Santa Catarina, Brazil by Valdeir P. Lima

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Abstract

1. Designing multispecies systems with suitable climatic affinity, and identifying species' vulnerability under human-driven climate change are key steps to achieve successful adaptation of natural systems.
2. To identify species with similar climatic niche requirements, that can be grouped for mixed cropping, we employ Ecological Niche Models (ENMs), and Spearman's ρ for overlap. Then, we used prioritization algorithms to map areas of high conservation value using two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) to assess mid-term (2041-2060) and long-term (2061-2080) climate change impacts.
3. We identified multiple groups of species with high climatic similarity that can be combined in mixed cropping systems under current and future climatic conditions. In addition, we observed that climate change is predicted to modify the spatial association of these groups under different future climate scenarios, causing a mean negative change in climatic similarity between 9.5–13.7% under the SSP2-4.5 scenario and between 9.5–10.5% under the SSP5-8.5 scenario for 2041–2060 and 2061–2080, respectively. Each group display a variety of plant growth forms (trees, shrubs, subshrubs, vines and herbs) and consequently a considerable potential to be integrated into multistrata agroforestry systems. Areas of high conservation value under current and future climate conditions varied among all native agroforestry species groups in Brazil.
4. Synthesis and applications. Our findings provide a framework for the agrobiodiversity conservation through the establishment of agroforestry systems adapted to different climate conditions due to the combination of key species. In addition, policymakers, conservation organizations and farmers should use this information on the priority areas mapped across Brazil and species with suitable climatic similarity to promote different actions as these particular species can potentially be conserved in urban and peri-urban areas.

KEYWORDS Atlantic Forest, biodiversity loss, conservation biogeography, global change biology, ecological niche modeling, mixed cropping, pampa, polycultures.

Introduction

Human-driven climate change is shifting species distribution patterns globally (Cámara-Leret et al., 2019; Lima et al., 2022; Marchioro et al., 2020), resulting in unprecedented impacts on ecosystem functioning of ecosystems and human welfare worldwide (Díaz et al., 2018; Pecl et al., 2017). Changing climate conditions not only results in shifting and often reduced ranges of native plant species, but it also poses serious challenges to maintain agricultural production in the coming years, especially for smallholders (Gomes et al., 2020). Agroforestry is one of the oldest techniques of land use and represents the newest frontier in advancing agricultural research in tropical regions today (Gupta et al., 2022; Carolina Levis et al., 2018; Liu, Kuchma, & Krutovsky, 2018). These multispecies crop systems contribute more to climate change mitigation, since they sequester more carbon dioxide from the atmosphere than monocultures (De Giusti, Kristjanson, & Rufino, 2019; Reppin et al., 2020) and they emit less than other land use activities, if managed properly (F. Montagnini & Nair, 2004; Rosenstock et al., 2014). In addition, agroforestry can combine valuable forest species and agricultural crops, optimizing production while generating income for local communities (Gomes et al., 2020; Liu et al., 2018; Oliveira & Carvalhaes, 2016; Santos et al., 2021; Souza et al., 2010). But first, is it essential to design multispecies systems in the face of climate change, because combinations of agroforestry species rely on specific climatic conditions (Liu et al., 2018).

Harboring more species than any other country on Earth and large biocultural heritage, Brazil is a global conservation priority (Levis et al., 2020; Oliveira et al., 2017). More than ever, conservation approaches, encompassing the sustainable use of biodiversity and engaging local communities are necessary as Brazil's environmental legislation and governance of important ecosystem services are currently jeopardized (Abessa, Famá, & Buruaem, 2019; Levis et al., 2020; Vieira et al., 2018). Brazil has great potential to increase agroforestry areas and, consequently, boost multiple regulatory ecosystem services (IPBES, 2019; Schuler et al., 2022; Torres et al., 2021). One of the major challenges involved in effective conservation planning is the identification of ecologically relevant portions of the landscape to be conserved, taking into account drivers of biodiversity loss (de Lima et al., 2020; Zwiener et al., 2017) and the projected impacts of climate change. In this way, the identification of areas of high conservation value is pivotal to inform policymakers, and agroforesters of potential areas for cultivation, since many species with different uses (e.g. construction, food, medicine and ornament) can be conserved over a wide range of sites (Coradin et al., 2011; Reis et al.,

2018). As climate change shifts species distributions and extinction risks, prioritization assessments taking into account this global driver of biodiversity are crucial to the implementation of successful conservation policies (Bagchi et al., 2018; Hannah et al., 2020; Lima et al., 2022; Pecl et al., 2017; Tittensor et al., 2019).

ENMs are widely used to predict climate change impacts on species distribution and in establishing priority areas for conservation (Guisan & Zimmermann, 2000; Lima et al., 2022). Ecological applications, such ENMs, niche similarity metrics and macro-ecological analyses provide valuable information on species distribution patterns across geographic space and time, allowing to incorporate global climate change predictions into conservation planning. Here, we employ ENMs to (1) identify species with similar climatic niche requirements, that can be grouped for mixed cropping under different climate conditions. Then, to inform policy, we (2) map current and future areas of high conservation value using two Shared Socioeconomic Pathways (minimum - SSP2-4.5 and maximum - SSP5-8.5) to assess mid-term (2041-2060) and long-term (2061-2080) future climate impacts.

Material and methods

Study area and species occurrence data

We studied the distribution of 95 plant species native from the Atlantic Forest and Pampa grasslands, Southern Brazil (latitudes 60°S-15°N and longitudes 90°-30°W). These species have a great potential to agroforestry and a wide variety of uses such as condiment, fibrous, food, medicinal, ornamental and timber (Coradin et al., 2011) (Table S1).

We obtained the species occurrence records from the Global Biodiversity Information Facility (GBIF, 2022), and we used the R package 'flora' (Carvalho, 2017) to standardize the botanical nomenclature following the Brazilian Flora 2020 project (<http://floradobrasil.jbrj.gov.br/>). Next, we applied the record cleaning pipeline proposed by Gomes *et al.* (2018), which consists of two main steps. Firstly, we removed the occurrence records without geographic coordinates using the function 'cleancoordinates' from the R package 'CoordinateCleaner' (Zizka et al., 2019). Secondly, we estimated the kernel density of occurrence records and removed the spatial outliers through the 'density' function from the R package 'stats' (R Core Team, 2021). To reduce spatial autocorrelation (Aiello-Lammens et al., 2015) and over-representation of certain environmental conditions (Daru et al., 2018; Oliveira et al., 2016), we spatially filtered the species records at a distance of 20km

using the R package 'spThin' (Aiello-Lammens et al., 2015). For the ENM procedures (see section 'Current and future projections' below) we used only species with more than 10 spatially-unique records in order to guarantee a minimum model accuracy (Beaumont et al., 2016; Proosdij et al., 2016). To avoid modeling truncated niches, we included all species records beyond geographically occupied areas (Raes, 2012). We listed all taxonomic authorities and species common names in Table S1.

Environmental predictors

To assess species' climatic requirements, we downloaded the 19 bioclimatic predictors provided by the Worldclim version 2.1 (<http://worldclim.org/>) at a resolution of 5 arc-minutes (Fick & Hijmans, 2017). Selecting predictors based on the known ecology or physiology of the species is pivotal to assess the biological significance of distribution models (Austin & Van Niel, 2011; Petitpierre, Broennimann, Kueffer, Daehler, & Guisan, 2017). Thus, the identification of true drivers of species distribution should involve a priori knowledge during the step (Murray et al., 2009). Due to the lack of ecological information at a specific level, we selected a priori predictors for species based on different plant growth forms (Fourcade et al., 2018; IUCN, 2020). Then, we examined the multicollinearity of these predictors through the variance inflation factor (VIF) using the function 'vifstep' in the R package 'usdm' (Naimi, 2015). Only predictors with VIF values below 5 were retained to minimize collinearity within our predictors (Fremout et al., 2020) (Table 1).

Table 1. Most relevant candidate bioclimatic variables selected *a priori* for different plant growth forms, based on the existing ENM studies with plant species and variance inflation factor values (VIFs). Only the VIF values for the variables finally included in the analyses (VIF <5) are presented.

Plant Growth Forms ¹	<i>a priori</i>	References	Retained predictors and VIFs
Herb (n=20)	bio1, bio3, bio4, bio5, bio7, bio8, bio9, bio12, bio13, bio14	(Aguiar-Melo et al., 2019; Barros et al., 2015; Cámara-Leret et al., 2019; Maciel et al., 2017; L. T. A. Vieira et al., 2015)	bio4 3,11 bio7 4,03 bio8 2,74 bio9 4,66 bio13 2,43 bio14 1,41
Shrub (n=10)	bio2, bio4, bio5, bio6, bio8, bio9, bio16, bio17, bio18	(Amaral et al., 2017; Cámara-Leret et al., 2019; Mäder et al., 2021; K. J. P. Silva & Souza, 2018)	bio2 1,79 bio4 2,44 bio5 1,29 bio16 3,40 bio17 2,33 bio18 2,04

Subshrub (n=4)	bio1, bio2, bio4, bio5, bio8, bio10, bio11, bio12, bio15, bio16	(Amaral et al., 2017; Cámara-Leret et al., 2019; Mäder et al., 2021; K. J. P. Silva & Souza, 2018)	bio3 1,92 bio4 2,82 bio10 1,33 bio15 1,56 bio16 2,67
Tree (n=53)	bio1, bio3, bio4, bio5, bio6, bio11, bio12, bio14, bio15, bio16, bio17	(Assis, Araújo, & Serrão, 2018; Cámara-Leret et al., 2019; V. H. F. Gomes et al., 2020, 2019; O. J. Wilson et al., 2019; Zwiener et al., 2017)	bio3 1,90 bio5 1,29 bio15 2,69 bio16 2,15 bio17 2,32
Vine (n=8)	bio1, bio2, bio6, bio7, bio12, bio14, bio17	(Barros et al., 2018; Teixeira et al., 2016)	bio1 1,89 bio2 3,23 bio7 4,31 bio12 3,84 bio14 2,57

¹ We followed the IUCN Plant Growth Forms Classification Scheme (<https://www.iucnredlist.org/>)

Current and future projections

We used MaxEnt (version 3.4.1k), a machine-learning algorithm which uses maximum entropy modelling to estimate species' probability distribution to predict current and future potential habitats for species based on presence-only data (Phillips et al., 2006). Then, we tested the predictive capacity of each ENM against a bias corrected null-model, as proposed by Raes and ter Steege, and only significant ENMs were used for future predictions (Raes & ter Steege, 2007). Following the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021), we projected significant ENMs for 2041-2060 and 2061-2080, based on two SSPs (SSP2-4.5 and SSP5-8.5). To account for variability across individual models, we averaged eight global climate models: BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6 and MRI-ESM2-0 (Araujo & New, 2007). To allow transparency and reproducibility for reporting ENMs, we adopted the ODMAP (Overview, Data, Model, Assessment, Prediction) protocol v1.0. (Zurell et al., 2020). For information on the modelling procedures, see the Supplementary information (Table S2).

