The role of future climate change refugia in Brazilian conservation planning

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Thesis submitted for the degree of Doctor of Philosophy

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March 2021

“Il ne sert de rien à l'homme de gagner la Lune s'il vient à perdre la Terre.”

François Mauriac

Abstract

The ongoing biodiversity and climate crises are interlinked and need to be addressed together. Hitherto global and regional assessments of priorities for biodiversity conservation and ecosystem restoration generally do not account for future climate change. To plan climate resilient conservation, it is important to prioritize creation of new protected areas (PAs) and ecosystem restoration in refugia projected to remain climatically suitable for most biota currently present. This thesis builds on Wallace Initiative, assessing the implications and limitations of using refugia to create spatial conservation plans for Brazil for amphibians, birds, mammals, plants, and reptiles. Using a novel cross-taxon and biome-specific analysis, it explores the opportunity for expanding PAs and for ecosystem restoration of converted areas to protect or recover refugia. Uncertainties in climate change projection for levels of global warming between 1.5 and 6.0ºC above pre-industrial levels are considered. Cross-taxon refugia in Brazil shrink by 56% as warming increases from 1.5ºC to 2.7ºC, almost disappearing in Amazon and falling to less than 30% of Cerrado and Pantanal, indicating these biomes may be more sensitive than previously thought. With 2.7ºC warming, refugia for all taxa combined are restricted mainly to Pampa and central and southern Atlantic Forest, a largely fragmented biome. Only if global warming is kept below 1.5ºC, will there be PAs in all biomes projected to be refugia for all taxa. Cross-taxon refugia in Brazil and in all biomes fall mainly outside the current PA network but still have native vegetation, except for Atlantic Forest, highlighting the urgency of safeguarding these refugia from deforestation and degradation. Key areas to protect include northern and north-west of Amazon, northern Caatinga, the Amazon-Cerrado border and Cerrado-Atlantic Forest border, and western Pantanal. Refugia in Atlantic Forest and Pampa are particularly important to conserve and restore, because they persist at higher levels of warming.

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Acknowledgements

Throughout my doctoral studies, I have received immeasurable encouragement, assistance, and advice. I am truly thankful to all colleagues, friends, and family that have supported me in countless ways.

First, I would like to thank my supervisors Prof. Rachel Warren, Prof. Jeff Price, and Dr. Will Simonson, for the numerous enlightening discussions, incredible guidance, and invaluable advice. Since the beginning of my studies, I have considered myself lucky to have had such a great team of experts by my side. Your suggestions have help me shape this research without limiting my independence to design, create, err, and rectify.

My thanks also go to the many collaborators I had during my doctoral studies. I would particularly like to thank Mariana Egler (Brazilian Ministry of the Environment), Eduardo Canina (WWF-Brazil), and Aline Soterroni (National Institute for Space Research) for all the Skype meetings, phone calls, and for the ideas exchanged through emails.

I must also thank the EnvEast Doctoral Training Partnership for the opportunity to increase my knowledge in areas beyond my research field, and The Brazilian National Council for Scientific and Technological Development (CNPq) for funding this research. I would also like to express my gratitude to the Tyndall Centre for Climate Change Research for the opportunity to represent the Centre at the 2017 Conference of the Parties of the United Nations Framework Convention on Climate Change Conference and for enriching my knowledge about various facets of climate change research.

A huge thank you to all my friends in BH and Norwich that have made these years pass by so smoothly. A special thanks to ones that have gone through the PhD experience with me: Anderson, Barney, Becci, Camila, Carla, Chris May, Christoph, Dave, Jackie, Leo, Matthew, Marta, Marina Azaneu, Marina Conrado, Nathalia, Nico, Nicole, Osgur, Rich, Rhosanna, and Ulysse. And to my Brazilian friends in Norwich: Aniele, Marcelo, Moysés, and Sophia. Sharing tears and pints with you made me delight my life in this fine city.

A huge thank you o my cousins, Daniel and Sofia, their partners, Ana and Marcelo, and the friends João and Rejane, that by chance also decided to live in UK for a while. Having you nearby was truly amazing. The support you gave to André and me while we were settling was essential to us.

My thanks must also go to all my family in Brazil and Portugal for keeping in touch through chats and video calls, and sometimes visiting me in Norwich (it was fabulous having you with us Dani and Vanda!). A special thank you to tio Henrique, Andrea, and Guigo who have kindly made me feel at home during my training in Rio. And to my tios that have also gone through the doctoral training process, tios João, Pedro and Paulo for empathizing with my achievements and frustrations.

I have no words to thank my parents, António and Cida, for allowing, encouraging and helping me to follow my dreams. I am also deeply thankful to my brother, Guilherme, and my sister-in-law Natália, for supporting me since the application process. I would not have gone this far if it were not for your unconditional support.

I must say a massive thank you to my husband, André, for moving across the Atlantic with me. You always show me the bright side of things and offer an extra pair of hands to deal with [IT] issues. And finally, big thank you to my daughter, Alice, who can easily put a smile upon my face.

Most of you have celebrated with me a small victory at some point of the past years (yeah, the code finished running!). I hope that we can soon celebrate this major one together.

Chapter 1: Introduction

1. Overview

The research presented in this thesis examines the nexus of climate change, biodiversity conservation and land use. In particular, it aims to inform biodiversity conservation policy in Brazil by demonstrating how to make this more resilient to climate change. Specifically, it looks at the benefits and limitations of using 'climate change refugia' as a basis for planning area-based conservation measures for the country. It builds on previous works by the Wallace Initiative (WI – (Warren et al. 2013a; Warren et al. 2018a)) that have identified globally the locations projected to remain climatically suitable for the majority of terrestrial species modelled to be currently present (i.e., 'climate change refugia'). It goes on to identify and analyse future climatic cross-taxon refugia (i.e., refugia for at least two taxa simultaneously) in Brazil and for each biome within Brazil. Next, it links this to conservation policy by looking at the overlap between refugia and the existing protected area (PA) network. Finally, it explores the opportunity for expanding the PA network and for ecosystem restoration of converted areas to protect or recover potential refugia.

Therefore, this thesis begins by reviewing existing scientific understanding on the nexus of climate change, biodiversity conservation and land use, explaining how future climate change refugia fits into this nexus, presenting related literature for the Brazilian context and highlighting the current knowledge gaps this thesis addresses (chapter 1). Following that, the background datasets on climate change and biodiversity that were obtained from the Wallace Initiative that are used in this thesis are described, and their applicability to Brazil is assessed (chapter 2). Next, chapter 3 explores projected climate change in Brazil in a new way by showing future projected changes in the bioclimatic variables that underpin the WI data described in the previous chapter (chapter 3). Then, the WI data is used to identify the future climatic cross-taxon climate refugia, i.e., locations that are projected to be refugia simultaneously for at least two taxa (chapter 4). Following that, chapter 5 explores for Brazil as a whole and for each Brazilian biome: (a) the extent to which Brazilian protected areas (PAs) will remain climatically suitable for most species currently present by acting as potential future climatic cross-taxon refugia; and (b) the potential of these locations identified as refugia to be employed in conservation measures such as the expansion of the current PA network or the restoration of converted ecosystems (chapter 5). Finally, the key messages are presented along with an overall discussion and conclusions (chapter 6).

2. Research topic

a. The nexus of climate change, biodiversity conservation and land-use

Biodiversity loss is happening at unprecedented rates, directly or indirectly due to human activities (IPBES 2019). Five major direct drivers of biodiversity loss have been identified in the Millennium Ecosystem Assessment (Assessment 2005), Living Planet Report (Fund 2016; Almond, Grooten, and Peterson 2020), and in the IPBES Global Assessment Report (IPBES 2019): habitat loss / land-use change, climate change, invasive alien species, overexploitation, and pollution. The interaction of these drivers usually leads to cascading effects that exacerbates their individual threat to biodiversity (Brook, Sodhi, and Bradshaw 2008).

Habitat loss due to land-use change has been indicated as a leading driver of biodiversity loss in global terrestrial ecosystems during the past 50 years (IPBES 2019), and as a significant source of anthropogenic carbon emissions that intensify climate change (Jia et al. 2019). Nearly 86% of threatened birds, 86% of threatened mammals and 88% of threatened amphibians are being negatively impacted by the destruction of their habitat (Butchart et al. 2004), giving habitat loss the status of leading cause of species extinction in the 20th century (Pimm and Raven 2000). Natural habitat destruction and degradation are especially driven by the expansion of agricultural and/or forestry activities (Laurance, Sayer, and Cassman 2014; Feng et al. 2022). More specifically, in Asia 38% of the deforestation was reported to be driven by a combination of agricultural expansion, wood extraction and infrastructure extension, and in Latin America, 32% of the deforestation was driven by the combination of agriculture expansion and infrastructure extension (Watson et al. 2005). Infrastructure expansion, a driver that includes the expansion of roads, other transportation infrastructure and urban areas, has also been identified as a threat to biodiversity (Seto, Güneralp, and Hutyra 2012; IPBES 2019).

