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Climate change and biodiversity in Brazil: What we know, what we don’t, and Paris Agreement’s risk reduction potential

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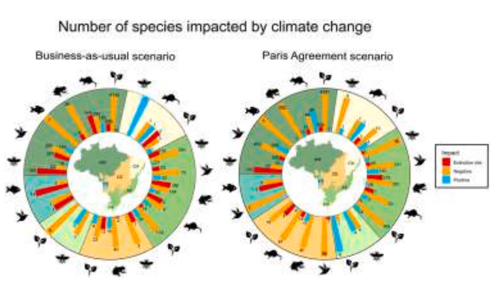
HIGHLIGHTS

- We synthesize knowledge on the impacts of climate change on Brazil’s biodiversity.
- The greatest predicted impact is in the Pantanal, and the lowest in the Pampa.
- There are still large knowledge gaps due to spatial and taxonomic biases in studies.
- Paris Agreement could reduce impacts by 21% and cut extinction risk by half.

GRAPHICAL ABSTRACT



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ABSTRACT

Over recent decades, Brazil has amassed a wealth of knowledge regarding the potential effects of climate change on its biodiversity. Studies have predicted mostly negative impacts and some positive ones, and it is time to synthesize this information. We did a systematic review of the literature and quantitative analysis, gathering 20,582 risk projections from 131 papers. We then estimated the effect size of the projected risks. We found that climate change impacts on biodiversity vary spatially. The Pantanal wetlands are predicted to experience the most significant negative impacts, followed by the Amazon and the Atlantic Forest, while the Pampa grasslands are expected to see lower impacts. Our analysis also reveals biases and knowledge gaps. For example, the shortage of studies on marine environments precluded their inclusion in the analysis, and there was a strong bias towards the Amazon and the Atlantic Forest, with a shortage of studies on the Pantanal and the Pampa. Moreover, there was a taxonomic bias towards plants and terrestrial vertebrates, which comprised >90% of the data. Finally, while adherence to the Paris Agreement is unlikely to eliminate climate change impacts on biodiversity, our analysis predicts that it could reduce these impacts by 20% and halve the number of species at risk of extinction from climate change in Brazil.

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Introduction

Climate change is a major threat to biodiversity, with impacts already being observed and even greater projected for the future (IPCC, 2021). The average global temperature has risen by 1.09 °C since the end of the 19th century, with unprecedented speed (IPCC, 2021). Temperature increases, changes in precipitation patterns, and increased frequency of extreme events can majorly impact ecosystems and biodiversity, as the climate is an important determinant of macroecological patterns of species distribution (Pearson and Dawnson, 2003). The Paris Agreement, signed in 2015 in the context of the United Nations Framework Convention, was an important reference for climate mitigation by setting international targets to limit the increase in global average temperature to well below 2 °C (UNFCCC, 2015).

Brazil is considered a megadiverse country, including biodiversity hotspots such as the Atlantic Forest and Cerrado (Myers et al., 2000), and some of the Global-200 ecoregions such as the Southwestern Amazonian and Rio Negro-Juruá Moist Forests and Pantanal Flooded Savannas (Olson and Dinerstein, 2002). Its impressive biodiversity makes Brazil an important target for conservation in the face of climate change. Increases in mean temperature are predicted country-wide, with more severe increases in the central and northern portions (Gutiérrez et al., 2021), especially in the Pantanal wetlands and the Amazon, the latter also with a great reduction in total precipitation (PBMC, 2013; Gutiérrez et al., 2021). Such rainfall reduction acts in synergy with deforestation, potentially leading to a worrisome savannization of the Amazon (PBMC, 2013; Castellanos et al., 2022). In the northeast portion of the country, climate change is already causing a decrease in rainfall in the Caatinga dry forests, which is expected to intensify in the near future, aggravating the water deficit in the region (PBMC, 2013; Gutiérrez et al., 2021; Castellanos et al., 2022). In addition to increases in temperature and reduction in rainfall in the northern part of the country, increases in the frequency and intensity of extreme rainfall events are forecasted across the country, especially towards the south within the Atlantic Forest and the Pampa grasslands (PBMC, 2013; Castellanos et al., 2022), together with an increase in fire-prone conditions in the Amazon, Caatinga and the Cerrado (Arias et al., 2021; Viegas et al., 2022). All these alterations intensify in the most severe climate change scenarios (known as 'business as usual'), pointing to the urgency of climate mitigation and adaptation measures.