Species for mixed cropping systems

Niche overlap allows us to identify species with similar ecological requirements (Corrêa, Albrecht, & Hahn, 2011; Sá-Oliveira, Angelini, & Isaac-Nahum, 2014), and can be measured using different niche similarity metrics such as Schoener's Index - D (Schoener, 1968; Warren, Glor, & Turelli, 2008), Hellinger's Distance - I (Van der Vaart, 1998; Warren et al., 2008), and the rank correlation coefficient rho (Spearman, 1987; Warren et al., 2021). These statistics range from 0, where the niche models have no overlap, to 1, where the niche

models are totally similar (Warren et al., 2008). To select species for mixed cropping systems, we quantified the niche overlap among ENM predictions across climate change scenarios and for different time periods. As Schoener's Index - D , and Hellinger's Distance - I tend to overestimate similarity when many grid cells are of similar values, we used Spearman's ρ for measuring species niche overlap using the 'raster.cor.matrix' function implemented in the R package 'ENMTools' (Warren et al., 2021). We built hierarchical clusters using the pairwise similarity values through 'hclust' function from the R package 'stats' (R Core Team, 2021). This function creates clusters through a set of differences for the n objects to be grouped (Dodge, 2008). Then each object is allocated to its own cluster, and the algorithm iteratively continues at each stage joining the two most similar clusters until only a single cluster remains (Dodge, 2008). The distances between the clusters were recomputed by the Lance-Williams dissimilarity update formula, using the 'complete linkage method' (R Core Team, 2021). We set 15 clusters ($k=15$) to identify finer climatic affinities among the species. For data visualization, we created fan dendrograms using the 'circlize_dendrogram' function in the R package 'dendextend' (Galili, 2015). All analyses were conducted using the version R 4.1.1 (R Core Team, 2021).

Spatial conservation prioritization

To prioritize areas for conservation, we used the Zonation v. 4.0 software (Moilanen et al., 2005, 2014). Zonation is a large-scale spatial software package that is widely used for conservation planning, identifying critical areas to conserve high habitat quality and connectivity for multiple species over the entire landscape (Moilanen et al., 2014). ENM predictions for 135 potential native agroforestry plant species were used as input for both current and future climate predictions for different scenarios and years. We selected the 'core area zonation' (CAZ) function as the cell-removal rule (Cámara-Leret et al., 2019; Duan, Xia, Hou, Liu, & Yu, 2019; Spiers, Oatham, Rostant, & Farrell, 2018), which ranks cells based on the importance of the occurrence of a given species in a cell; thus allowing the identification of priority areas even for rare species (Cámara-Leret et al., 2019). We enabled the 'edge removal rule' to maintain structural connectivity throughout the removal process and set the warping factor to 1 (run time and precision) to ensure the optimization operation performed well (Duan et al., 2019). Based on the preliminary conservation status assessed by Lima et al. (2022), we assigned the following IUCN conservation status weights to the 95 target species CR (5), EN (weight 4), VU (weight 3), NT (weight 2) and LC (weight 1) (Di Minin et al., 2016; Santangeli et al., 2019). We set a maximum dispersal capacity at 100 km, assuming no

plant dispersal rates over 0.1 km/year for vascular and non-vascular plants or above 100 km for Brazilian tree species in a climate change scenario (Gomes et al., 2019; Hannah et al., 2020; Thuiller et al., 2008; Warren et al., 2013). As the studied species can potentially be conserved in both urban and peri-urban areas, we did not include a land use penalty layer in the analysis.

Results

Multispecies combination

We identified multiple groups of species with high climatic similarity that can be combined well in mixed cropping systems under current and future climatic conditions (Figure 1-3, Table S9). In addition, we observed that climate change is predicted to modify the spatial association of these groups under different future climate scenarios (Figure 2, Figures S1-S3), causing a mean negative change in climatic similarity between 9.5–13.7% under the SSP2-4.5 scenario and between 9.5–10.5% under the SSP5-8.5 scenario for 2041–2060 and 2061–2080, respectively. To illustrate, the species *Ilex paraguariensis* (Yerba mate) that has been traditionally cultivated and managed in southern Brazil shows higher current climatic similarity with *Mimosa scabrella* ($\rho = 0.88$) (Figure 1, Table S3). However, under the future SSP5-8.5 scenario (2061-2080), this species is predicted to show higher climatic suitability with *Jacaranda puberula* ($\rho = 0.83$) (Figure 2, Table S7). The species with the lowest climatic similarity were: *Epidendrum fulgens* and *Philodendron corcovadense* under the current climate; *Annona crassiflora*, *Jodina rhombifolia*, *E. fulgens*, *Gynerium sagittatum* under the SSP2-4.5 scenario (2041-2060); *Opuntia elata* and *E. fulgens* under the SSP2-4.5 and SSP5-8.5 for 2061-2080 and *A. crassiflora*, *J. rhombifolia*, *Parodia ottonis* and *Hypericum caprifoliatum* under the SSP5-8.5 for 2041-2060 (Figure 1-3, Table S9).

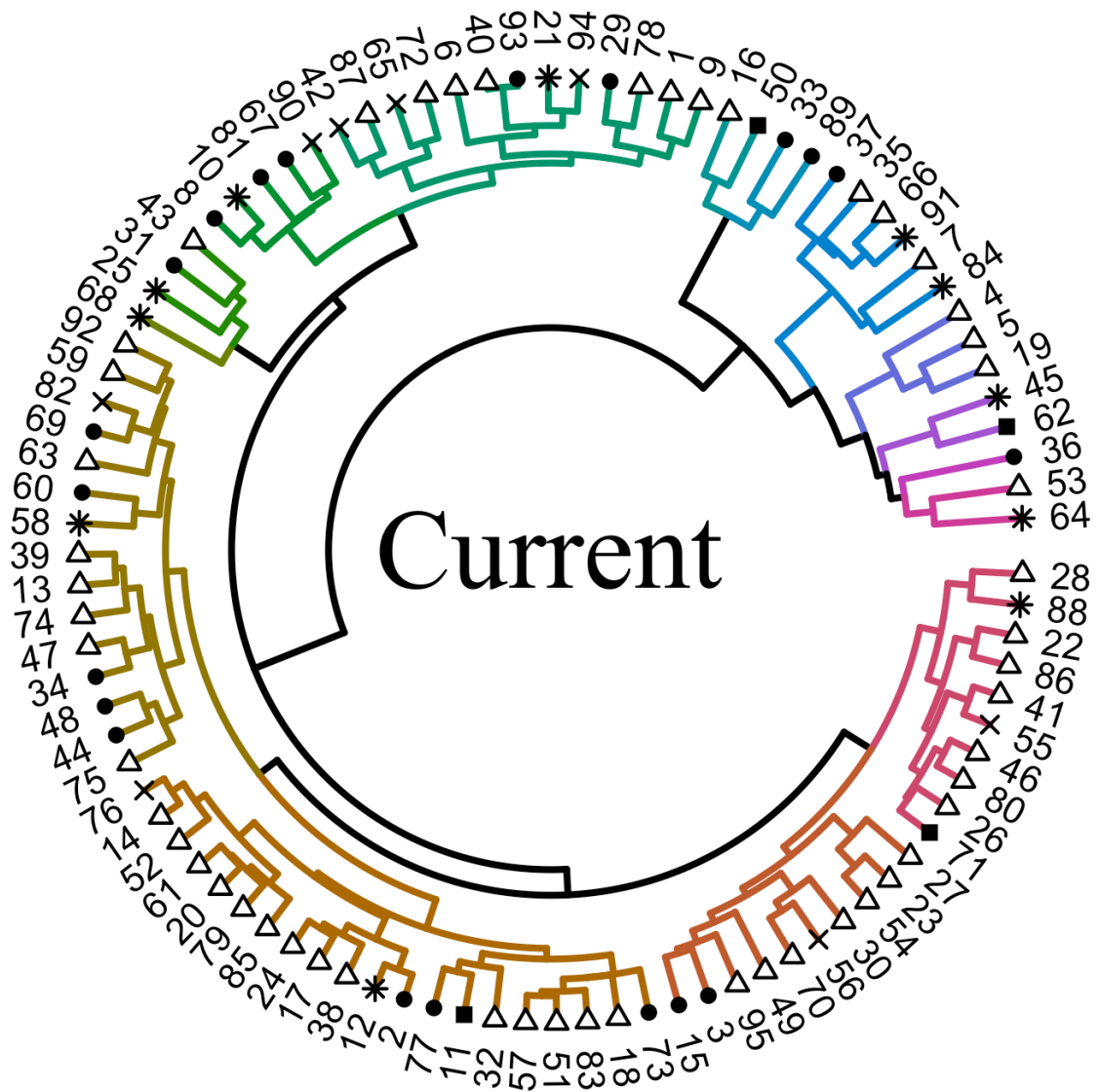


Figure 1. Hierarchical clustering dendrograms showing multiple groups of species for mixed cropping systems obtained by overlapping ENM predictions (Spearman's ρ for overlap) from 95 native Brazilian agroforestry plant species under current scenario. Plant life form is represented by different symbols, trees (Δ), herbs (\bullet), vines ($+$), shrubs ($*$) and subshrubs (\blacksquare). List of species for numerical codes are in Table S8.