Historically, the second most common threat to terrestrial biota globally has been overexploitation (Fund 2016; IPBES 2019). For Latin America and Caribbean, climate change is listed as third biggest threat to terrestrial and freshwater populations (Almond, Grooten, and Peterson 2020). Nevertheless, if the ongoing climate crisis is not tackled, this century extinction rate could be greater than ever seen (IPCC 2014).The ongoing changes in climate have already impacted biodiversity. There is strong evidence supporting that climate change is the cause of coral bleaching and mortality (De'ath, Lough, and Fabricius 2009), changes in phenology (including egg laying and migration dates of birds, and spring bud burst - Settele et al. (2014), terrestrial species’ ranges shifting to higher latitudes (~17km poleward/decade – Hoegh-Guldberg et al. (2018)) or altitudes (~11m up/decade – Hoegh-Guldberg et al. (2018)) and that many land and ocean ecosystems and some of the services they provide have already changed due to global warming (high confidence – Hoegh-Guldberg et al. (2018)).

In addition to species’ range shifts, future climate change is projected to become the main driver of species loss (Urban 2015), negatively impacting biota at every level, from genes to ecosystems (Diversity 2009). For example, future changes in climate are projected to lead to biomes shifts (Hoegh-Guldberg et al. (2018) – also explored in chapter 4). Ecosystems at risk of severe change in a world ~3ºC warmer than pre-industrial times include the largest tropical forest, the Amazon (Warszawski et al. 2013). If global warming stays between 3-4ºC above baseline, the Cerrado is also projected to be at risk of a severe ecosystem change (Warszawski et al. 2013). It is important to highlight that these alarming findings consider future climate change alone as a driver of biome shifts, even though deforestation could accelerate these changes, especially in the eastern, southern, and central parts of the Amazon (Nepstad et al. 2008; Lovejoy and Nobre 2018).

Further climate changes are projected to increase changes in phenology, such as flowering time of gladiola in the south of Brazil (Becker et al. 2021), which could lead to phenological mismatch between plants and pollinators, and plants and seed dispersers (Settele et al. 2014). In addition, future range shifts are projected to lead to large scale loss of potential geographical ranges of species. For example, the WI team projected that for a global warming of 3.2ºC 49% of insects, 44% of plants, 26% of vertebrates globally are projected to lose more than half of their range (Warren et al.

2018a). The combination of these widespread and extensive range losses and phenological miss-matches, together with effects of extreme weather events (which are not included in these studies) creates strong risks to the functioning of ecosystems, as losing species affects ecosystems functioning and services (Symstad et al. 1998; Isbell et al. 2011).

Since early 2000s, ambitious goals have been set under the United Nations Convention on Biological Diversity (CBD) to reverse the current rates of global biodiversity loss. In 2010 parties of the CBD committed to achieve a set of 17 goals, the Aichi targets (CBD 2011) as part of the convention's 'Strategic Plan for Biodiversity 2011-2020'. Considering that protected areas (PAs) are a traditional measure to promote biodiversity conservation (Kramer and Mercer 1997; Rodrigues, Andelman, et al. 2004; Chape et al. 2005; Joppa, Loarie, and Pimm 2008; Saout et al. 2013) , the Aichi target 11 called countries to increase their PAs and/or other effective area-based conservation measures (OECMs) to cover at least 17% of their land area by 2020.

The effectiveness of PAs in safeguarding biota has been largely linked to their potential to avoid land-use change, such as deforestation and ecosystem degradation, within their boundaries (Andam et al. 2008; Gray et al. 2016; Cazalis et al. 2020). Yet, as changes in climate force widespread shifts on species' ranges, the effectiveness of PAs has been questioned due to their static nature (Araújo et al. 2004; Hannah et al. 2007; Lemes, Melo, and Loyola 2013; Ferro et al. 2014). To shed light on this matter, an assessment of empirical evidence of PAs performance since 1970s showed among other findings that observed declines on species number inside PAs were often lower than outside, and that PAs have been used as stepping-stones while species colonize new locations. Therefore, it is generally considered that PAs have been and are likely to continue to be crucial for long-term biodiversity conservation despite changes in climate (Thomas and Gillingham 2015).

However, creating new PAs is not enough to reverse the ongoing biodiversity decline in ecoregions or biomes that have already been largely degraded or converted, and restoration actions would be essential to limit species loss there (Venter et al. 2016; Mappin et al. 2019; Luther et al. 2020). At the same time, the CBD recognizes that restoration actions enhance 'the contribution of biodiversity to carbon stocks' and hence to climate change mitigation and adaptation (CBD 2011). Considering that ecosystem restoration can potentially deliver co-benefits for biodiversity and climate change mitigation and adaptation, Aichi target 15 called CBD’s parties to restore at least 15 per cent of their degraded ecosystems by 2020, and the Bonn Challenge and the New York Declaration on Forests gather countries and regions restoration pledges to achieve 350 million hectares restored worldwide by 2030. Moreover, most parties of another Rio Convention, the United Nations Framework Convention on Climate Change (UNFCCC), have committed to promote restoration or reforestation on their National Determined Contributions (NDCs) towards achieving the UN Paris Agreement. Finally, this global momentum for ecosystem restoration was boosted by the UN declaration of the 2020s as the ‘UN Decade on Ecosystem Restoration’.

It is vital to emphasise that to explore the full potential of delivering co-benefits for species and climate, ecosystem restoration must be more than simply planting trees and crucially avoiding doing so in non-forest ecosystems (Seddon et al. 2020; Sutherland et al. 2020). For grassy biomes, for instance, restoration actions that aim to increase tree cover or ‘recover forests’ would have catastrophic effects on biodiversity, the ecosystem services these biomes provide (Veldman et al. 2015; Silveira et al. 2020), to climate change mitigation (Veldman et al. 2019), and could weaken their resilience to climate change (Seddon et al. 2020). Forest plantations for commercial use are also discouraged, as they store less carbon than natural forests (Lewis et al. 2019) and provide little if no benefits for biota when established as a replacement of natural ecosystems (Bremer and Farley 2010).

Considering all this, an increasing body of literature has been performing global assessments based on multicriteria approaches to identify priority places for the PA network expansion (Rodrigues, Akçakaya, et al. 2004; Brooks et al. 2006; Venter et al. 2014; Brum et al. 2017) and more recently for implementing restoration actions (Luther et al. 2020; Strassburg et al. 2020). Identifying priorities is important as resources for implementing both conservation measures are often scarce (Lynch and Blumstein 2020). Moreover, a higher priority should be given to locations that can deliver co-benefits, e.g., to biodiversity and climate (Strassburg et al. 2020). Nevertheless, the extent to which the long-term effectiveness of these measures could be jeopardized by the same climatic changes they intend to mitigate or promote adaptation to (Anderegg et al. 2020) has not been explored by these assessments.

Therefore, these global assessments of priorities for conservation and restoration that fail to consider projections of impacts of future climate change on biota, risk (a) prioritizing the creation of new PAs in locations that are projected to become climatically unsuitable to biota due to future changes in climate, and (b) promoting restoration actions targeting vegetation types and species for which the future climate is projected to be unsuitable.

b. Future climate change refugia for biota

One approach for addressing such gap is to include the analysis of locations projected to act as future climate change refugia for biota in conservation planning (Morelli et al. 2020). Refugia are locations where species have “retreated to, persisted in and expanded from” during previous periods of climate instability, e.g., cyclical warming and cooling in the Quaternary (Keppel et al. 2012). Although projected changes in future climate do not suggest a return to pre-industrial levels in this century under any explored scenario (IPCC 2014), the concept of refugia as areas where species could survive despite future climate change is still considered valuable for biodiversity conservation (Keppel et al. 2012; Morelli et al. 2020). Therefore, considering future climate change, refugia can be defined as locations where species are projected to have the best survival chances despite future changes (Keppel et al. 2012). Selecting refugia for implementing conservation measures could avoid unsought outcomes, such trees not thriving due to droughts (Locatelli et al. 2015) or not stocking as much carbon as expected due to changes in climate (Bastin et al. 2019).

A growing body of research has aimed at identifying future refugia (Keppel et al. 2012; Baumgartner, Esperón-Rodríguez, and Beaumont 2018) and planning their conservation and protection (Keppel et al. 2015; Morelli et al. 2016; Graham et al. 2019). However, most proposals are usually targeted at one or few species of the same taxonomic group (e.g., Monsarrat, Jarvie, and Svenning (2019), Ribeiro, Sales, and Loyola (2018), Borges and Loyola (2020)) and are mainly not at scales most pertinent to biodiversity conservation (Selwood and Zimmer 2020).

Identifying future refugia for a single species is important and should be included in species focused conservation plans (e.g., such as the ones aiming to reduce threats of future changes to critically endangered, endemic, small ranged or keystone species).