Until the early 2000s, there were very few studies on the likely impacts of climate change on Brazilian biodiversity (Vale et al., 2009). However, this literature has grown in the last decades, placing the Atlantic Forest as one of the best-studied biodiversity hotspots in the world on this topic (Manes et al., 2021; Manes and Vale, 2022). Some studies have identified severe negative impacts from climate change, such as a 37% reduction in tree richness in the Amazon (Gomes et al., 2019), while others have predicted possible benefits, such as a threefold increase in primate species' ranges, also in the Amazon (Sales et al., 2020). It is time, therefore, for a synthesis of the knowledge produced on the likely impacts of climate change on Brazilian biodiversity, to derive general trends.

Here, we developed the first and most comprehensive systematic review of the predicted future impact of climate change on Brazilian biodiversity using a quantitative approach. We used Brazil as our case study due to the large number of studies on future climate change impacts on biodiversity, its great environmental heterogeneity, and its vast biodiversity. We obtained 20,177 risk projections for biodiversity, identifying biases and knowledge gaps, and quantifying predicted impacts under business-as-usual and Paris Agreement scenarios.

Methods

Study area

Brazil has six major phytogeographic domains, called "biomes" hereafter for conciseness: the Amazon and the Atlantic Forest rainforests, the Caatinga dry forest, the Cerrado savannas, the Pampa grasslands, and the Pantanal wetlands. The Atlantic Forest and the Cerrado are both considered biodiversity hotspots (Myers et al., 2000). Climatic projections for the end of the century indicate a significant increase in temperature in all Brazilian biomes, with the greatest increases in the Amazon, Pantanal, and Cerrado. Furthermore, changes in precipitation patterns are also predicted in all biomes, with strong reductions in the Amazon, Pantanal, Caatinga, Cerrado, and northern Atlantic Forest, and increases only for the southern region of the Atlantic Forest and Pampa (Souza et al., 2014).

Literature search

We searched for scientific papers on the impacts of climate change on Brazilian biodiversity using the *Web of Science*, *Scopus,* and *Scielo* databases, plus the journal *Perspectives in Ecology and Conservation*, known as a reference journal for Brazilian biodiversity conservation. We used the following keywords, both in English and in Portuguese: ("Amazon*" or "Atlantic Forest*" or "Atlantic Rainforest*" or "Mata Atlântica" or "Brazilian savanna*" or "Cerrado" or "Pantanal" or "Caatinga" or "Brazilian dry forest*" or "Pampa" or "Brazilian grassland*" or "Brazil" or "Brasil" or "Brazilian" or "Brasileir*" or "Southwest Atlantic" or "Brazilian Coast*") and ("biodiversity" or "Biodiversidade") and ("climate change" or "Global warming" or "Mudanças climáticas"). The search was conducted on June 28, 2022, targeting the title, abstract, and keywords. We used the same search string across all databases, except PECON, to ensure consistency and comprehensiveness. Our search retrieved 2,879 unique papers. After excluding papers that: (i) did not predict climate change impact for Brazil; (ii) did not have a prediction of the future impact of climate change on biodiversity; (iii) did not specify the climate change scenario used in the predictions; (iv) based their analysis on current years with a date before 1970 (as the disparity to recent years could bias the analysis), (v) did not provide numerical values regarding the projections made for the future (e.g., species' distribution area in the present and the future or percentage difference), and (vi) did not use spatial analysis to derive estimates, including both species distribution models (aka ecological niche models) or spatial analysis investigating emergence or disappearance of climatic conditions needed for the species, there were 131 papers left. Table S1 presents excluded articles and reasons for exclusion. Our search followed the PRISMA 2020 statement (Page et al., 2021).

From each paper, we extracted the projected climate change impacts on each species, habitat, or community for the future. Impacts were calculated as effect sizes: the percentage difference between present and future estimates for biodiversity. Negative effect sizes represent negative climate change impacts on biodiversity, such as a decrease in species range or richness, whereas positive effect sizes represent increases in those estimates. We refer to these values, which represent the difference between present and future biodiversity parameters, as 'risk projections'. We calculated these values for each species, but for papers that did not report the values individually, we used an average value for all of them.