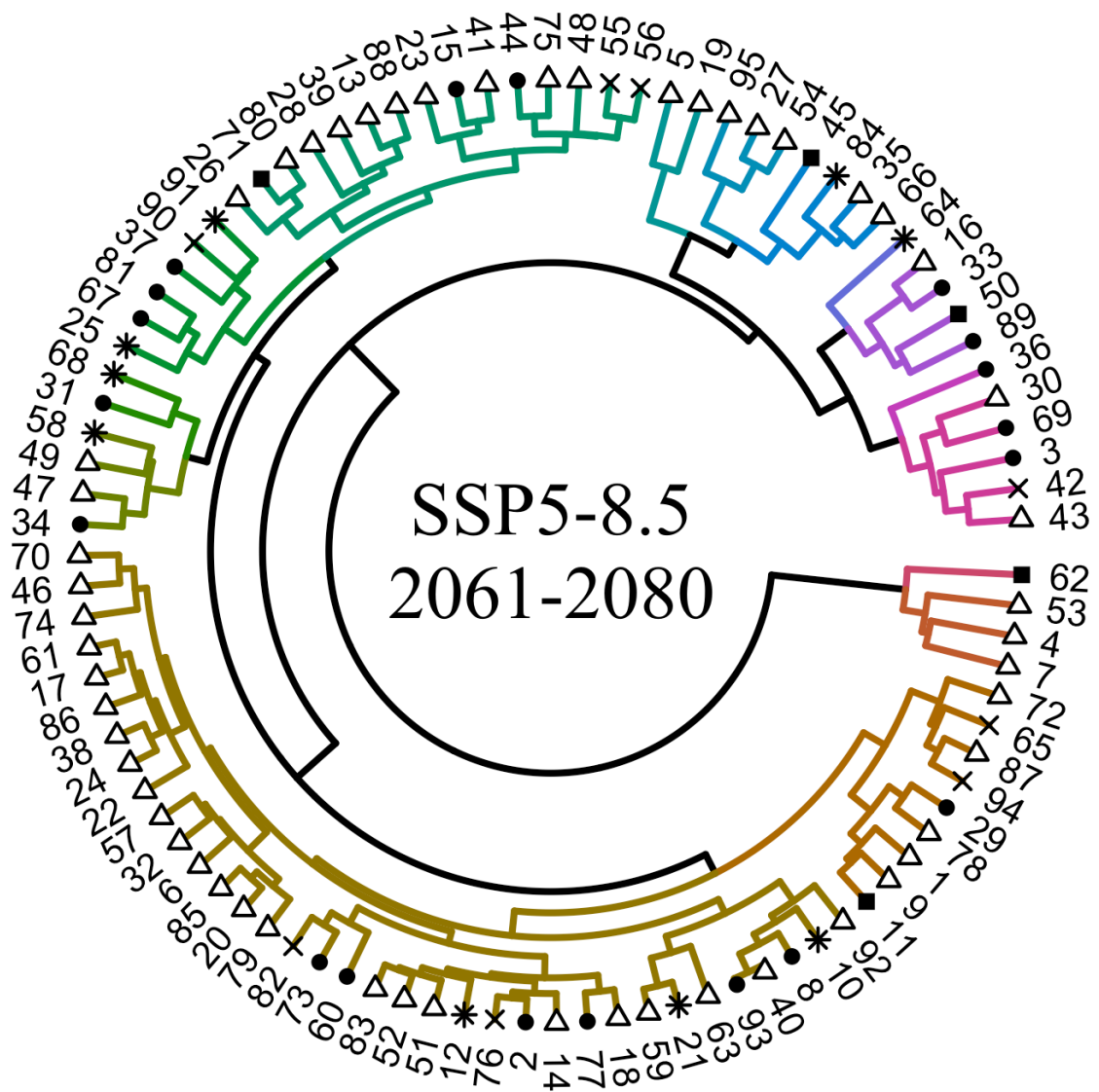


Figure 2. Hierarchical clustering dendrograms showing multiple groups of species for mixed cropping systems obtained by overlapping ENM predictions (Spearman's ρ for overlap) from 95 native Brazilian agroforestry plant species under the SSP5-8.5 scenario for 2061-2080. Plant life form is represented by different symbols, trees (Δ), herbs (\bullet), vines ($+$), shrubs ($*$) and subshrubs (\blacksquare). List of species for numerical codes are in Table S8.

<i>Plantago australis</i> <i>Calliandra tweedii</i> <i>Solanum mauritianum</i> <i>Ilex paraguariensis</i> <i>Mimosa scabrella</i> <i>Drimys brasiliensis</i> <i>Baccharis crispa</i> <i>Rumohra adiantiformis</i> <i>Achyrocline satureioides</i> <i>Baccharis dracunculifolia</i> <i>Eugenia involucrata</i> <i>Cabralea canjerana</i> <i>Cedrela fissilis</i> <i>Sorocea bonplandii</i> <i>Schinus terebinthifolia</i> <i>Campomanesia xanthocarpa</i> <i>Ocotea puberula</i> <i>Jacaranda puberula</i> <i>Bauhinia forficata</i> <i>Pyrostegia venusta</i>	<i>Fuchsia regia</i> <i>Tibouchina sellowiana</i> <i>Passiflora actinia</i> <i>Piptocarpha angustifolia</i> <i>Araucaria angustifolia</i> <i>Eugenia uniflora</i> <i>Verbena rigida</i> <i>Capsicum flexuosum</i> <i>Wilbrandia ebracteata</i> <i>Cortaderia selloana</i> <i>Sambucus australis</i> <i>Acca sellowiana</i> <i>Ateleia glazioveana</i>	<i>Psidium cattleianum</i> <i>Gomesa flexuosa</i> <i>Heliconia farinosa</i> <i>Echinodorus grandifloras</i> <i>Handroanthus heptaphyllus</i> <i>Plinia peruviana</i> <i>Balfourodendron riedelianum</i> <i>Eugenia pyriformis</i> <i>Monteverdia ilicifolia</i> <i>Ocimum carnosum</i> <i>Parapiptadenia rigida</i> <i>Physalis pubescens</i> <i>Smilax campestris</i> <i>Nectandra lanceolata</i> <i>Vasconcellea quercifolia</i>
<i>Equisetum giganteum</i> <i>Enterolobium contortisiliquum</i> <i>Peltophorum dubium</i> <i>Varronia curassavica</i> <i>Aspidosperma polyneuron</i> <i>Solanum paniculatum</i>	<i>Copaifera trapezifolia</i> <i>Cecropia glaziovii</i> <i>Miconia cinnamomifolia</i> <i>Croton celtidifolius</i> <i>Mikania laevigata</i> <i>Pimenta pseudocaryophyllus</i> <i>Hyeronima alchorneoides</i> <i>Zollernia ilicifolia</i> <i>Ananas bracteatus</i> <i>Bromelia antiacantha</i>	<i>Cordia trichotoma</i> <i>Trichilia catigua</i> <i>Casearia sylvestris</i> <i>Syagrus romanzoffiana</i> <i>Euterpe edulis</i> <i>Mikania glomerata</i> <i>Handroanthus chrysotrichus</i> <i>Schizolobium parahyba</i> <i>Colubrina glandulosa</i> <i>Piper umbellatum</i>
<i>Aspilia montevidensis</i> <i>Baccharis articulata</i> <i>Schoenoplectus californicus</i> <i>Petunia integrifolia</i> <i>Tropaeolum pentaphyllum</i>	<i>Coleataenia prionitis</i> <i>Cunila microcephala</i> <i>Geonoma gamiova</i>	<i>Annona crassiflora</i> <i>Apuleia leiocarpa</i> <i>Calophyllum brasiliense</i>
<i>Epidendrum fulgens</i>	<i>Jodina rhombifolia</i> <i>Parodia ottonis</i>	<i>Dyckia distachya</i> <i>Trichocline catharinensis</i>
<i>Philodendron corcovadense</i>	<i>Gynerium sagittatum</i> <i>Opuntia elata</i>	<i>Butia eriospatha</i> <i>Hypericum caprifoliatum</i>

Figure 3. Groups of species for mixed cropping systems obtained by overlapping ENM predictions (Spearman's ρ for overlap) with greater climatic affinities under current scenario.

The species within each group displayed a variety of plant growth forms (trees, shrubs, subshrubs, vines and herbs) and consequently a considerable potential for integration under multistrata agroforestry systems (Figures 1 and 2). For instance, the critically endangered species *A. angustifolia* that has already been incorporated into agroecosystems, can currently be combined with other trees as long as they do not occupy the same stratum (*Campomanesia xanthocarpa*, *Drimys brasiliensis*, *Mimosa scabrella*, *Schinus terebinthifolia* and *Sorocea*

bonplandii), shrubs (*Baccharis articulata*, *Baccharis dracunculifolia* and *Capsicum flexuosum*), vines (*Pyrostegia venusta* and *Smilax campestris*) and herbs (*Achyrocline satureioides*, *Aspilia montevidensis*, *Ocimum carnosum*, *Plantago australis*, *Rumohra adiantiformis* and *Verbena rigida*). Further, for 2061-2080 (SSP5-8.5) with trees (*Bauhinia forficata*, *Cabrlea canjerana*, *Calliandra tweedii*, *C. xanthocarpa*, *Casearia sylvestris*, *Cedrela fissilis*, *D. brasiliensis*, *Eugenia involucrata*, *Eugenia uniflora*, *Handroanthus chrysotrichus*, *I. paraguariensis*, *Jacaranda puberula*, *M. scabrella*, *Nectandra lanceolata*, *Ocotea puberula*, *Parapiptadenia rigida*, *Pimenta pseudocaryophyllus*, *Plinia peruviana*, *S. terebinthifolia*, *Solanum mauritianum*, *S. bonplandii*, *Syagrus romanzoffiana* and *Vasconcellea quercifolia*), shrubs (*B. articulata*, *B. dracunculifolia* and *C. flexuosum*), vines (*P. venusta* and *S. campestris*), and herbs (*A. montevidensis*, *V. rigida*, *R. adiantiformis*, *A. satureioides*, *O. carnosum* and *P. australis*).