Despite that, as resources for conservation are often scarce (Lynch and Blumstein 2020), conservation planning aimed at the ecosystem level would greatly benefit from the identification of locations that are projected as potential future refugia simultaneously for more than one taxon, i.e., cross-taxon refugia, keeping most of the community's current species assemblage.

This thesis adopts the simplistic assumption that cross-taxon refugia are more likely to retain their current ecosystem structure and function under future conditions of climatic change due to their higher number of species and taxa "retreated" there in comparison with non-refugia locations. However, it is worth emphasising that ecosystem resilience is much more complex and likely to be determined by several other factors not considered in this thesis, such as the resilience of keystone species to future changes in climate or the ones explored by Tom (2015), and that there are still several questions related to the role of biodiversity on ecosystems functioning unanswered as pointed out by Hooper et al. (2005).

Nevertheless, identifying cross-taxon refugia is useful for long-term conservation measures that aim to protect currently healthy ecosystems (creation of new PAs) or to recover the functionality of degraded ecosystems (restoration actions). Moreover, cross-taxon glacial refugia for birds and mammals during the Last Glacial Maximum in the sub-Saharan Africa matched the locations previously suggested as refugia for individual species or taxonomic group within those clades (Levinsky et al. 2013), supporting the representativeness of cross-taxon refugia.

Therefore, identifying single and cross-taxon refugia and planning their conservation and protection is pivotal to guarantee the delivery of benefits for biodiversity and climate, and forms an important part of this thesis.

c. The Brazilian context

Including future climate change refugia in conservation planning is especially important for Brazil, the most diverse country of the world, with at least 103,870 animal species and 43,020 plant species currently known (CBD 2021). It is home of the majority of the Amazon, and of two hotspots for conservation priorities (Myers et al. 2000): the Atlantic Forest and Cerrado, the most species rich savannah in the world. In addition to these, three other terrestrial biomes also happen within Brazil: Caatinga (mainly dominated by xeric shrubland), Pantanal (tropical wetland) and Pampa (mainly grassland – see Figure 1 for the geographical location of the Brazilian biomes, Roesch et al. (2009) for a complete description of each biome). Brazilian biomes vary not only in land area but also in number of species, threatened or not, that they host. A comparison of the numbers of species included in the IUCN Red List database and in the Wallace Initiative database for the Brazil is presented in Chapter 2 section 4.b.

Figure 1: Geographical location of the six Brazilian biomes: Amazon, Caatinga, Cerrado, Atlantic Forest, Pampa, and Pantanal. Map created using ArcGIS v10.3.1.

National policies that addressed the use, management and protection of the Brazilian forests and native vegetation arose simultaneously to the post-industrial deforestation process. In 1965 a new version of the 1934 Forest Code (FC) was published (Brasil 1965) and 20 national parks were created between 1937 and 1979 (Rocha, Drummond, and Ganem 2010). Nevertheless, it was not until late 20th century that the environment was perceived as a national interest and gained political space in Brazil with the creation of the Ministry of the Environment in 1992 (Brasil 1992) and the publication of several presidential decrees that enforced the FC of 65 (Soares-Filho et al. 2014). Moreover, during the first years of the 21st century, the Brazilian government created the National System of Protected Areas (SNUC in Portuguese - Brasil (2000)), a system that has unified and synthesised the criteria for creation, implementation and management of all types of Brazilian protected areas (called in Brazil conservation units) and amended the FC of 65 increasing the rate of protection of the native vegetation inside private properties (Brasil 2001). At the end of the 2010, to fulfil its obligations with the FC, each property should spare at least 20 percent of its area as "legal reserve" (a protected area that every private property is demanded to maintain since the Code of 1965), and if the property was inside the legal Amazon, the legal reserve should be of 80, 35 or 20 percent, depending of the vegetation type: Amazon forest, Cerrado and others respectively Stickler et al. (2013) presents a more detailed chronology the forest code changes). In addition to the legal reserve, it was also mandatory to the landowners to spare the "permanent protected areas" that are lands along rivers or watercourses, around lakes, lagoons, reservoirs or natural springs, hilltops, high altitude areas, or steep slopes, and other specific phytophysiognomies. At this point, all the private areas that were protected (legal reserves and permanent protected areas) were also expected to be restored, in case of law disobedience, by the landowner and at his expenses (Soares-Filho et al. 2014).

Following a great pressure from the agribusiness lobby, the FC was revised in 2012 (Nepstad et al. 2014). One of the major changes that this new version made was the differentiation between the requirements for protection and restoration, by not demanding the restoration of the protected areas inside private lands (legal reserves and permanent protected areas) that were illegally deforested before 2008 (Brasil 2012) what lead to a reduction of 58% of the areas that were expected to be restored throughout the country but mainly affecting the three previously mentioned biomes (Soares-Filho et al. 2014). Furthermore, even though the 2012 FC only made small changes on the protection requirements, it decreased the amount of hilltop areas that are legally protected, possibly leading to major consequences for future biodiversity conservation as species are moving towards higher altitudes with climate change (Parmesan 1996; Parmesan, Ryrholm, Stefanescu, Hill, Thomas, Descimon, Huntley, Kaila, Kullberg, and Tammaru 1999; Chen, Hill, Ohlemuller, et al. 2011). Finally, considering the current legislations, the area of native vegetation in private land that is unprotected and, therefore, could be legally deforested was calculated as 88 ± 6 Mha (similar area to France and United Kingdom together) or 18 ± 4 GtCO2e by Soares-Filho et al. (2014).

The Brazilian commitments under the CBD usually reflects the variety of land area, species and ecosystems richness, and the different legal requirements among the Brazilian biomes. As an example, for the period between 2010-2020 Brazil has committed to increase its PA network to cover 30% of the Amazon land area and 17% of other biomes (national target 11) (Brazil 2013; CONABIO 2013). The achievement of this target could be measured by considering the land area covered in each biome by the four groups of protected areas recognized in Brazil: conservation units (UCs), indigenous lands (TIs), quilombolas lands and areas protected under the Forest Code (all groups are explained in detail in Chapter 5 section 3.b). However, the technical report of the national targets' indicators that complements the country 6th national report only has measurable indicators related to the area extent of UCs (MMA 2019). Therefore, to what extent Brazil will consider PAs and OECMs other than the UCs is still unclear.

Nonetheless, at the time of writing this thesis (early 2021), 28% of the Amazon is protected as Conservation Units (all types of Brazilian PAs are explained in detail in Chapter 5 section 3.b), representing 76% of the national UCs network. Meanwhile, less than 10% of the Atlantic Forest, Caatinga and Cerrado is protected as UCs, representing respectively 7%, 5% and 11% of the national UCs network. The smaller biomes, Pampa and Pantanal are even less protected, with 3% and 5% of their land areas registered as UC (representing ~0.5% of the national UC network – see Table 9 for the proportion of land area considered by this study as PA versus currently included in the national database).

Moreover, the alarming deforestation rates in the Amazon and Cerrado (Strassburg et al. 2017; Walker et al. 2020) and the recent increase in the frequency of forest fires in the Amazon (Barlow et al. 2020; Brando et al. 2020; Xu et al. 2020) have underscored the urgency to identifying and safeguarding refugia in this country. It is worth noting that while deforestation and ecosystem degradation are undoubtedly lower inside PAs than elsewhere, they are not completely absent within the PA network (Françoso et al. 2015; Lapola et al. 2020; Walker et al. 2020). At the same time, PAs in Brazil are in constant threat to be downsized, downgraded, degazetted, and / or reclassified (Bernard, Penna, and Araujo 2014; Brazil 2020b).

In addition, a meta-analysis of predicted species extinction risks from climate change revealed that South America has the highest worldwide risk, exceeding the risks of North America and Europe by a factor of 4 (Urban 2015). Other disturbing findings have also highlighted the relevance of assessing refugia in Brazil: future changes in climate alone are projected to cause greater species loss in tropical forests than temperate ones (Newbold 2018), and when combined to the pressure caused by different types of land-use tropical forests (e.g., Amazon and Atlantic Forest) and grasslands (e.g., Cerrado), along with Mediterranean biomes, show the highest sensitivity among all biomes (Newbold et al. 2020).

The extent to which future climate change threatens Brazilian biomes and biota has also been assessed at the national or subnational scale. Different vegetation modelling techniques have projected that future changes in climate will lead to shifts in current biomes' distribution, suggesting an encroachment of the Amazon forest by Cerrado and an expansion of the Caatinga (Salazar, Nobre, and Oyama 2007; Cook and Vizy 2008), a seasonally dry tropical forest. Within Caatinga itself, aboveground biomass estimates suggest that the driest physiognomies will expand under increased future climate change (Castanho et al. 2020). For the most southern Brazilian biome, Pampa, projected changes in climate are associated with an increase in forest cover at the expense of grassland areas (Salazar, Nobre, and Oyama 2007; Anadón et al. 2014).