Because impacts are projected for different years (e.g., for 2050 or 2070), we calculated an effect size rate value by dividing the effect size by the number of years into the future (Manes et al., 2021). The effect size rate represents the annual increment of the impact during the timespan. Although the increase in the actual impact is not constant over time, this method is useful as it reduces the bias associated with the projected future year, as the impact tends to magnify with increasing projection horizons. The present year used in the article was typically 1975 or 1985, defined based on the climatic data used (e.g., WorldClim or CHELSA). We excluded articles that used earlier baselines to avoid biases because the impact (effect size) was divided by the number of years into the future (effect size rate).

We ran an outlier analysis using the GraphPad Prism software

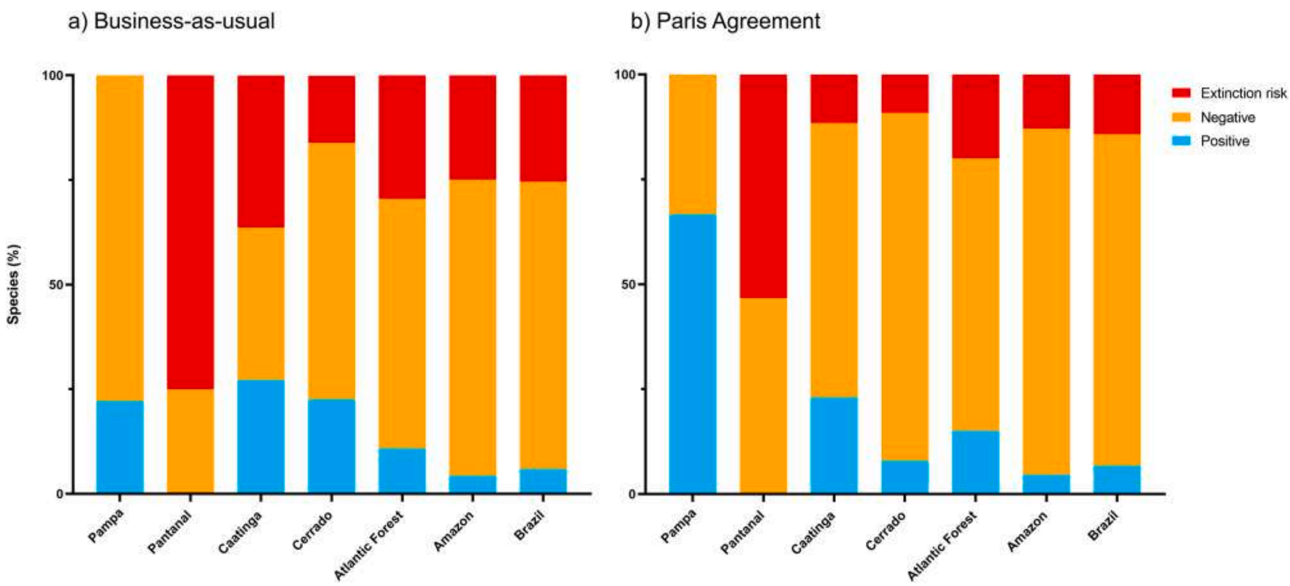

Fig. 1. Percentage of risk projections of species at extinction risk, positively and negatively impacted in the future projections. We evaluated 7,650 species in the BAU scenario and 7,515 in the Paris Agreement scenario, but the total count is higher since a species can have different projections in different scenarios. The number of species at risk of extinction is higher in the BAU scenario.

version 8.0.1 (www.graphpad.com), using the ROUT method and removing only the definitive outliers (Q = 0.1%). A total of 889 outliers were removed, resulting in a final dataset of 20,582 risk projection measures for biodiversity.

All risk projections were classified according to: i) the Brazilian phytogeographic domain assessed (biome); ii) major taxonomic group studied (arthropods, birds, herpetofauna, mammals, plants, freshwater fishes); iii) whether the species was a Brazilian endemic or a non-endemic native (hereafter called "native"); iv) climate change scenario; and v) type of impact over biodiversity (spatial, diversity or habitat change). "Spatial changes" correspond to data derived from papers that conducted spatial analyses to project changes in species' distribution areas or habitat suitability under future climate change conditions. As for "diversity change", we encompassed papers that examined shifts in richness, functional diversity, or other diversity metrics within a community, such as phylogenetic diversity. Finally, "habitat change" refers to data derived from papers that employed spatial analyses to project changes associated with land-use change, such as changes in mean patch size, the proportion of habitat patches capable of sustaining populations, and alterations in vegetation at the landscape scale. Species-level data were unavailable in these last two categories, so community and habitat-level values were used.