Areas of high conservation value

Priority sites for conservation under current and future climate varied among all potential native agroforestry plant species groups in Brazil. Under current conditions, the areas retaining the highest habitat quality values for all species are concentrated primarily in areas surrounding the Federal District, central and northern regions of Minas Gerais (MG), southern Espírito Santo (ES) and Rio de Janeiro (RJ), central and eastern regions of São Paulo (SP), Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS) (Figure 4).

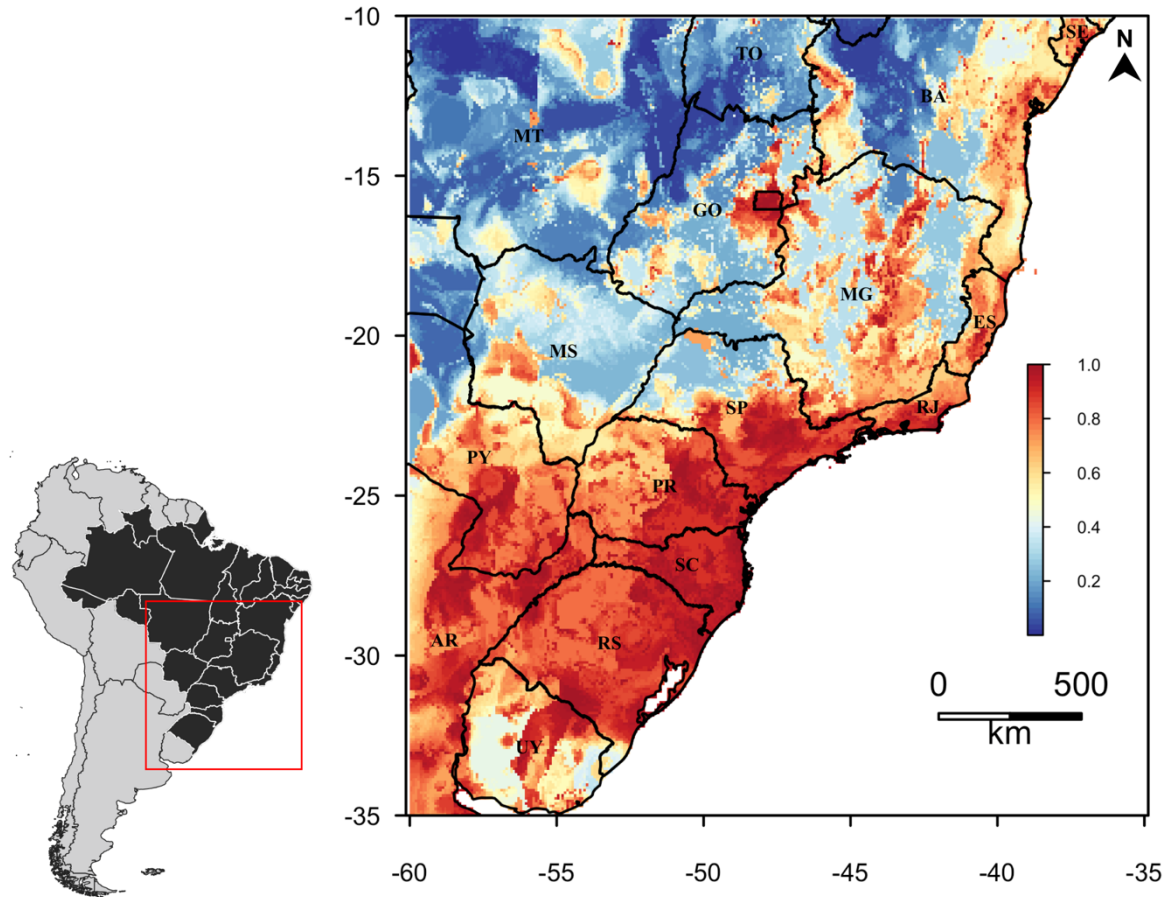


Figure 4. Areas of high conservation value for 95 potential native Brazilian agroforestry plant species under current conditions. Priorities are ranked from highest (red) to lowest (blue).

Priority areas shifted for different plant uses and climate change scenarios (Table 2, Figure 5, Figures S4, S5 and S6). Considering all future scenarios and species, the areas with the highest habitat quality values comprised primarily the states of MG, MT, SP, PR, SC and RS and particular areas of BA, Sergipe (SE), TO, GO, ES, RJ, MT and Mato Grosso do Sul (MS). Although we focused on Brazil, specific areas in Argentina (AR), Paraguay (PY) and Uruguay (UY) were also ranked as high priority for holding large habitat quality portions of the landscape (Figure 6).

Table 2. Brazilian regions of high conservation value for potential native agroforestry plant species according to different uses under SSP2-4.5 and SSP5-8.5 scenarios for 2041-2060 and 2061-2080.

Plant uses	2041-2060	2061-2080
Condiment species (n=4)	South of MG and ES, central region of RJ, east of SP, and	South of MG and ES, east of SP, and most areas of RJ, PR, SC and RS

	most areas of PR, SC and RS	
Fibrous species (n=5)	South of SP, south and east of PR, and most areas of SC and RS	South of ES and RJ, east and central region of SP, and most areas of PR, SC and RS
Food species (n=15)	North of MG, east of Mato Grosso (MT), east of SP, south of PR, and most areas of SC and RS for	Metropolitan region of Salvador, central and western region of BA, southern MT and GO, central and northern region of MG, central region of ES and RJ, east of SP, and most areas of PR, SC and RS
Medicinal (n=32)	Central and east region of Bahia (BA), east of SP, most areas of PR, SC and RS	East and central region of BA, north of MT, south of MG, central region of ES and RJ, east of SP, and most areas of PR, SC and RS
Ornamental (n=19)	South of MG, ES and RJ, east of SP, most areas of PR, SC and RS	Central region of MG, east of SP, and most areas of RJ, ES, PR, SC and RS
Timber (n=20)	South of Tocantins (TO), central and north of Goiás (GO), north of MG, south of ES, central and east of SP, most areas of PR, SC and RS	South of TO, central region of GO, north and central region of MG, south of ES, northeast of SP, and most areas of PR, SC, and RS

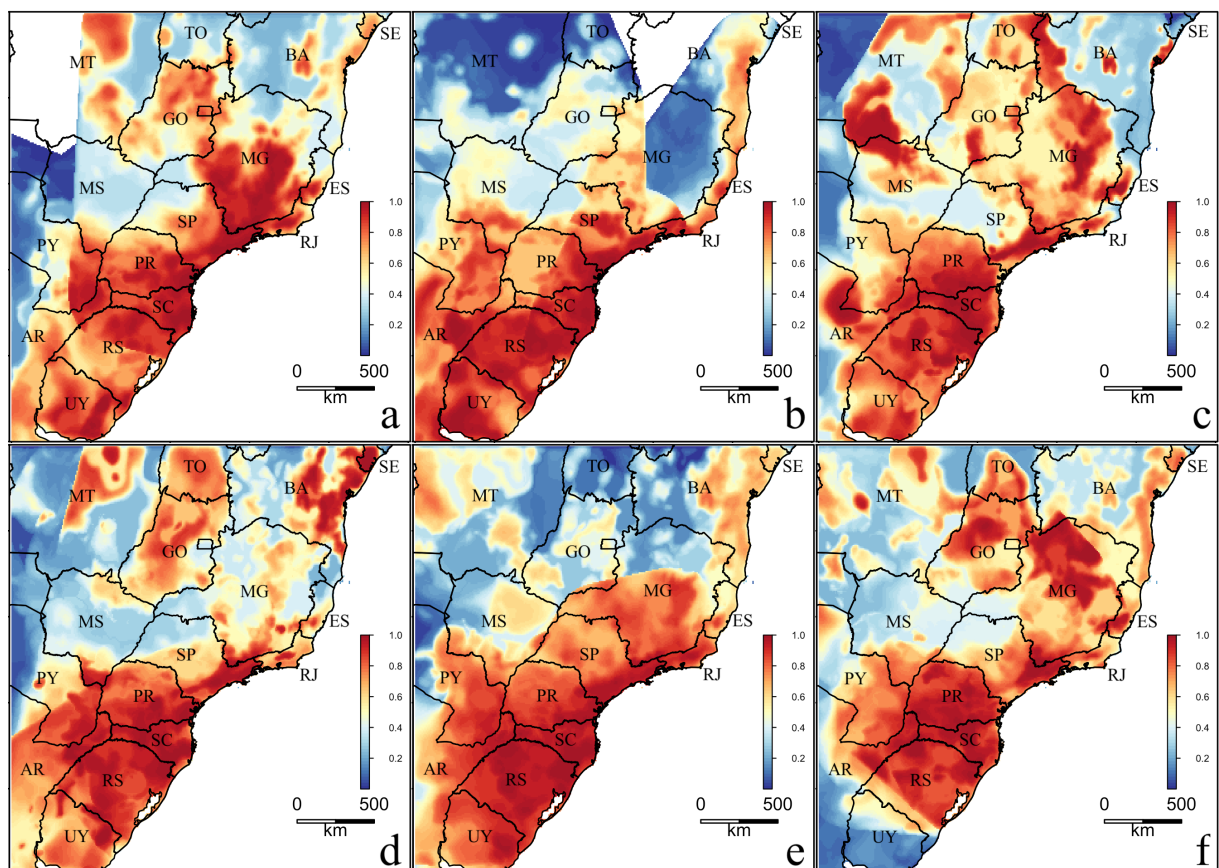


Figure 5. Areas of high conservation value for potential native agroforestry plant species according different uses under the SSP5-8.5 scenario for 2061-2080. **a)** Condiment

(n=4) **b) Fibrous** (n=5) **c) Food** (n=15) **d) Medicinal** (n=32) **e) Ornamental** (n=19) and **f) Timber** (n=20). Priorities are ranked from highest (red) to lowest (blue). The abrupt shifts across some areas are due to different study areas for each species.