Comparing the threats from future climate change and land-use, an assessment of the extent to which 255 amphibian species in the Amazon are exposed to future changes in climate, deforestation and hydroelectric expansion showed that future climate change is projected to cause more range loss than the other two threats. At least half of the species of five amphibian families (out of the 19 analysed) are projected to lose more than 50% of their potential geographical distribution due to future climate change. (Silva et al. 2018).

For Cerrado and Pantanal, future changes in climate lead to plant species range contractions, especially on the northern part of the biome, decreasing the flora species richness throughout the biome and inside PAs (Velazco et al. 2019). Similar findings were found regarding 430 amphibian species and the PA network of the Atlantic

Forest, suggesting that PAs in this biome will host less species under future climatic conditions (Lemes, Melo, and Loyola 2013). In addition to these trends, an analysis of the overlap between current and future potential geographical ranges of 507 tiger moth species and the PA network of the Atlantic Forest showed that even if an unlimited dispersal is considered under future climate change, only few PAs in the southern region of this biome will gain species, and PAs protect less species in the future than randomly selected areas (Ferro et al. 2014).

The vulnerability of the Brazilian PA network to future climate change has also been assessed, showing that the projected changes in climate and the consequent transition in vegetation increase the vulnerability of PAs in the Amazon and western Cerrado, and that most PAs identified with refugia potential (defined as high resilience and low hazard and not as the areas that will remain climatically suitable for biota) are along the Brazilian coast (Lapola et al. 2020).

Locations with potential to act as future climate and land-use change refugia for birds have also been spatially identified outside the Cerrado PA network (Borges and Loyola 2020). This previous analysis considered as refugia the locations that by 2050 are projected to remain with native vegetation and that are also projected to undergo less changes in climate under a future scenario of high greenhouse gases emissions. For the purpose of identifying the areas that are projected to undergo ‘less changes in climate’, this study did not perform bioclimatic species distribution modelling, doing a simple analysis of projected changes in two bioclimatic variables from only the average of four GCMs (as compared to the full SDMs approach used in this thesis that is based on the output of 21 GCMs). Thus, its finding that by mid-century 13% of Cerrado (mainly on its eastern portion) will hold the potential to act as refugia for birds does not take into consideration if those locations are projected to remain climatically suitable for the 103 bird species included in the study.

Moreover, few other attempts to geographically identify conservation priorities in Brazil considering biota sensitivity to future climate change have been made so far, agreeing that avoiding ecosystem degradation and expanding the current PA network are pivotal actions for biodiversity conservation in their study areas (de Oliveira et al. 2012; Zwiener et al. 2017; Ribeiro, Sales, and Loyola 2018; Vasconcelos, Nascimento, and Prado 2018), and that for Atlantic Forest restoration actions are also needed

(Zwiener et al. 2017). Yet, all focused on one (de Oliveira et al. (2012) – Caatinga, Zwiener et al. (2017) – Atlantic Forest, Ribeiro, Sales, and Loyola (2018) – Amazon) or two biomes (Vasconcelos and Prado (2019) – Atlantic Forest and Cerrado) and used species of one taxonomic group (Zwiener et al. (2017) – 2,255 woody plant species, Ribeiro, Sales, and Loyola (2018) – 256 mammal species, Vasconcelos and Prado (2019) – 350 and 155 anuran species) or just endemic species of vertebrates (de Oliveira et al. (2012) – 32 species). To project future potential geographical species ranges all studies used three GCMs (not always the same, therefore totalling six GCMs) forced by one or two future climate change scenarios, demonstrating the lack of robustness in those studies.

In addition, one study has identified at the national scale priority places to implement and monitor climate change adaptation measures that aim at reducing biodiversity and society's vulnerabilities to these changes (Kasecker et al. 2018). This latter analysis examined which municipalities have extensive natural vegetation cover, high levels of poverty, and will be exposed to natural disasters related to drought due to future changes in climate (used as a proxy for high degree of exposure to future climatic changes). Therefore, this existing assessment analysed only the exposure of natural vegetation in Brazil to drought caused by future climate change.

Hence, the locations in Brazil where future climate is projected to remain suitable for most species, giving biota the best survival chances despite future changes in climate, i.e., future climate change refugia, remain unknown for several combination of taxonomic groups and biomes, such as Atlantic Forest and birds, mammals, reptiles; Caatinga and plants, Cerrado and amphibians, mammals, reptiles; Pampa and all taxa; Pantanal and vertebrate taxa. And the extent to which those locations could be used in biodiversity conservation planning under several future climate change scenarios has not been fully explored for the country and its biomes. Finally, a national assessment that handles a broad range of scenarios of future climate change and the uncertainties therein consistently across a broad range of taxa and all Brazilian biomes has not been performed yet.

3. Research gap

Despite the growing body of research on the interaction of future climate change and biodiversity in Brazil, the localities in the country that have the potential to act as future climate change refugia for a taxonomic group or for a combination of taxa remain largely unknown. Moreover, to better assess the potential threats that future climate change could pose on the Brazilian biota, projections from biodiversity modelling exercises that considered several species from a broad range of taxa and have assured robustness by considered more GCMs under more future climate scenarios need to be evaluated, especially if the aim is to inform conservation planning (Porfirio et al. 2014)

In comparison with previous studies that have analysed few species of one or several taxa, or few thousand for one taxon, this thesis analysis the impacts of future climate change on the geographical distribution of more than 22 thousand terrestrial species in Brazil, using future climate projections from 21 GCMs under different levels of future climate change to explore the full range of 1.5ºC to 6.0ºC global warming. In addition, an analysis of locations in Brazil and its biomes where the implementation of conservation measures, such as the creation of new PAs or restoration actions, would safeguard the most resilient ecosystems despite future climate change (i.e., future climate change refugia) has not yet been conducted. Finally, the extent to which these refugia could be used as part of the national effort to achieve its commitments under the CBD and UNFCCC related to area-based protection and ecosystem restoration has not yet been explored.

4. Aim and objectives

This research explores the nexus of climate change, biodiversity conservation and land use in Brazil with the overarching aim of demonstrating how the location of future climate change refugia for terrestrial biota can be used to design area-based conservation planning that takes into consideration future effects of climate change.

This research question is asked in the context of current and future conservation and climate change mitigation targets and commitments, such as the Aichi targets, the National Biodiversity Strategies and Action Plan (NBSAP), the Post-2020 Global Biodiversity Framework, the Paris Agreement targets related to temperature, and

Nationally Determined Contribution (NDC). That is to say, all pledges made by the Brazilian government under the umbrellas of the UNFCCC and CBD related to area-based conservation or restoration and reforestation are considered by this study.

Moreover, this research considers six different levels of future global warming (1.5, 2, 2.7, 3.2, 4.5, 6ºC above pre-industrial levels) and uses downscaled projections derived from 21 general circulation models (GCMs) to ensure robustness. Additionally, analyses are performed at the biome level in order to capture possible differences throughout Brazil's continental extension and to discuss current national legislations and commitments (detailed information on these three topics can be found in chapter 2).

Finally, four specific objectives are defined to fulfil this study's aim:

- To analyse how bioclimatic variables are projected to change in Brazil and how these changes vary across biomes (chapter 3)
- To analyse the proportion of Brazil and its biomes that is projected to remain climatically suitable for most of the terrestrial biodiversity they presently contain, by acting as future climatic cross-taxon refugia (chapter 4)
- To identify, for each biome within Brazil, the extent to which the PA network is projected to have the potential to act as future climatic cross-taxon refugia for terrestrial biota under different levels of future global warming (chapter 5)
- To identify future climatic cross-taxon refugia outside of the current PA network where conservation efforts could be focused to (a) avoid deforestation or degradation (e.g., through extension of PAs or OECMs) or (b) restore degraded or converted ecosystems (chapter 5).

5. Research significance

The study presented in this thesis fills gaps in the literature by spatially identifying locations in Brazil that are projected as potential future climate change refugia simultaneously for several vertebrate taxa (Amphibia, Aves, Mammalia, Reptilia) and plants, i.e., future climatic cross-taxon refugia, and, based on their current land-use, suggesting where biodiversity conservation measures (e.g., the expansion of the PA network and ecosystem restoration) could take place. By analysing the overlap of these future refugia with Brazilian PAs, this research shows projections of climate change impacts on flora and fauna filling gaps left by previous assessments of the efficiency of Brazilian protected area network under future climate change that have only considered the climate sensitivity of one taxon in one or two biomes (Lemes, Melo, and Loyola 2013; Ferro et al. 2014; Velazco et al. 2019) or the probability of habitat transition for the country (Lapola et al. 2020).