We classified all risk projections into two scenarios: (i) the "Paris Agreement" scenario, for future projections with a temperature increase <2 °C, and (ii) the "Business-as-usual" (BAU) scenario, for projections with a temperature rise ≥2 °C. This classification was made using the scenario used in the study, the future year of the projections, and the specific climatic region of the study, following Manes et al. (2021). By using the predicted temperature increase for the specific region where the biome occurs, we minimized the bias of using global estimates. The warming level classification was made for the Special Report on Emissions Scenarios (SRES) projections (IPCC, 2007), for the Representative Concentration Pathway (RCP) scenarios (IPCC, 2013), and for the Shared Socioeconomic Pathway (SSP) scenarios (IPCC, 2021). To assess temperature rise in specific regions, we use data provided by IPCC reports and the IPCC WGI Interactive Atlas (Gutiérrez et al., 2021), using 1986–2005 as a baseline, as temperature rise data for the RCP and SRES scenarios were only available in that format (See Supplementary Tables S2–S4 for temperature values used). When it was impossible to determine a specific temperature increase value, the study was excluded from the analysis comparing different scenarios but was still used in other types of comparisons.

We also defined species at risk of extinction, following Manes et al. (2021) and Urban (2015), considering species with >80% distribution loss as at risk. Only spatial change data for species were used to estimate the proportion of species impacted positively (increase in distribution area), negatively (reduction in distribution area <80%), and at risk of extinction (loss >80%).

To test for statistical differences between the two future climate change scenarios (BAU and Paris Agreement), we built linear mixed models (LMMs) using the study identity (DOI) as a random factor and the climate scenarios as the explanatory variable. Additionally, we performed an ANOVA to evaluate the significance of the explanatory variable in the LMM. The use of the study's identity (DOI) as a random factor is important to reduce potential bias due to the data source, as a study may provide more than one line of data. All statistical analyses were conducted in the R environment (R Core Team, 2019) using the package *nlme*. We developed the graphs using GraphPad Prism software. All data presented in the graphs were extracted using the software Data Thief III version 1.7 (Tummers, 2006). Our complete dataset is presented in Table S5.

Results

Our review identified a strong bias in the distribution of information country-wide (Table S6; Fig S1). The Atlantic Forest was the most studied biome (39% of studies), followed by the Amazon (17%) and Cerrado (15%, Fig. S1). Although the Atlantic Forest has been the focus of most studies in Brazil, we compiled far more risk projections for the Amazon (77% of effect sizes, Table S6), mainly due to Gomes et al. (2019), who projected the impacts on 4,935 plants in multiple scenarios (Fig. S1). About 1% of the risk projections assessed species whose distribution is not limited to a single biome (hereafter 'widespread'). Only 0.5% of the risk projections were for the Caatinga, while the Pampa and Pantanal together also accounted for 0.5%, highlighting a knowledge gap. We identified substantial bias towards terrestrial species, with very little information for freshwater species (Fig. S1). Only five papers assessed impacts on coastal and marine biodiversity. These were removed because we considered this number too small to capture patterns in such a diverse environment. We also identified a clear bias