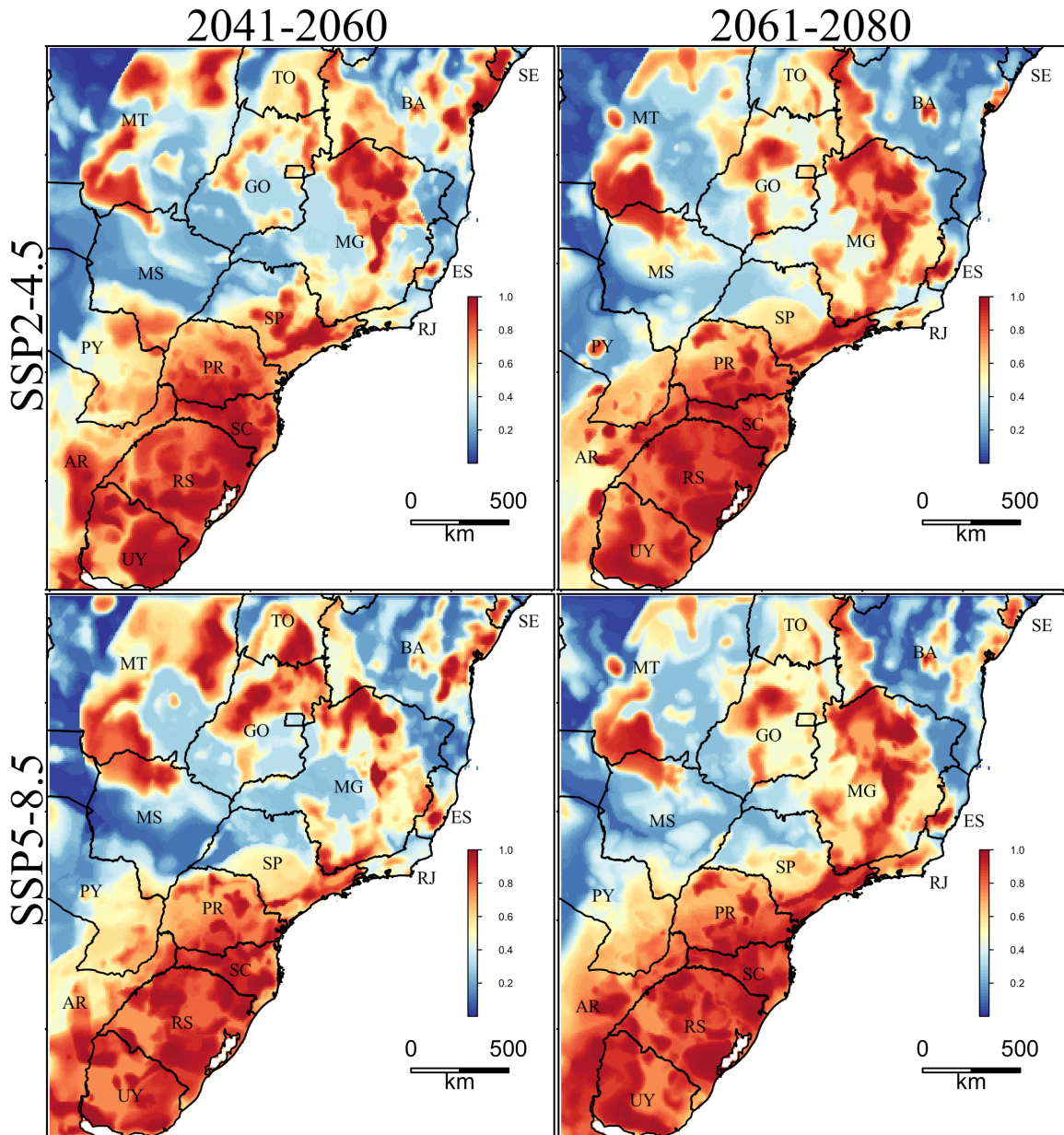


Figure 6. Areas of high conservation value for 95 potential native agroforestry plant species under different climate change scenarios and years. Priorities are ranked from highest (red) to lowest (blue).

Discussion

Traditional agroforestry systems practiced for millennia have regained attention in the context of climate change adaptation (Gomes et al., 2020; Reppin et al., 2020; Siminski, dos Santos, & Wendt, 2016). Besides promoting ecosystem integrity and income for local communities, these systems can contribute to the persistence of species over the time (Levis et al., 2017; Liu et al., 2018). Integrating multiple species allows farmers to make better use of the land, sell their products in different periods of the year, and include short-term income by using annual plants with short life-cycles (Brown, Miller, Ordonez, & Baylis, 2018; Isbell et al., 2017). Here, we identify several groups of species that can be combined in mixed cropping systems based on similar climatic niche requirements under current and future climatic conditions. Important economic species such as *A. angustifolia* (Zechini et al., 2018), *Acca sellowiana* (Donazzolo et al., 2020), *Euterpe edulis* (Favreto et al., 2010), *I. paraguariensis* (Siminski et al., 2016), and *M. scabrella* (da Silva, Machado, Galvão, & Filho, 2016) have already been traditionally combined with other agricultural crops in managed landscapes in southern Brazil. However, many others as *Solanum mauritianum*, *Monteverdia ilicifolia*, and *O. carnosum* remain neglected and underutilized.

Drastic changes in species distribution have been detected over recent years due to climate change (Castro et al., 2020; Gomes et al., 2019; Lazo-Cancino et al., 2020; Wilson, Walters, Mayle, Lingner, & Vibrans, 2019). However, not many studies on species spatial association impacts have gained notoriety (Marchioro et al., 2020). Here, we show that climate change will either increase or decrease the spatial associations of native agroforestry species in the coming decades, which can directly affect people livelihood. It is well documented that climate change triggers discordant range shifts, phenological asynchronies and spatial mismatches among biotic interactions (Barreto, Graham, & Rangel, 2019; Marchioro et al., 2020), and as a consequence undermines ecosystem functioning as well as human welfare (Dakhil et al., 2019; Pecl et al., 2017). Understanding how climate change will impact these commonly-used species is essential to plan new species combinations by local communities, once the success of human societies rely on components of natural resources and their management systems (Liu et al., 2018; Pecl et al., 2017).

Multistrata agroforestry systems are characterized by the occupation of at least two or more strata of trees or shrubs (De Giusti et al., 2019; Sistla et al., 2016). Plant growth forms have widely different mechanical architectures and are critical to understand the processes of

succession (Rowe & Speck, 2005). Exploring species that occupy different forest strata for these systems requires careful planning, mainly because of the effect of each species on the performance and productivity others (Gomes et al., 2020). Our findings display multispecies combinations belonging to different plant growth forms, for instance trees (*B. forficata*), shrubs (*B. dracunculifolia*), vines (*P. venusta*) and herbs (*A. satureioides*), allowing to design species combinations that occupy all forest strata. When the species and their respective strata are correctly combined, the use of the land, resources, and labor become more efficient, thus promoting earlier returns and diversification of farm yields (Souza et al., 2010; Waldron et al., 2017; Wilson & Lovell, 2016). Although local climate is the most significant factor when selecting plant species for agroecosystems, other ecological characteristics such as successional groups and habitats need to be considered (Liu et al., 2018; Schoeneberger, Bentrup, & Patel-Weynand, 2017).

Identifying spatial gradient of species' vulnerability under human-driven climate change is a key step to achieve successful adaptation of natural systems (Krechemer & Marchioro, 2020; Ribeiro, Sales, & Loyola, 2018; Watson, Iwamura, & Butt, 2013). We identified several areas of high conservation value for different groups of useful species (condiment, fibrous, food, medicinal, ornamental and timber), considering different climate change scenarios (Figure 6). Brazil has great potential to increase areas under agroforestry, and consequently strengthen ecosystem service provision (Schuler et al., 2022). Agroforestry practices cover merely 5% of the Brazilian territory, and it is unknown whether they strictly follow agroecological principles (Schuler et al., 2022). The establishment of agroforestry to maintain and restore legally protected areas is endorsed by changes in environmental legislation (BRASIL, 2012; Martins et al., 2019). Further, they have been highly recommended for restoration through the Brazilian National Plan for the Recovery of Native Vegetation (Ministry of Environment, 2017). Finally, neglected ornamental species such as the orchids *Gomesa flexuosa* and *E. fulgens* can easily be grown in urban parks, home garden, or even apartments. Thus, identifying climatically stable areas for species use is essential to achieve sustainability, especially in contexts where biodiversity conservation is overlooked by decision makers (Levis et al., 2020; Myers, Mittermeier, Mittermeier, Fonseca, & Kent, 2000).

Our findings provide a framework for a conservation strategy through sustainable use in new agroforestry systems in different suitable areas. Policymakers, conservation organizations, and donors can use the provided information here to promote different

interventions and avoiding future biodiversity losses, since some species can be conserved even in (peri)urban areas.