Moreover, the research here presented represents the most comprehensive analysis of the impacts if climate change on Brazilian biota in terms of number of species (22,535 species – 293 amphibians, 2432 birds, 367 mammals, 19380 plants, and 63 reptiles – for more information see Table 1 in chapter 2) and number of Brazilian biomes (6 biomes) included, and the most robust in terms of number of future climate change scenarios considered (126 projections derived from 21 GCMs under six different levels of future global warming: from 1.5ºC to 6.0ºC). Therefore, it complements current efforts led by Brazilian Environmental Ministry (MMA in Portuguese) to evaluate climate change impacts on the Brazilian biodiversity and ecosystems, as the National Adaptation Plan, and more specifically one of its three targets for the biodiversity section "the development of modelling studies about climate change impacts on biodiversity to be used by the several public policies for biodiversity conservation, restoration and sustainable use" (Brazil 2016b).

Finally, this study contributes to the ongoing discussion about the importance and interconnection of the objectives of international agreements made under the CBD and UNFCCC.

6. Thesis structure

Having introduced the research topic, main aim, and objectives, and how they fill major knowledge gaps, the rest of this thesis is organised as follows:

- Chapter 2: Data – this chapter presents an explanation of the main datasets used in this study followed by an assessment of their applicability to the Brazilian scenario.
- Chapter 3: Projections of bioclimatic variables for Brazil under future climate change – first data chapter. Here the observed and future

projections of the eight bioclimatic variables used by the Wallace Initiative (WI) to model current and future potential geographical species’ ranges globally are presented for Brazil and its biomes.

- Chapter 4: Future climate change refugia for terrestrial biota in Brazil – second data chapter. This chapter explores the methodology of identifying refugia and presents two sensitivity analyses around the thresholds embedded in identifying future climate change refugia for terrestrial biota in Brazil. Based on the findings it then shows an analysis of the size and geographical location of the locations projected as potential future climatic cross-taxon refugia (i.e., locations projected to act as refugia for at least two taxa simultaneously) for Brazil and for each Brazilian biome.
- Chapter 5: Planning in a changing climate: how can future climatic refugia help inform biodiversity conservation planning in the context of future climate change? – Here the extent to which the current Brazilian PA network is projected as potential future climatic cross-taxon refugia is investigated. In addition, it shows an analysis of that considers the current land-use of the locations identified as future climatic cross-taxon refugia to evaluate their potential to be employed as conservation efforts such as expanding the PA network or restoring degraded or converted ecosystems.
- Chapter 6: Final remarks – this chapter presents the key messages of this thesis, a discussion around the role of refugia in conservation planning under future climate change, a summary of the limitations and caveats of this study, and the overall conclusions.
- References – this section presents a complete list of references cited throughout the thesis.

Chapter 2: Data

This research is based on data from the Wallace Initiative (WI) database for climate and terrestrial biodiversity climate envelope modelling. It also considered georeferenced data for Brazil and its biomes, current Protected Area network and current land use.

This research was designed to explore the refugia at different levels of global warming from 1.5ºC to 6.0ºC above pre-industrial levels to inform adaptation and mitigation policies. Comparing different levels of warming allows mitigation decision makers to easily compare outcomes. At the same time, comparing different levels of warming enables adaptation decision makers to plan for the best- and worst-case scenarios. In other studies adaptation is planned by looking at the range of possible future climate in a given time-period (e.g., 2050). However, here the full range of uncertainty in climate projections is still captured but the use of specific future warming levels means that some of the uncertainty about the time at which the specific warming levels are reached while the differences between the regional patterns of climate projection for a given warming level are taken into account. Considering that the aim of this research is to inform long-term conservation measures that would foster biota throughout the 21st century and beyond despite future changes in climate, the use of specific levels of warming instead of a time-slice approach is particularly appropriate. This approach contrast with the human system where adaptation e.g., in engineering projects may need to be aligned with planning horizons.

This chapter presents data that are used in more than one chapter (country and biomes boundaries) or that are important for the general understanding of this thesis (WI climate and biodiversity data). Thus, this chapter first shows the georeferenced data for the Brazilian biomes (used in chapters 3 to 5), and then a description of the Wallace Initiative (WI) database for climate (used in chapter 3) and terrestrial biodiversity climate envelope modelling (used in chapter 4) is presented. Following that, the applicability of the WI global data to Brazil is assessed.

The data on current Protected Area network and current land use for Brazil is explained in chapter 5 and all manipulations and post-processing methods are described in subsequent chapters.

1. Country and biomes boundaries – as used in chapters 3 to 5

This research adopted biomes as a sub-national division not only to capture in more detail the impacts of climate change throughout Brazil's continental extension, but also to compare and discuss area-based national protection legislations or targets (such as the Forest Code and the National Biodiversity Strategies and Actions Plans, respectively) that set different thresholds or goals of land area that needs to be protected, depending on the biome.

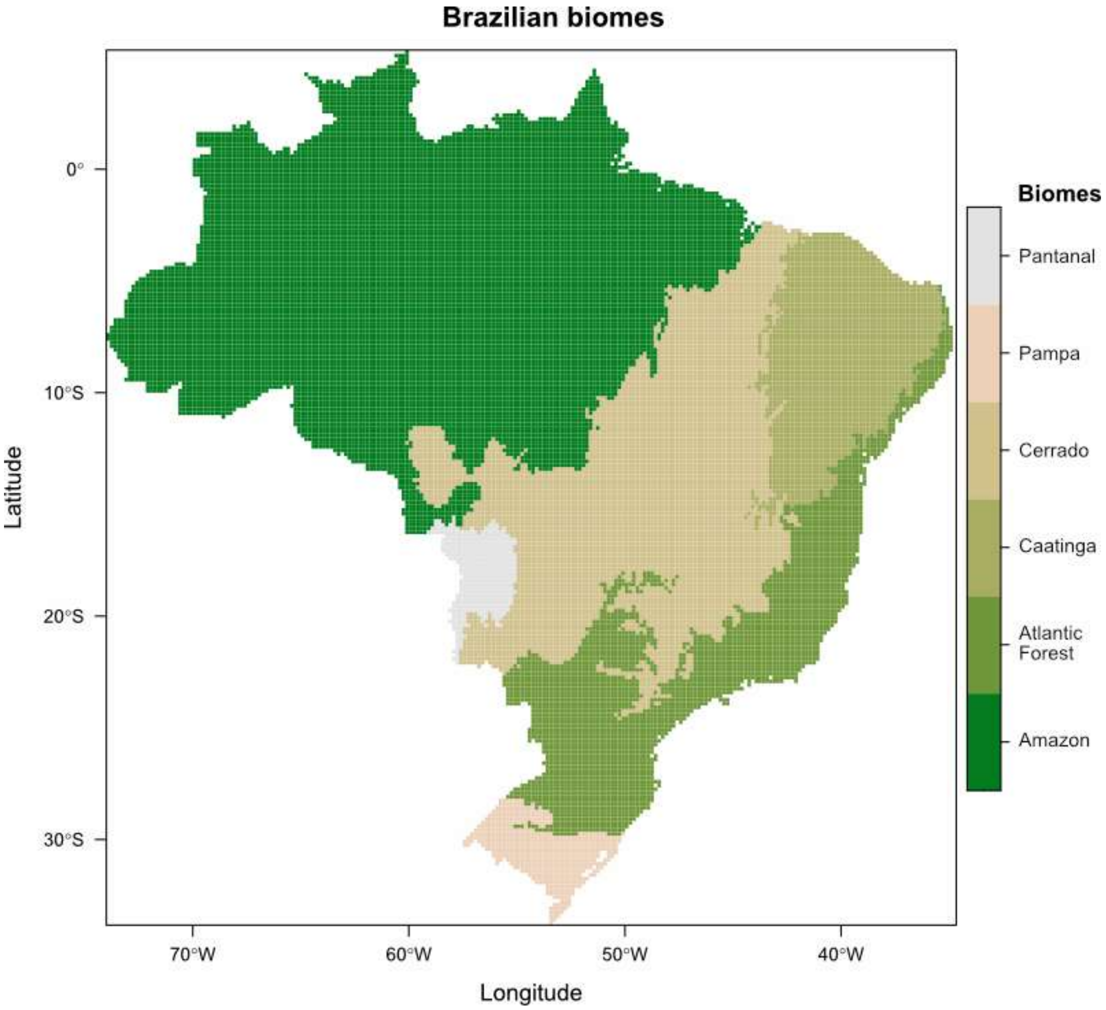


Figure 2: Rasterized version of the Brazilian biomes datum considered by this research.

The spatial data on the Brazilian biomes used by this research were processed by the Brazilian Institute of Geography and Statistics (IBGE in Portuguese) and were obtained as vector from IBGE's website (IBGE 2017). The IBGE is a Brazilian federal government body that processes and provides data and information about the country, and its datasets are widely used by the scientific community (e.g.,Overbeck et al. (2007) and Soares-Filho et al. (2014)) and other sectors of the civil society.

IBGE provides spatial datum on the Brazilian biomes as a vector. Therefore, it was converted to raster using ArcGIS's 10.5 tool 'Polygon to Raster' with optional settings selected to match the coordinate system, extent, and cell size of the WI-III data. The rasterized biomes were corrected using QGIS Serval Plugin to make sure their boundaries were perfectly aligned. The resulting datum, which is used by this research, is presented in Figure 2.