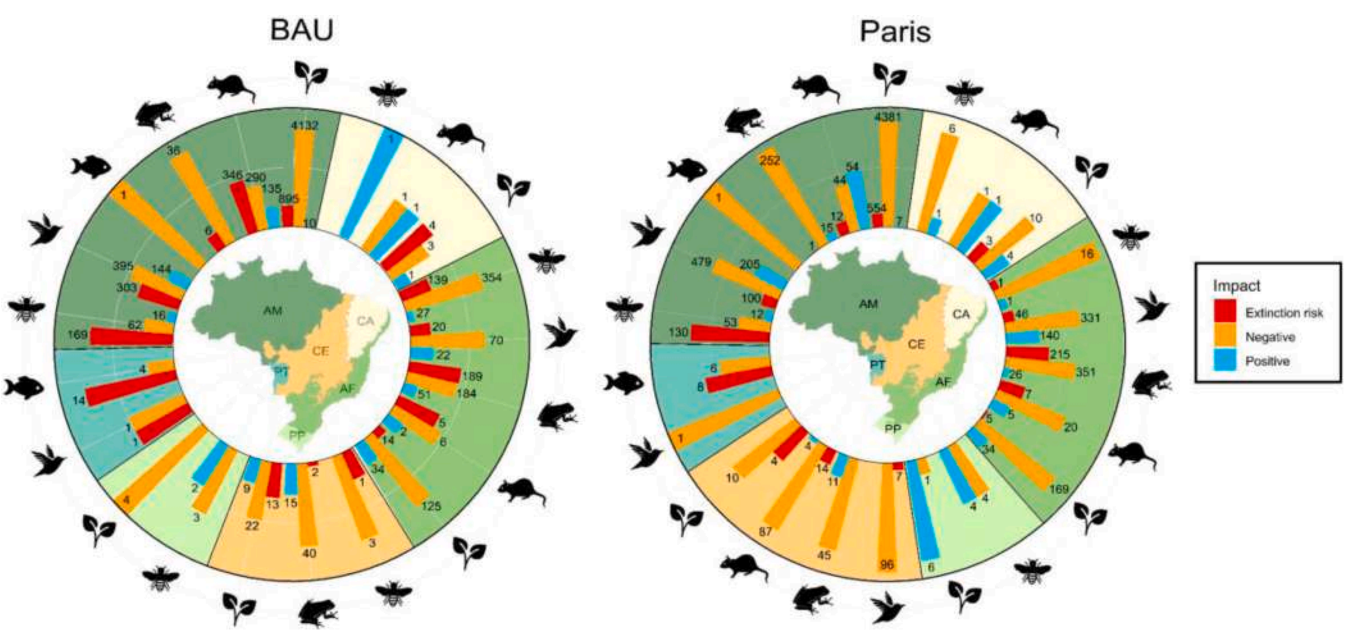

Fig. 2. Different impacts of climate change on Brazilian biomes and taxa. Predictions are shown for business-as-usual (BAU) and Paris Agreement (Paris) scenarios. The columns represent the percentage of risk projections that are positive, negative, or indicating a potential extinction risk for each taxon in each biome. The numbers indicate the number of species affected. The figures represent the different taxon analyzed e.g., arthropods, birds, fishes, herpetofauna, mammals, and plants. AM = Amazon, CE = Cerrado, CA = Caatinga, PT = Pantanal, AF = Atlantic Forest, PP = Pampa.

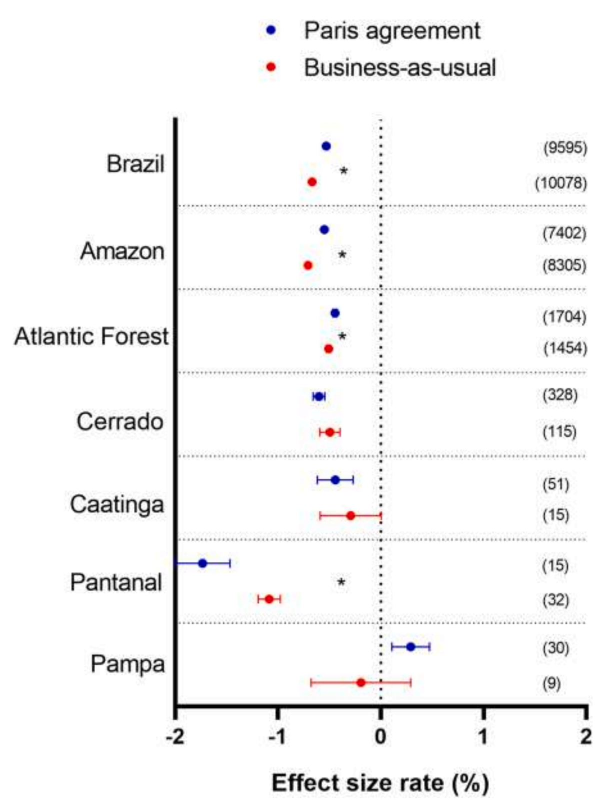

Fig. 3. Climate change impacts on biodiversity for Brazil and each biome (mean ± 95% CI) in two scenarios. Negative numbers represent a detrimental impact, and positive numbers represent a beneficial impact of climate on biodiversity. Numbers in parentheses show the count of risk projections used to calculate the mean.

towards plants and vertebrates (54% and 38% of data, respectively). Almost all of our dataset was classified as spatial change (99.5%), while diversity and habitat changes accounted for only 0.5%.