Online supplementary information for “Planning conservation for potential native agroforestry plant species under climate change in Brazil”

Tables S1-S9 are available on GitHub repository <https://github.com/vplima/SI.git>

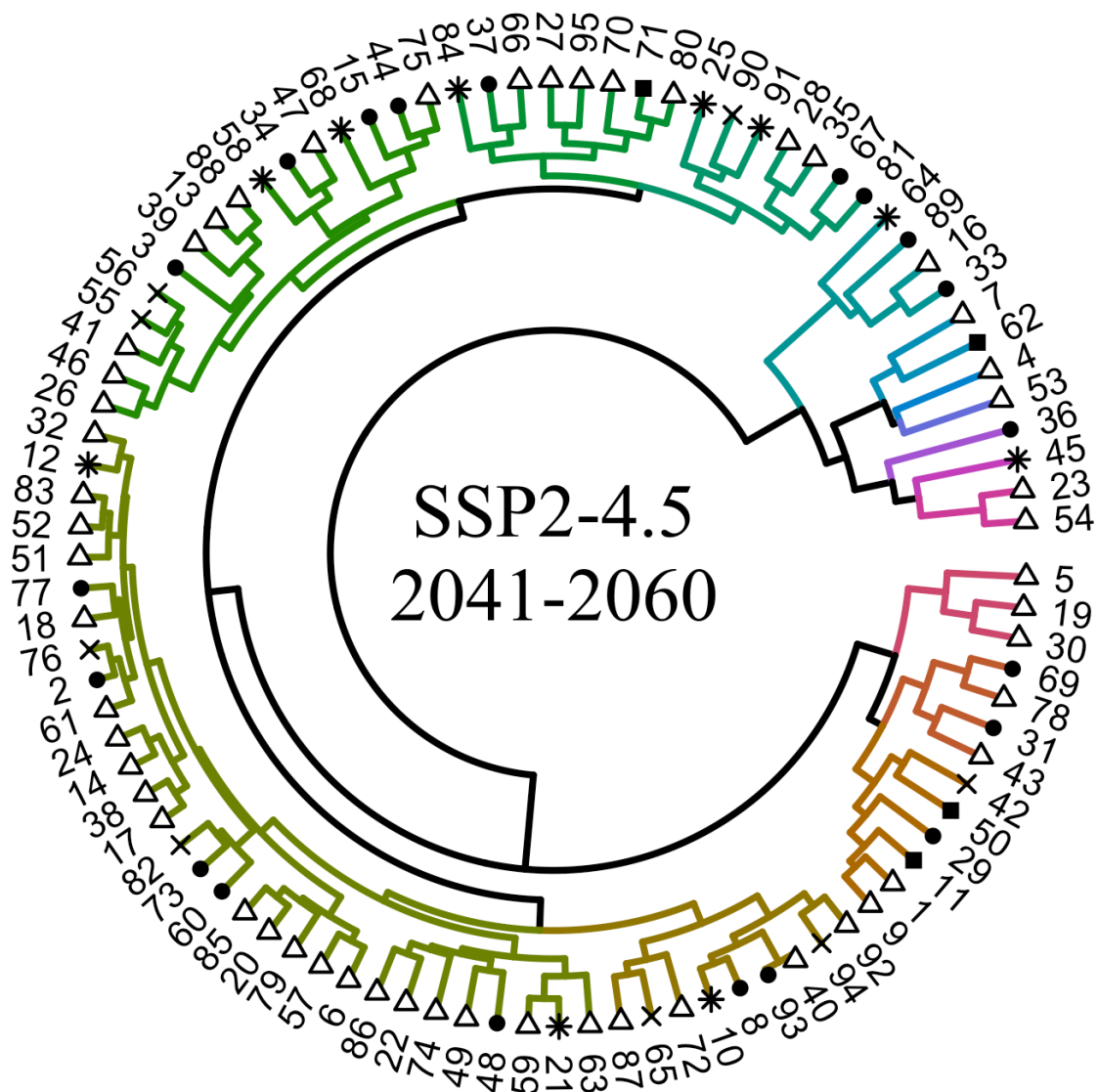


Figure S1. Hierarchical clustering dendrograms showing multiple groups of species for mixed cropping systems obtained by overlapping ENM predictions (Spearman's ρ for overlap) from 95 native Brazilian agroforestry plant species under the SSP2-4.5 scenario for 2041-

2060. Plant life form is represented by different symbols, trees (Δ), herbs (\bullet), vines (\oplus), shrubs ($*$) and subshrubs (\blacksquare). List of species for numerical codes are in Table S8.

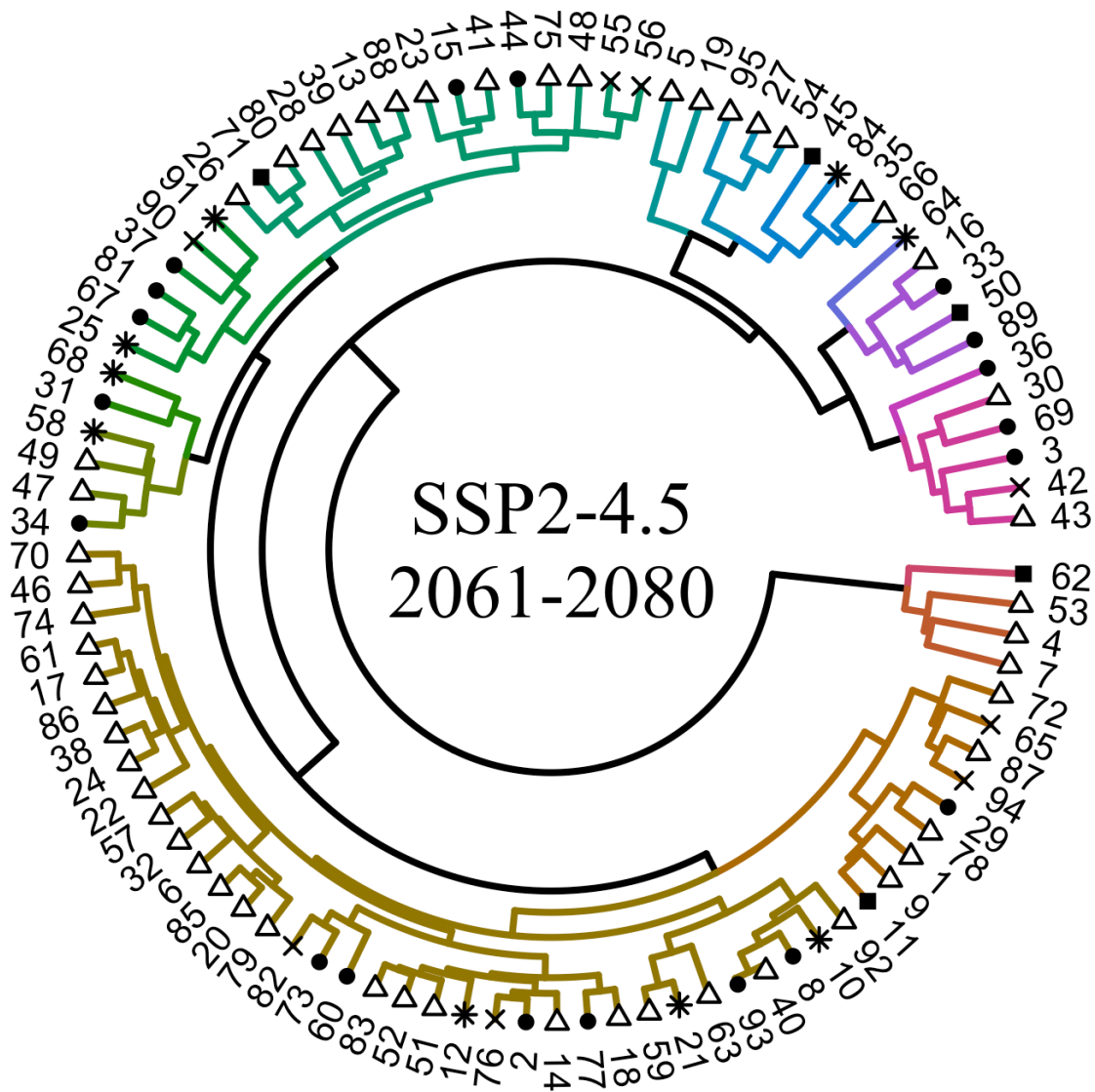


Figure S2. Hierarchical clustering dendrograms showing multiple groups of species for mixed cropping systems obtained by overlapping ENM predictions (Spearman's ρ for overlap) from 95 native Brazilian agroforestry plant species under the SSP2-4.5 scenario for 2061-2080. Plant life form is represented by different symbols, trees (Δ), herbs (\bullet), vines (\oplus), shrubs ($*$) and subshrubs (\blacksquare). List of species for numerical codes are in Table S8.