2. Wallace Initiative climate database

The WI climate database includes global data of observed and projected climatic variables, used by the WI to create the future climate change scenarios; and of observed and projected bioclimatic variables, used by the WI to model species potential geographic distribution (current and future).

As the observed and projected climate datasets were used by the WI to derive the bioclimatic datasets used in chapter 3 of this thesis, they are presented first, and then the bioclimatic datasets are explained.

a. Observed climate dataset

The observed climate data for the period between 1950 and 2013 were provided by the Climate Research Unit of the University of East Anglia (CRU-UEA) to the Wallace Initiative. The period 1961-1990 was used by the WI as baseline to generate future climate change scenarios following (Osborn et al. 2016).

b. Projected climate dataset

Climate projections used in this research were generated for the Wallace Initiative using the Community Integrated Assessment System (CIAS) (Warren et al. 2008). In CIAS, the climate model MAGICC (Wigley and Raper 2001) was used to project future climate from observed climate data (CRU-UEA) under four representative concentration pathways (RCPs 2.6, 4.5, 6.0 and 8.5 (Moss et al. 2010)) simulating the patterns of 21 general circulation models (GCMs) from the Coupled Model

Intercomparison Project Phase 5 (CMIP5). Then, these results were downscaled by ClimGen (Osborn et al. 2016) to create 0.5° x 0.5° gridded future climate data. This pattern-scaled approach has been validated for a range of global warming levels and showed that “they perform best for global warming up to approximately 3.5ºC above pre-industrial, but beyond this the pattern diagnosed from only the RCP8.5 data clearly performs better” (Osborn et al. 2018). Afterwards, anomalies were applied to the WorldClim (Hijmans et al. 2005) 20 km observed database producing a finer resolution future climate dataset. An updated version of this future climate dataset was created by the UK Met Office Hadley Centre for the UK Government under the AVOID project (Bernie and Lowe 2014) and consisted of monthly projections for future climate changes derived from 21 patterns (corresponding to the 21 GCMs) under four RCPs that were later averaged in three thirty-year time-slices: 2011 to 2040, 2041 to 2070 and 2071 to 2100. To simultaneously investigate measures that would promote climate change mitigation and adaptation, six specific future global warming levels are used in this research, similarly to Warren et al. (2018a) and Warren et al. (2018b), as proxy for specific combinations of RCP (giving preference for the use of RCP 8.5 data that performed better in the pattern-scaling validation, as above mentioned), time-slice (represented by a middle decade) and percentile of the models’ runs:

- RCP8.5 2020s / 50th percentile – 1.5ºC above preindustrial levels – Paris Agreement lowest temperature target.
- RCP2.6 2080s / 50th percentile – 2.0ºC above preindustrial levels – Paris Agreement highest temperature target.
- RCP4.5 2080s / 50th percentile – 2.7ºC above preindustrial levels – low end of the NDCs.
- RCP6.0 2080s / 50th percentile – 3.2ºC above preindustrial levels – high end of the NDCs.
- RCP8.5 2080s / 50th percentile – 4.5ºC above preindustrial levels – business as usual scenario.
- RCP8.5 2080s / 90th percentile – 6.0ºC above preindustrial levels – pessimistic scenario.

c. Observed bioclimatic dataset – as used in chapter 3

Bioclimatic variables are biologically meaningful climate variables derived from monthly measurements of temperature and precipitation. The nineteen bioclimatic variables from WorldClim (WorldClim 2017) are often mentioned as the most broadly employed set of environmental data in species distribution modelling (SDM) approaches (Booth et al. 2014; Manzoor, Griffiths, and Lukac 2018).

Following the definition from WorldClim, the Wallace Initiative derived the ‘observed bioclimatic dataset’ with values for eighteen bioclimatic variables from the ‘observed climate dataset’ monthly measurements for temperature and precipitation of the period between 1950 and 2000. All bioclimatic variables were first calculated annually and then had their values per year averaged for the time-period under analysis.

d. Projected bioclimatic dataset – as used in chapter 3

Moreover, the projected bioclimatic variables used in the future species distribution modelling were generated by the WI from the monthly future climate projections for temperature and precipitation developed for the AVOID project (as explained in the ‘future climate dataset’ section of this chapter).

Finally, the eighteen bioclimatic variables generated by the WI were used during the biodiversity data cleaning process, and up to eight were used on the biodiversity models training part (Warren et al. 2013a). This same set of eight bioclimatic variables were analysed in chapter 3 of this thesis and are hereafter named as: (1) annual mean temperature – AMT, (2) temperature seasonality – TS, (3) maximum temperature of warmest month – MTW, (4) minimum temperature of coldest month – MTC, (5) annual total precipitation – ATP, (6) precipitation seasonality – PS, (7) precipitation of wettest quarter – PWQ, and (8) precipitation of driest quarter – PDQ.

3. Wallace Initiative biodiversity database

WI biodiversity database includes data on current and future individual species potential geographical distribution and datasets that summarises these data: current species richness dataset, future species remaining richness dataset, and future climatic refugia dataset. This section first explains the modelling approach employed by the WI and then how the three above-mentioned summary datasets were created.

a. Modelling approach

The WI projected globally the current and future potential geographic distribution of terrestrial biota, in a species by species approach, using species' observed occurrence data from the Global Biodiversity Information Facility (GBIF – an online repository), observed and future climate data derived from 21 GCMs (as previously explained in section 2 of this chapter) and the Maxent model (Phillips, Anderson, and Schapire 2006; Phillips and Dudík 2008) within the CIAS framework explained on the previous section of this chapter (Warren et al. 2013a).

Maxent is a species distribution model (SDM) tool that takes into consideration observed species' occurrence (presence data) and environmental information of sites across the study area irrespective of the presence/absence of the species (background data) to estimate the probability of that species presence over a region (Elith et al. 2011). Moreover, Maxent does not require absence data, i.e., data for places where the species was searched for but was not observed; or pseudo-absence data, i.e., data for places where the species has not been observed, whether or not sampling efforts occurred (definitions adapted from (Araújo et al. 2019)). And, therefore, Maxent can make use of data from museum and herbarium collections and online repositories such as the GBIF (Koshkina et al. 2017).

To create the WI database, Maxent was used to estimate the relationship between 8 bioclimatic variables and the observed presence data from GBIF of over 130,000 species to model the potential geographic distribution of these species globally (Warren et al. (2013a) with updates described on Warren et al. (2018a)). The WI has opted to use occurrence data from GBIF to include the highest number of species as possible (GBIF is the largest platform of primary biodiversity data, Luo et al. (2021) and see Table 2 and Table 3 for comparison of number of species used by WI and number of species in IUCN database for Brazil). Moreover, WI counted with expert knowledge to clean occurrence data (as explained below) and to "examine and validate SDM predictions", a good practice suggested by Fourcade (2016) to reduce potential bias embedded in the GBIF data. The WI opted to use GBIF occurrence data instead of IUCN Red List range maps because the latter are often generalised polygons (Foden et al. 2013) that do not mean that the species is distributed equally within that polygon or occurs everywhere within that polygon and "and thus may include areas not actually occupied by the species and for which climate projections differ" (Foden et al. 2013). Ultimately, if WI were to use IUCN Red List range maps, pseudo-occurrence records would need to be chosen to train the models, and this choice could affect the resulting predictions (Fourcade 2016).

The WI performed an extensive check on the species records provided by GBIF removing records that were not in land areas or had no location or that the location did not match the reported country of collection. Then, a Tukey outlier test was performed with the species records and 18 bioclimatic variables from WorldClim plus elevation to exclude records that were considered outliers for each species (Warren et al. 2013a).

After that, the WI only included in the training of Maxent models species that remained with at least 10 records. For species that remained with 10 to 40 records the WI used four bioclimatic variables (AMT, TS, ATR, and RS) to avoid models over-fitting, and used eight variables (AMT, TS, TWM, TCM, ATR, RWQ, RDQ, and RS) for species that remained with more than 40 records. Also, only a single record per ~10 km pixel was used in this training. Background data consisted of '10,000 random points from each of the eight (later updated to 11 – Warren et al. (2018a)) biogeographic realms (defined by Olson et al. (2001)) in which the species had been recorded'. Moreover, only species models with an Area under the Receiver Operating Characteristic (ROC) curve (AUC) above 0.7 were considered for the next steps (this threshold was tested and explained by Warren et al. (2013a)). The AUC is a performance measure that evaluates the discriminatory capacity between true positives and false positives of a modelling exercise and is commonly used to assess the accuracy of SDMs (Shabani, Kumar, and Ahmadi (2018) but see Jiménez-Valverde (2012) for limitations of the AUC usage). Finally, a species-specific threshold based on the shortest ROC distance to the upper-left corner of the ROC plot, one of the good approaches pinpointed by (Liu et al. 2005), was used to consider whether a species present in a grid cell (Warren et al. 2013a).

b. Current species richness dataset

Then the WI corrected the predicted current distributions by selecting only the climate suitable areas resulting from the Maxent models that were in the same biogeographic realm(s) in which the species had observed records and that were within 2,000 km from the edges of the observed range (Warren et al. 2013a). This step created the current potential geographic distribution of each species in the WI dataset and was later combined to create a summary of the current potential species richness for each class (Amphibia, Aves, Mammalia and Reptilia) and phylum (Plantae).