We classified the species with projected impacts as at risk of extinction, negatively impacted, or positively impacted. We evaluated 7,650 species for the BAU scenario and 7,515 for the Paris Agreement scenario. Although few species are expected to be positively impacted, most species are likely to experience negative impacts, with a considerable portion being at risk of extinction (Fig. 1; Table S6). Impacts varied according to taxon and biome, but there is a trend towards a greater number of negatively impacted species in the BAU scenario, with a much higher number of species predicted to be at risk of extinction than in the Paris Agreement scenario (from 14% to 25% in BAU; Figs. Fig. 11 and Fig. 22 , Table S7).

Overall, Brazilian biodiversity will likely be severely negatively impacted under the BAU scenario (−0.7%). However, the magnitude of these impacts is significantly reduced under the Paris Agreement scenario (−0.5%, $p < 0.0001$, $t = -6.10$) (Fig. 3, Table 1). The Paris Agreement will significantly reduce the magnitude of impacts from the BAU scenario for the Amazon (from −0.71% to −0.55%) ($p < 0.0001$, $t = 16.77$) and the Atlantic Forest (from −0.51% to −0.45%) ($p < 0.0001$, $t = 16.77$), the biomes with the most information available (Fig. 3, Table 1). For the other biomes, the very low number of projections precludes the identification of general trends. The projections suggest that the Pantanal will likely be the most negatively impacted biome under both the BAU scenario and Paris Agreement, albeit projections were almost exclusively for freshwater fishes (Fig. 3, Fig. S1). Similarly, the Paris Agreement did not significantly reduce impacts for Cerrado and Caatinga. Finally, the Pampa is the biome with the lowest projected impacts, which are even positive under the Paris Agreement, although not significantly so.

We also found a significant difference in the impacts on invasive, endemic, and native species in Brazil (Fig. S2). Invasive species are predicted to suffer much smaller negative impacts than native and endemic species ($p < 0.05$; Table 1).

Projections also varied across taxa, with fish and arthropods as the most negatively impacted even under Paris Agreement scenarios, although with limited data, reducing confidence in results (Fig. S2).

Table 1
Mean impact values for biomes and species type in the different scenarios. The 'Difference' column was calculated as the percentage value of the difference between the impact value in the Business-as-usual scenario and the Paris Agreement scenario. The results generated by the linear mixed models (LMM) and the marginal and conditional R^2 are also presented. We used these models to test differences in biodiversity impact under different climate change scenarios.