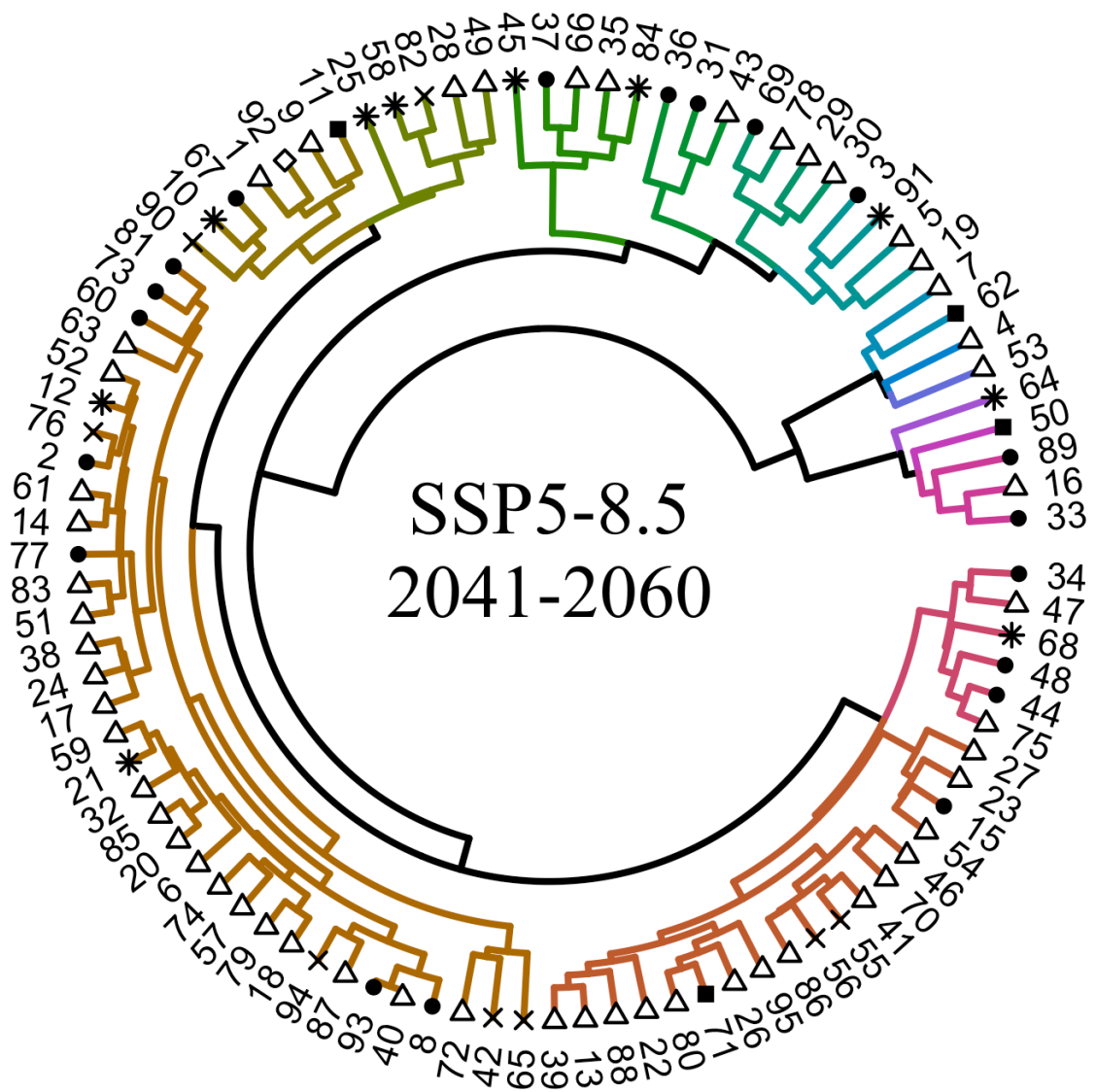


Figure S3. Hierarchical clustering dendrograms showing multiple groups of species for mixed cropping systems obtained by overlapping ENM predictions (Spearman's ρ for overlap) from 95 native Brazilian agroforestry plant species under the SSP5-8.5 scenario for 2041-2060. Plant life form is represented by different symbols, trees (Δ), herbs (\bullet), vines ($+$), shrubs ($*$) and subshrubs (\blacksquare). List of species for numerical codes are in Table S8.

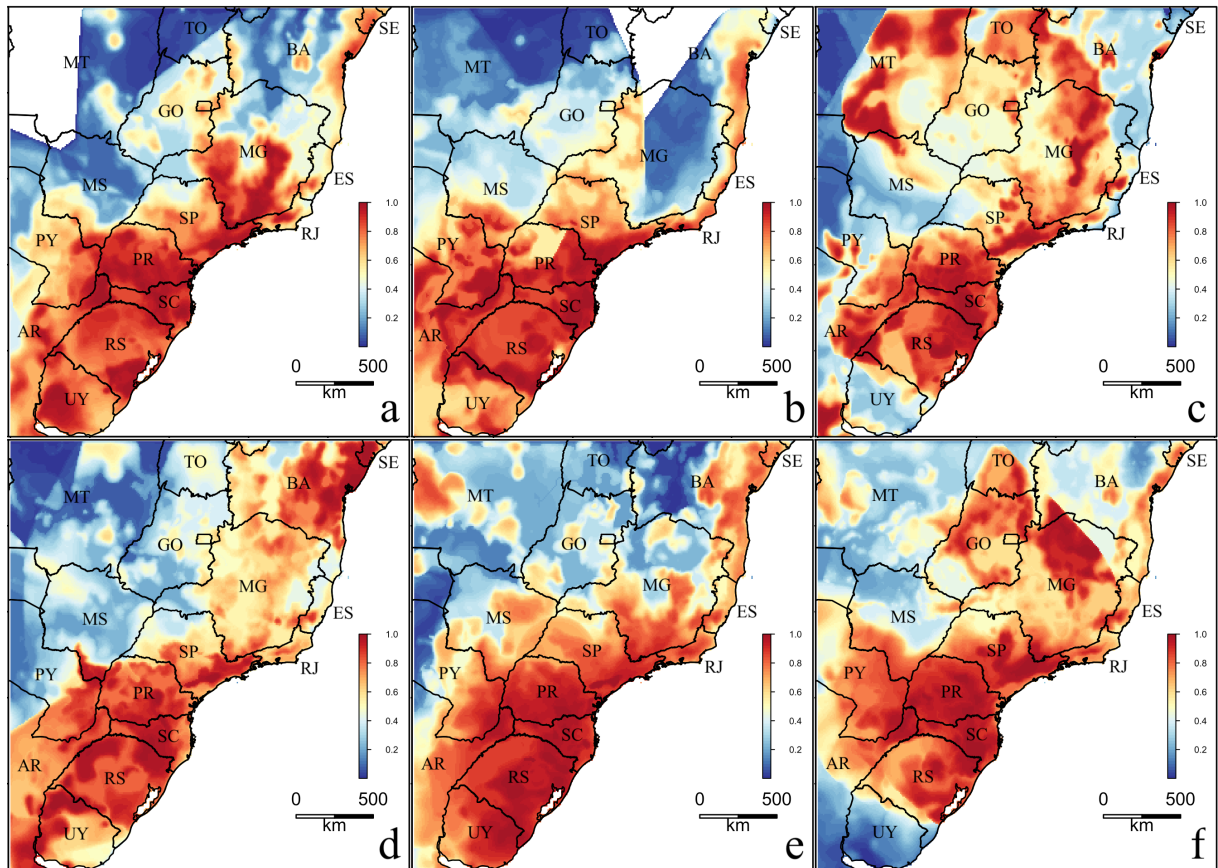


Figure S4. Areas of high conservation value for potential native agroforestry plant species according different uses under the SSP2-4.5 scenario for 2041-2060. **a)** Condiment (n=4) **b)** Fibrous (n=5) **c)** Food (n=15) **d)** Medicinal (n=32) **e)** Ornamental (n=19) and **f)** Timber (n=20). Priorities are ranked from highest (red) to lowest (blue). The abrupt shifts across some areas are due to different study areas for each species.

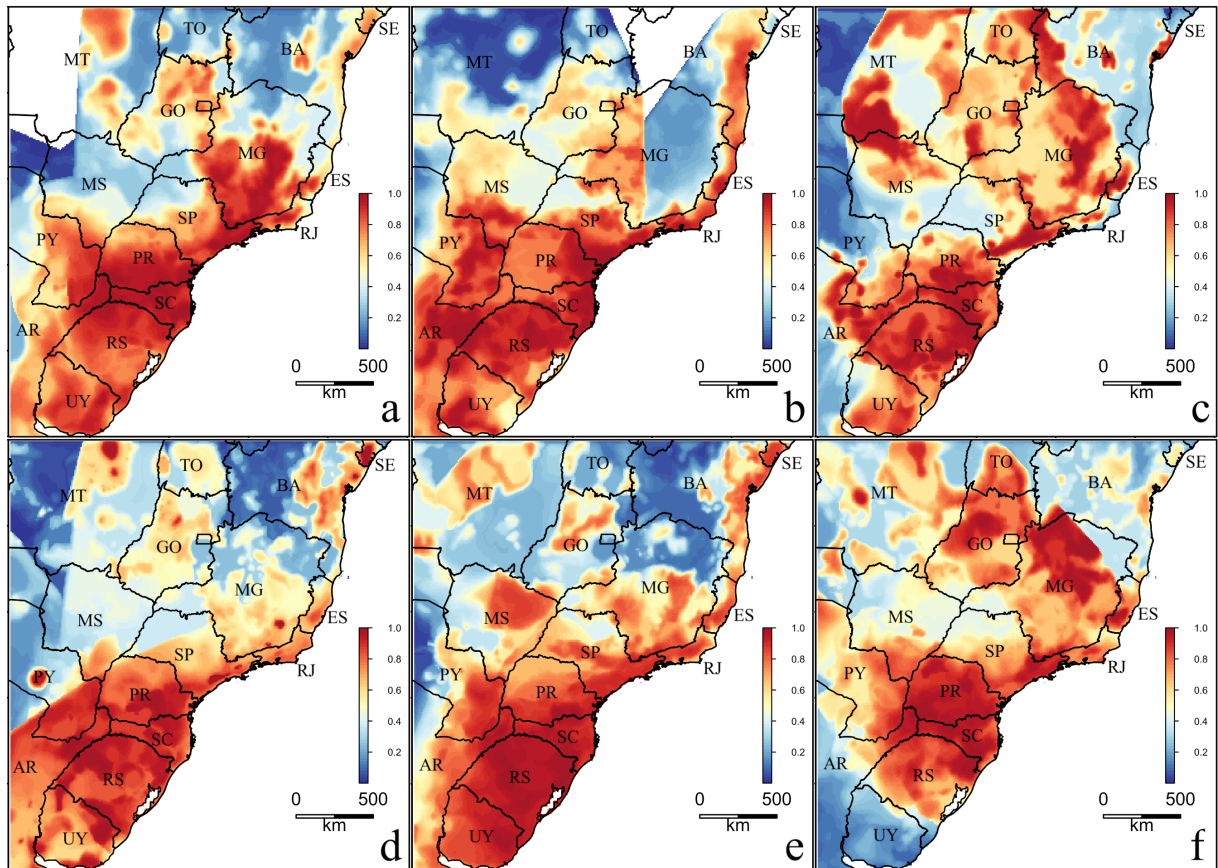


Figure S5. Areas of high conservation value for potential native agroforestry plant species according different uses under the SSP2-4.5 scenario for 2061-2080. **a)** Condiment (n=4) **b)** Fibrous (n=5) **c)** Food (n=15) **d)** Medicinal (n=32) **e)** Ornamental (n=19) and **f)** Timber (n=20). Priorities are ranked from highest (red) to lowest (blue). The abrupt shifts across some areas are due to different study areas for each species.