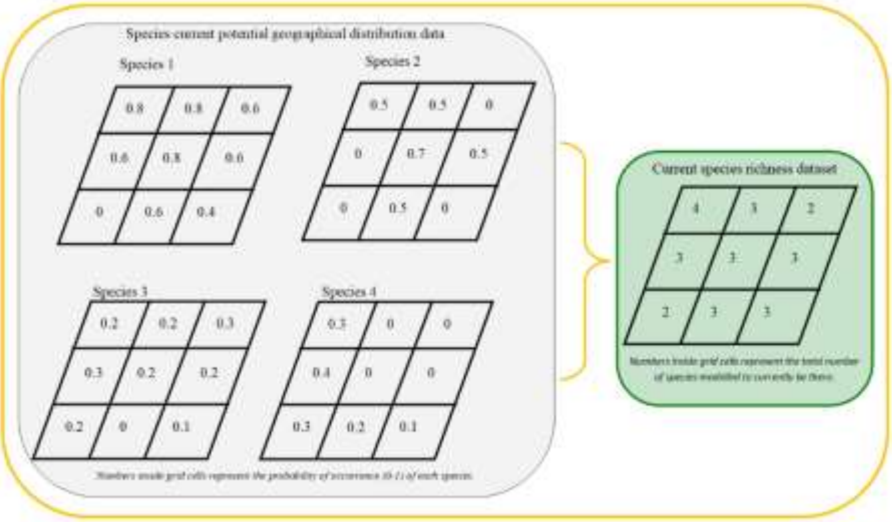


Figure 3: Schematic illustration of the process adopted by the WI to obtain the 'current species richness' dataset for each taxonomic group from the species current potential geographical distribution data.

Figure 3 shows how these summaries represent the total number of species of the taxonomic group under analysis that was modelled to currently be present in each pixel of the world land area. These summaries are hereinafter referred as the 'current species richness' dataset.

c. Future species remaining richness dataset – as used in chapter 4

Finally, the WI used the six projected climates (1.5, 2, 2.7, 3.2, 4.5 and 6^{o}C above pre-industrial levels – explained in section 2 of this chapter) and trained models to project the future geographical distribution of each species globally. Each future projection also considered three levels of GCMs agreement (10, 50 or 90% of the 21 GCMs) and three dispersal scenarios (no, realistic, and optimistic dispersal) (Warren et al. (2013a) with updates on Warren et al. (2018a)). In the no dispersal scenario, the future species distributions were restricted to their current climate suitable areas. On the other hand, in the realistic and optimistic dispersal scenarios, each species' future distribution could shift beyond the current distribution (but only on connecting land areas within its native biogeographic realm) to track the species' suitable climate, at rates considered either realistic or optimistic specific to each taxonomic group (Warren et al. 2013a).

Similar to the species current distributions, the future distributions were also combined to create a summary for each taxonomic group under each of the 54 possible combinations between future climate scenarios, GCMs agreement and dispersal scenarios. However, instead of showing the total number of species, the summaries for the future richness show the proportion (from 0 to 100%) of the current species richness of each pixel for which that pixel is projected to remain climatically suitable under one of the 54 above-mentioned combinations (i.e., WI created 54 global potential future richness summaries for each taxonomic group). These summaries are hereinafter referred as the 'future remaining species richness' dataset.

Wallace Initiative III

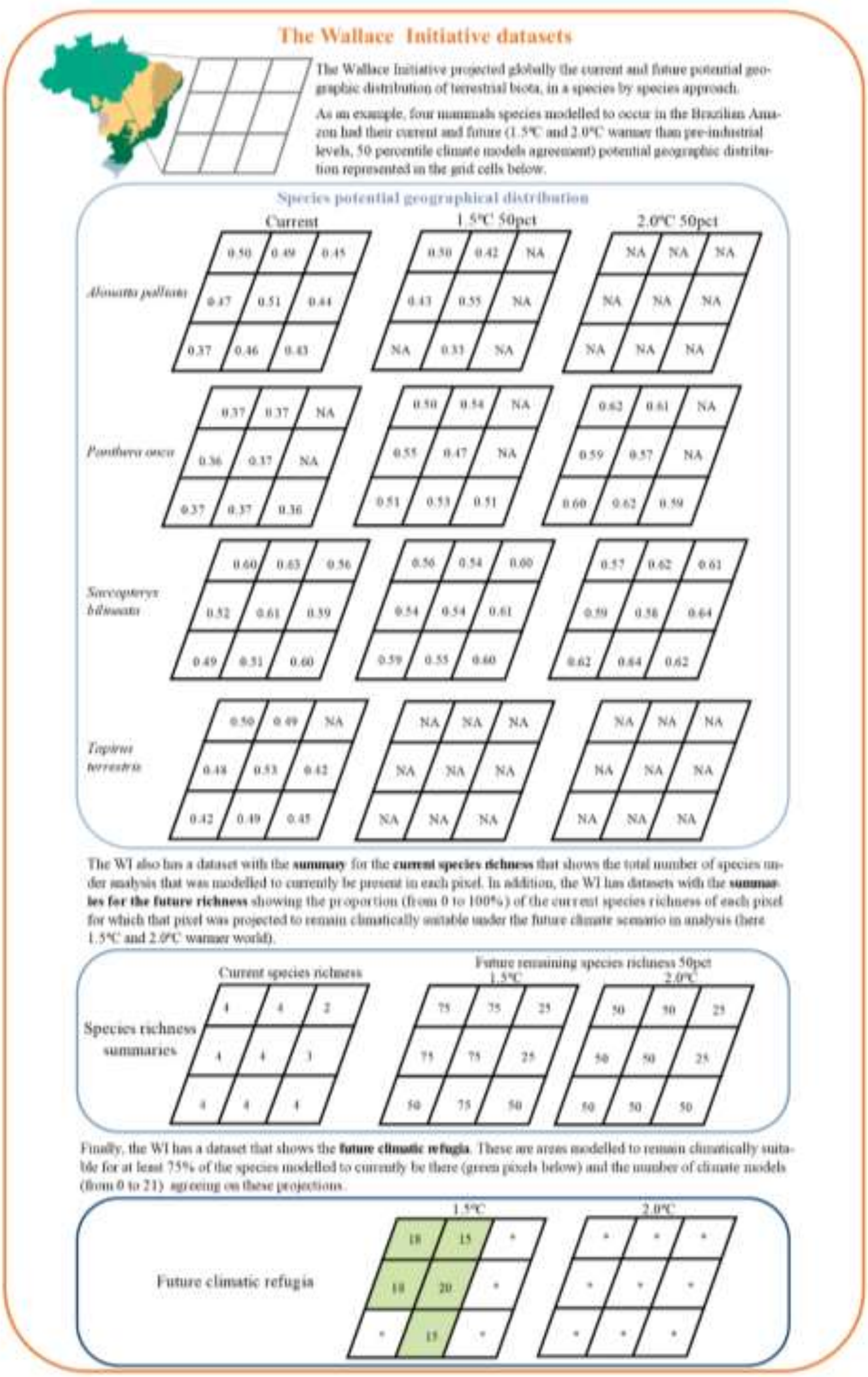
The third version of the WI (WI-III – described in Warren et al. (2018a)), produced 20 x 20km gridded datasets for global current species richness and projected future species richness under six global warming levels for the 21st century (1.5, 2, 2.7, 3.2, 4.5 and 6^{o}C – as explained in section 2 of this chapter). WI-III considered over 130,000 terrestrial species of fungi, plants, amphibians, mammals, birds, reptiles, and insects in the world (Warren et al. (2018a)). Moreover, the WI-III defined global future climatic refugia for terrestrial biota as areas that are projected to remain climatically suitable for at least 75% of the total number of species modelled to currently be there (Warren et al. (2018b). Warren et al. (2018b), considered that 'the threshold chosen is a compromise between identifying the highest quality refugia and identifying the most land that might still be available for conservation given land use constraints'. Thresholds lower than 75% would be more likely to imply that ecosystem structure and function would be lost, particularly if keystone species were lost. Thresholds higher than 75% would result in considerably smaller refugia that would constrain conservation options in landscapes were some conversion has already occurred. As the main aim/interest of this research is to explore the use of global future climatic refugia in conservation planning, this dataset is explained in detail in the following section.

d. Future climatic refugia dataset – as used in chapter 4

The WI future climatic refugia dataset shows for each taxonomic group the localities around the world that are projected to remain climatically suitable for at least 75% of the total number of species modelled to currently be in those pixels under one of the six future climate scenarios (1.5, 2, 2.7, 3.2, 4.5 and 6^{o}C above pre-industrial levels – described in the item ‘a’ of this chapter). This dataset also includes refugia projections that considered the realistic dispersal scenario, presenting therefore the localities projected to have the potential to act as refugia under a ‘no’ or a ‘realistic’ dispersal scenario.