	Scenario	Mean effect size rate (%)	Difference (%)	Fixed effects coefficients	S.E	P	t	df	R^2 Marginal (R^2m)	R^2 Conditional (R^2c)
Biome										
Brazil	BAU	−0.67	−20.9	−0.8715	0.2891	0.0043	−3.01	44	0.25	0.68
	Paris Agreement	−0.53		−0.6343	0.1040	0	−6.10			
Amazon	BAU	−0.71	−22.5	−0.5872	0.0754	0	−7.79	15682	0.01	0.41
	Paris Agreement	−0.55		0.1160	0.0069	0	16.77			
Atlantic Forest	BAU	−0.51	−11.8	−0.4730	0.0465	0	−10.17	3107	0.01	0.39
	Paris Agreement	−0.45		0.1107	0.0242	0	4.57			
Cerrado	BAU	−0.49	22.4	−0.5596	0.1034	0	−5.41	426	0.00	0.35
	Paris Agreement	−0.6		0.0463	0.0663	0.4856	0.69			
Caatinga	BAU	−0.29	51.7	−0.3038	0.2079	0.1497	−1.46	55	0.00	0.42
	Paris Agreement	−0.44		0.0183	0.1630	0.9112	0.11			
Pantanal	BAU	−1.08	60.2	−0.8715	0.2891	0.0043	−3.01	44	0.25	0.68
	Paris Agreement	−1.73		−0.6343	0.1040	0	−6.10			
Pampa	BAU	−0.19	−252.6	−0.1601	0.2857	0.579	−0.56	33	0.00	0.64
	Paris Agreement	0.29		0.0182	0.1907	0.9246	0.09			
Species type										
Native species	BAU	−0.68	−22.1	−0.4941	0.0403	0	−12.25	17721	0.01	0.40
	Paris Agreement	−0.53		0.1132	0.0067	0	16.85			
Endemic Brazil	BAU	−0.66	−25.8	−0.5925	0.0692	0	−8.56	1707	0.00	0.46
	Paris Agreement	−0.49		0.1110	0.0244	0	4.54			
Invasive	BAU	−0.04	250.0	0.0033	0.1507	0.9825	0.02	117	0.00	0.75
	Paris Agreement	−0.14		0.0319	0.1269	0.8021	0.25			
Taxon										
Arthropoda	BAU	−0.82	17.1	−0.3755	0.0996	0.0002	−3.77	1405	0.00	0.43
	Paris Agreement	−0.96		−0.0700	0.0302	0.0207	−2.31			
Birds	BAU	−0.55	−36.4	−0.6146	0.0924	0	−6.65	4050	0.02	0.29
	Paris Agreement	−0.35		0.2251	0.0186	0	12.07			
Herpetofauna	BAU	−0.57	−10.5	−0.4917	0.0932	0	−5.27	1717	0.00	0.39
	Paris Agreement	−0.51		0.0635	0.0498	0.2025	1.27			
Mammals	BAU	−0.65	−33.8	−0.4797	0.0901	0	−5.32	1453	0.00	0.39
	Paris Agreement	−0.43		0.0506	0.0467	0.2783	1.08			
Plants	BAU	−0.68	−11.8	−0.4516	0.0500	0	−9.03	10856	0.01	0.49
	Paris Agreement	−0.6		0.0944	0.0065	0	14.56			
Fishes	BAU	−1.08	32.4	−0.6191	0.3022	0.0459	−2.04	49	0.18	0.75
	Paris Agreement	−1.43		−0.5636	0.0960	0	−5.87			
Impact type										
Spatial change	BAU	−0.67	−20.5	−0.5057649	0.03728229	0	−13.56	19495	0.01	0.43
	Paris Agreement	−0.53		0.1129336	0.00651237	0	17.34			
Diversity change	BAU	−0.36	−60.3	−0.3335123	0.0884946	0.0009	−3.76	26	0.04	0.46
	Paris Agreement	−0.14		0.1317367	0.09193372	0.1638	1.43			
Habitat change	BAU	−0.22	−6.6	−0.3389616	0.1297997	0.0148	−2.61	26	0.00	0.29
	Paris Agreement	−0.21		0.053563	0.1082224	0.6248	0.49			

Contrastingly, taxa with the most available data, plants and birds, show a strong and significant reduction in impact under the Paris Agreement scenario compared to BAU ($p < 0.0001$). For mammals and herpetofauna, a decrease in impact was also observed, but it was not statistically significant.

Discussion

Our analysis shows that commitment to the Paris Agreement is of utmost importance to reduce the negative impacts of climate change on biodiversity in Brazil. Although the Paris Agreement scenario will not be able to neutralize impacts down to zero, the mitigation policies may reduce the predicted negative impacts for Brazil by 21% while also cutting by half the number of species at risk of extinction from climate change. The Atlantic Forest and the Amazon are the biomes predicted to benefit the most from the Paris Agreement. The risks of not complying with mitigation strategies are very high, as shown by our results for the BAU scenario.

We reveal important taxonomic and geographic biases in studies projecting the impacts of climate change on Brazilian biodiversity. Despite 8,500 km of coast under considerable susceptibility to climate change (Manes et al., 2023), the shortage of studies on coastal and marine environments precluded their inclusion in our analysis. Even in terrestrial environments, there was a substantial disparity in studies, with biomes severely understudied (only 0.5% of risk projections for Pantanal and Pampa), and a strong bias towards the country's rainforests (Amazon and Atlantic Forest) — a pattern that is surely associated with their greater biodiversity and appeal, but that leaves other important environments unattended, with dire consequences for biodiversity conservation in the face of climate change (Overbeck et al. 2015; Fernandes et al. 2023). We also found a strong taxonomic bias towards plants and terrestrial vertebrates that, together, represent >90% of our dataset, whereas the very few studies on invertebrates and aquatic fauna reveal an important knowledge gap and stress the need for more studies in such underrepresented taxa. These biases hinder the formulation of efficient climate adaptation strategies for Brazil's astonishing biodiversity.