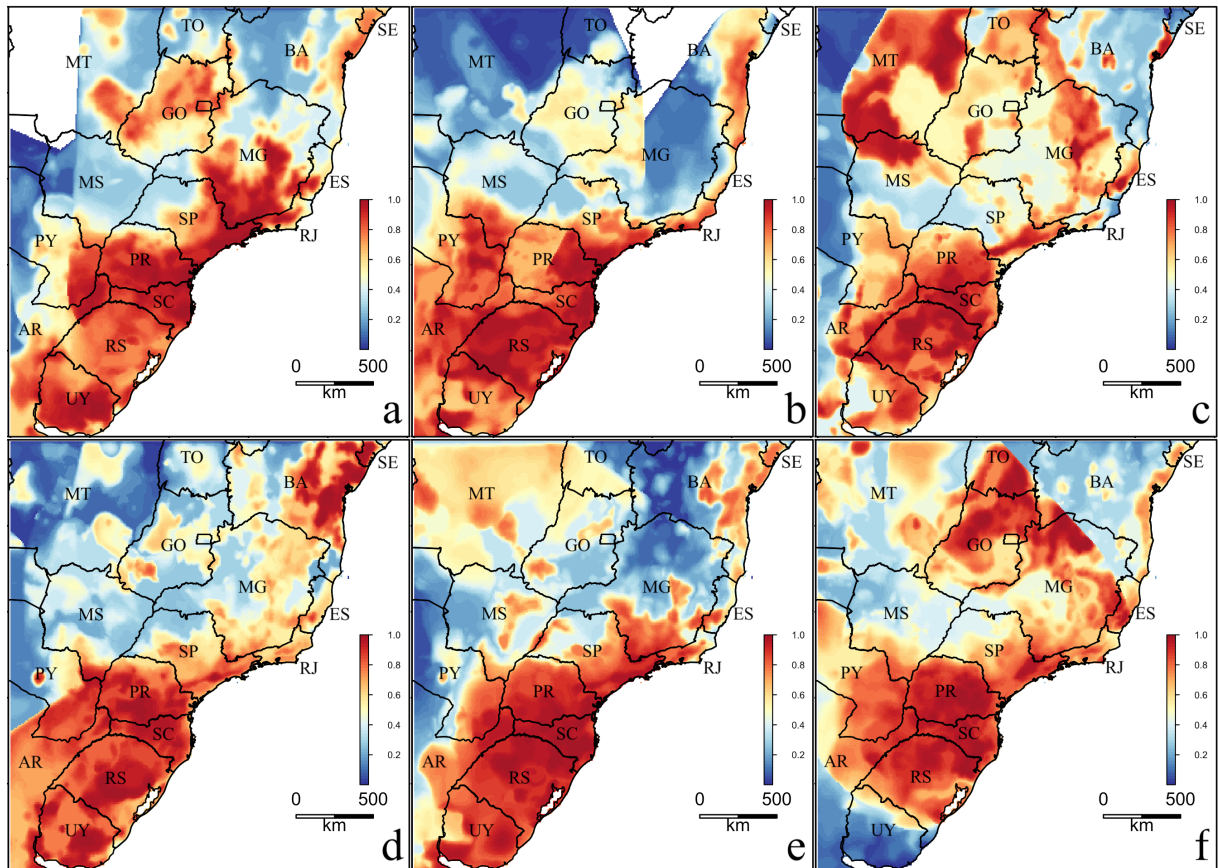


Figure S6. Areas of high conservation value for potential native agroforestry plant species according different uses under the SSP5-8.5 scenario for 2041-2060. **a)** Condiment (n=4) **b)** Fibrous (n=5) **c)** Food (n=15) **d)** Medicinal (n=32) **e)** Ornamental (n=19) and **f)** Timber (n=20). Priorities are ranked from highest (red) to lowest (blue). The abrupt shifts across some areas are due to different study areas for each species.

Chapter 5

Conclusions and perspectives



Acca sellowiana in São Joaquim, Santa Catarina, Brazil by Anyela Mayerly Rojas Molina

Here I found that *P. edulis* may currently grow and reproduce in the southern, southeastern and northeastern regions of Brazil specially within the Brazilian Atlantic Rainforest. However, projected future models predict a significant reduction (36-46%) in the environmental suitability across all scenarios evaluated. Additionally, *P. edulis* ranges are not adequately safeguarded by Brazilian protected areas, and the centroid analysis indicated that these changes in distribution occur in a southward direction.

Furthermore, quantifying potential changes in species' bioclimatic area of habitat (BAH) of 135 native potential agroforestry species prioritized by the Brazilian Ministry of the Environment initiative – Plants for the Future (Southern Region), I noticed that future climate is predicted to trigger a mean decline in BAH between 38.5-56.3% under the non-dispersal scenario and between 22.3-41.9% under the full dispersal scenario. In addition, I found that only 4.3% of the studied species could be threatened under the IUCN Red List criteria B1 and B2. However, when considering the predicted quantitative habitat loss due to climate change (A3c criterion) the percentages increased between 68.8-84.4% under the non-dispersal scenario and between 40.7-64.4% under the full dispersal scenario.

Employing niche similarity metrics and macro-ecological analyses, I identified multiple groups of species with high climatic similarity that can be combined well in mixed cropping systems under current and future climatic conditions. Also, I observed that climate change is predicted to modify the spatial association of these groups under different future climate scenarios, causing a mean negative change in climatic similarity between 9.5–13.7% under the SSP2-4.5 scenario and between 9.5–10.5% under the SSP5-8.5 scenario for 2041–2060 and 2061–2080, respectively. Finally, I showed that areas of high conservation value for conservation under current and future climate conditions varied among all potential native agroforestry plant species groups in Brazil.

These findings provide a framework for a conservation strategy through sustainable use. In such a context, I highly recommend a series of actions to ameliorate the impacts of climate change on the studied species in Brazil. First of all, the promotion of these species in agroecosystems, landscaping and homegardens since these actions are promising alternatives to increase their population. Although climate change is expected to be the main threat of the 21st century, plant populations have dynamic characteristics and, in this sense, different populations may respond differently to environmental changes over time. In this way, a focus on measuring, monitoring and increasing plant populations may favor their dynamics,

allowing them to withstand new climate scenarios predicted in the not too distant future.

A second action to ameliorate the impacts of climate change is the identification of matrices, production and distribution of seedlings, as well as the dissemination of their multiple uses. Climate change can harm reproductive development and consequently increase mortality rates in the coming decades, in this context, the identification of germplasm with high genetic diversity obtained from different vegetation zones and bioclimatic domains is essential when discussing changes in climate, as it allows the adaptation of ecological systems. Despite discussions about conservation strategies that occur primarily in the academic environment, the dissemination of this information in a broader way, particularly in local communities, is quite unusual. Unless information about the multiple uses of these natural populations studied here is disseminated, practical goals to avoid population declines as well as extinction rates will not be achieved. Thus, communication with farmers, indigenous peoples, decision makers and owners are crucial for these species not to be overlooked. It should be noted that conservation strategies through sustainable use are context-specific, thus requiring specific information about a given local community.

The adoption of public policies involving farmers and local communities is another pivotal action, since practices and management systems implemented by them have proven to maintain landscapes with productive forest fragments, and thereby favors species and forest conservation. Studies already carried out with some of the species studied here, such as yerba mate (*Ilex paraguariensis*), Paraná pine (*Araucaria. Angustifolia*) and Caraguatá (*Bromelia antiacantha*), clearly demonstrate that several communities that live within the Atlantic Forest are capable of favoring the conservation of natural systems. Historically Brazilian public universities and Brazilian environmental policy have distanced themselves from each other, however, there is an urgent need for a dialogue between the two. Although these groups often think in a similar way, a starting point is needed, because unless both are able to discuss measures to protect the ecosystem services and, consequently, the human well-being, it will not be possible to achieve sustainable targets in terms of species and forest conservation.

The incorporation of climate change impact assessments into conservation programs is another urgent and necessary action to achieve conservation goals. Current conservation programs only take into account current threats; however, we cannot neglect climate change, which is predicted to be the greatest threat to biological systems. Climate models help us to understand how and in which areas these changes will occur, thus allowing strategies to be

developed more specifically. Although the monitoring of present threats helps in the present decision making, knowing the future threats allows a total understanding of the system as a whole. Ecological Niche Modeling can be used to identify climatically stable areas over the time, which should be prioritized in municipal, state and national conservation programs. Furthermore, this tool can assist in the creation of protected areas, as it is able to identify areas of high conservation and use value, as I identified in chapter 4 of this thesis.

Another action is the development of scientific research towards conservation status assessments, using other major drivers of biodiversity loss, and biotechnological applications to select promising genotypes for a changing global climate. As evidenced in this thesis, 96% of all these common species that are distributed in the Atlantic Forest and Pampa have never been evaluated by the IUCN, which demonstrates a great concern. Assessing the conservation status of species is just the beginning when it comes to conservation. As we do not have accurate and scientific information about the species, the chances of these species being targeted by conservation policies become scarce. Here, I assessed species conservation status focusing on climate change. However, other threats such as habitat destruction, introduction of invasive species, over-exploitation of resources, pollution, among others are equally important to get an overview of the degrees of threat and the potential risk of loss. In addition to species status assessments, the selection of genotypes capable of withstanding the new climatic conditions as well as other environmental changes in the 21st century is extremely important to support conservation programs, since some of these species have already demonstrated high genetic diversity. Besides, research towards participatory genetic improvement should be considered, since this is a component that reflects the rescue, evaluation and characterization of plant genetic resources.

Further, I highly recommend the establishment and expansion of agroforestry systems in different suitable areas based on the combination of selected species and climatic conditions. Brazil has great potential for the expansion of biodiverse agroforestry systems, and consequently nature's contribution to people. However, for this approach to be effectively efficient, the results of the thesis regarding the combination of groups of species with greater climatic affinities under different climatic scenarios should be applied. In chapter 4, I indicate the species with the greatest affinities as well as the Brazilian regions for the implementation of these productive systems that favor conservation, especially in the tropics, and improve the livelihoods of local communities. This thesis advances scientific knowledge by providing information on the impact of global climate change on the distribution of species commonly

used by local communities from the context of the southern region of Brazil, and by structuring a framework for the proper use of these species in climatically stable areas. Therefore, although the Anthropocene has been characterized by remarkable declines in global biodiversity, policymakers, conservation organizations, and farmers should act in such a manner to avoid future losses, using the information provided in this thesis to promote different interventions once these particular species can potentially be conserved even in urban and peri-urban areas.

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