Climate change impacts varied across the Brazilian biomes. Pantanal presented the highest projected impact rates, which is strongly associated with risks towards freshwater fishes (93% of risk projections). Notably, this very severe prediction loses some strength due to the small number of risk projections on fish and due to the lack of papers evaluating more distinct taxa. Thus, further studies should assess the potential impacts on Pantanal's biodiversity, especially since it is one of the largest wetlands in the world (Harris et al., 2005) and is currently suffering from severe changes in rainfall (Lázaro et al., 2020), leading to severe droughts and increasing the frequency of wildfires (Viganó et al., 2018; Marques et al., 2021; Viegas et al., 2022). The severe negative impact on Brazilian rainforests, the Amazon and Atlantic Forest, is extremely worrisome since they harbor high biodiversity. Although the Amazon still maintains ~80% of its native vegetation cover (Souza et al., 2020), which increases its resilience, the biome is highly threatened by ongoing deforestation and its high climatic hazard. The Amazon is likely to suffer the greatest temperature increases in Brazil (Gutiérrez et al., 2021) and associated changes in rainfall patterns concomitant to increasing deforestation can lead to a replacement of tropical rainforest by savannah vegetation (PBMC, 2013; IPCC, 2022), representing a complete shift in the Amazon's structure. Contrastingly, the Atlantic Forest is not predicted to suffer such severe changes in climate, although increases in temperature and changes in rainfall patterns are likely (PBMC, 2013; Gutiérrez et al., 2021). Nonetheless, the risks to the Atlantic Forest are heightened as only 28% of its forest cover remains, fragmented into small and isolated patches (Rezende et al., 2018; Ribeiro et al., 2009), reducing its resilience to predicted environmental changes. The severe fragmentation in this biome should also hinder species range shifts (Opdam and Wascher, 2004), making one of the main responses of biodiversity to climate change unfeasible (Bellard et al., 2012). Lastly, the mildest projected impacts for the Pampa are coherent with the climate hazard projected for the region, which will likely have the lowest temperature increases in Brazil.

Given the severe predicted impacts, our findings emphasize the imperative nature of climate change mitigation measures. While the negative impact of climate change on biodiversity under Paris Agreement scenario does not drop to zero, mitigation efforts have the potential to significantly reduce these impacts. The importance of limiting temperature increase to reduce climate change's impacts on biodiversity has already been demonstrated in regional to global scale studies (e.g. Manes et al., 2021; Manes and Vale, 2022, and Warren et al., 2018). To achieve greater biodiversity conservation, however, we need to combine strong mitigation with adaptation measures, such as expansion and adaptation of protected areas in the context of climate change (Malecha et al., 2023; Manes and Vale, 2022). Certainly, this must be a truly international movement with active engagement particularly from nations that have significantly contributed to the climate crisis (i.e., the developed countries), as implementing measures within a single country cannot resolve the climate crisis. Each nation must propose and genuinely fulfill its commitments, enabling the international community to achieve an overarching global goal. The latest Brazilian Nationally Determined Contribution (NDC) prepared in 2024 commits to reducing greenhouse gas emissions by 59–67% by 2035, with the goal of achieving carbon neutrality by 2050 (Brazil, 2024). To achieve these goals, the Brazilian NDC includes several actions that have clear co-benefits to biodiversity, increasing its resilience to climate change. These include, for example, the elimination of illegal deforestation by 2030 (mostly in the Amazon) and the restoration of 24 Mha of degraded areas by 2050, showing the synergy between climate mitigation and adaptation so common in nature-based solutions. Brazil's National Adaptation Plan also encourages the production of knowledge about the impact of climate change on biodiversity. The synthesis provided here contributes to the development of adaptation strategies with a focus on biodiversity conservation. These strategies are needed to protect Brazil's biodiversity and increase people's resilience to climate change. Changes in the hegemonic over-exploitative development model are necessary and viable (IPCC, 2022), and are the only path to move towards a sustainable future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2025.03.004.

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