However, unlike the ‘current species richness’ and ‘future remaining species richness’ datasets, the refugia dataset does not show the number of species or a proportion of the number of species projected to occur in each pixel. Instead, this dataset shows the number of the GCMs agreeing that each location is projected to have the potential to act as future climatic refugia for a specific taxonomic group under a specific future climate scenario. Figure 4 illustrates a simplified example with four species to show the differences of the three WI datasets previously explained (current species richness, future remaining species richness and future climatic refugia).

The refugia dataset was used by Warren et al. (2018b) to quantify the spatial extent of the 35 global Priority Places (PPs) consolidated by WWF that are projected to have the potential to act as future climatic refugia for terrestrial biodiversity. Although there is an overlap between three PPs (Amazon-Guiana, Cerrado and Atlantic Forests) and three Brazilian biomes (Amazon, Cerrado and Atlantic Forest), the boundaries of the Amazon-Guiana and Atlantic Forests go beyond the Brazilian border and the extent of the PP Cerrado is different and excludes the north portion of the Cerrado biome. Most importantly, the analysis performed by Warren et al. (2018b) calculated the proportion of these PPs that are projected to act as future refugia but did not present the refugia location within these PPs nor analysed their current land use and potential to be used in biodiversity conservation measures. Therefore, this research goes beyond the analyses developed on the study by Warren et al. (2018b) providing an in-depth assessment of the future climatic refugia for terrestrial biota in Brazil, that includes location and conservation potential of refugia in a fitting scale (biomes), to inform national conservation planning and national area-based conservation targets.



The Wallace Initiative projected globally the current and future potential geographic distribution of terrestrial biota, in a species by species approach.

As an example, four mammals species modelled to occur in the Brazilian Amazon had their current and future (1.5°C and 2.0°C warmer than pre-industrial levels, 50 percentile climate models agreement) potential geographic distribution represented in the grid cells below.

	Current			1.5°C 50pct			2.0°C 50pct		
Alouatta palliata	0.50	0.49	0.45	0.50	0.42	NA	NA	NA	NA
	0.47	0.51	0.44	0.43	0.55	NA	NA	NA	NA
	0.37	0.46	0.43	NA	0.33	NA	NA	NA	NA
Panthera onca	0.37	0.37	NA	0.50	0.54	NA	0.62	0.61	NA
	0.36	0.37	NA	0.55	0.47	NA	0.59	0.57	NA
	0.37	0.37	0.36	0.51	0.53	0.51	0.60	0.62	0.59
Saccopteryx bilineata	0.60	0.63	0.56	0.56	0.54	0.00	0.57	0.62	0.61
	0.52	0.61	0.59	0.54	0.54	0.61	0.59	0.58	0.64
	0.49	0.51	0.60	0.59	0.55	0.60	0.62	0.64	0.62
Tapirus terrestris	0.50	0.49	NA	NA	NA	NA	NA	NA	NA
	0.48	0.53	0.42	NA	NA	NA	NA	NA	NA
	0.42	0.49	0.45	NA	NA	NA	NA	NA	NA

The WI also has a dataset with the **summary** for the **current species richness** that shows the total number of species under analysis that was modelled to currently be present in each pixel. In addition, the WI has datasets with the **summaries for the future richness** showing the proportion (from 0 to 100%) of the current species richness of each pixel for which that pixel was projected to remain climatically suitable under the future climate scenario in analysis (here 1.5°C and 2.0°C warmer world).

	Current species richness			Future remaining species richness 50pct 1.5°C			2.0°C		
Species richness summaries	4	4	2	75	75	25	50	50	25
	4	4	3	75	75	25	50	50	25
	4	4	4	50	75	50	50	50	50

Finally, the WI has a dataset that shows the **future climatic refugia**. These are areas modelled to remain climatically suitable for at least 75% of the species modelled to currently be there (green pixels below) and the number of climate models (from 0 to 21) agreeing on these projections.

	1.5°C			2.0°C		
Future climatic refugia	🟩 18	🟩 15	*	*	*	*
	🟩 18	🟩 20	*	*	*	*
	*	🟩 15	*	*	*	*

Figure 4: Schematic illustration of the WI datasets used by this research: current species richness, future remaining species richness and future climatic refugia for terrestrial biota. Numbers on ‘current species richness’ represent the total number of species per pixel that were modelled to currently be there (current number of species). Numbers on ‘future remaining

species richness' represent the proportion (from 0 to 100%) of the current number of species that was modelled to remain in each pixel considering the future climate scenario of 1.5ºC or 2.0ºC warmer than pre-industrial levels. In the future climatic refugia, the pixels coloured in green represent the ones that met the threshold of remaining climatically suitable for at least 75% of the current number of species, i.e., the future climatic refugia.

4. Assessing applicability to Brazil

a. WI-III climate data for Brazil

The WI used global data of observed and projected climatic variables to create the future climate change scenarios. Observed data for the period 1961-1990 were provided by the Climate Research Unit of the University of East Anglia (CRU-UEA). Future climate projections made by the WI considered the period above mentioned as baseline and followed Osborn et al. (2016)(explained in details in section 2 of this chapter).

In order to validate the use of the WI 'projected bioclimatic dataset' to model species potential geographical ranges in Brazil, this section first briefly presents the WI 'observed climate dataset' (provided by CRU) and then compares the WI 'projected climate dataset' to the projections made by the IPCC on its fifth assessment report, that were derived from 42 GCMs (IPCC (2013b), including the 21 used by the WI).

Observed climate dataset

Koppen's climate classification is largely accepted and widely used in the literature to describe the world's climate regions (Peel, Finlayson, and McMahon 2007; Kottek et al. 2006). Following the Koppen's climate classification, Alvares et al. (2013) showed that most of the Brazilian land area is classified under tropical climate and has both the annual mean temperature and the temperature of the coldest month above 18ºC. Data on the observed temperature used by the WI also shows this pattern (Figure 5 and Figure 6 – note that the WI climate data is averaged per season). Moreover, the presence of a dry season in most part of the country was described in Alvares et al. (2013) and can also be observed in the WI observed data for precipitation (Figure 7). A detailed description of the current and projected climate for each Brazilian biome is presented in chapter 3.

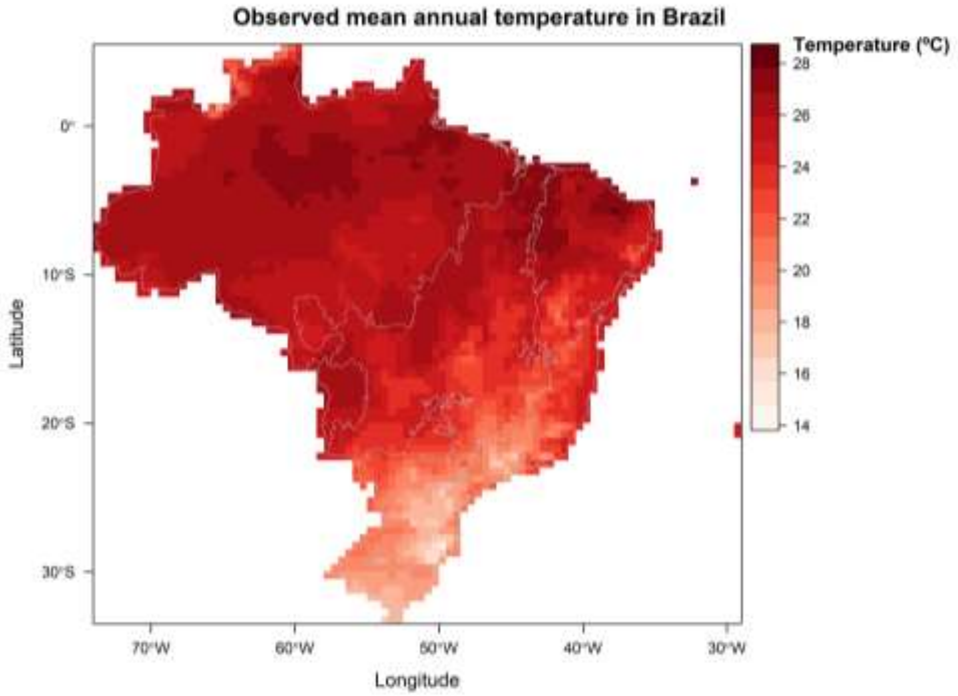


Figure 5: Observed mean annual temperatures in Brazil for the period between 1961 and 1990.

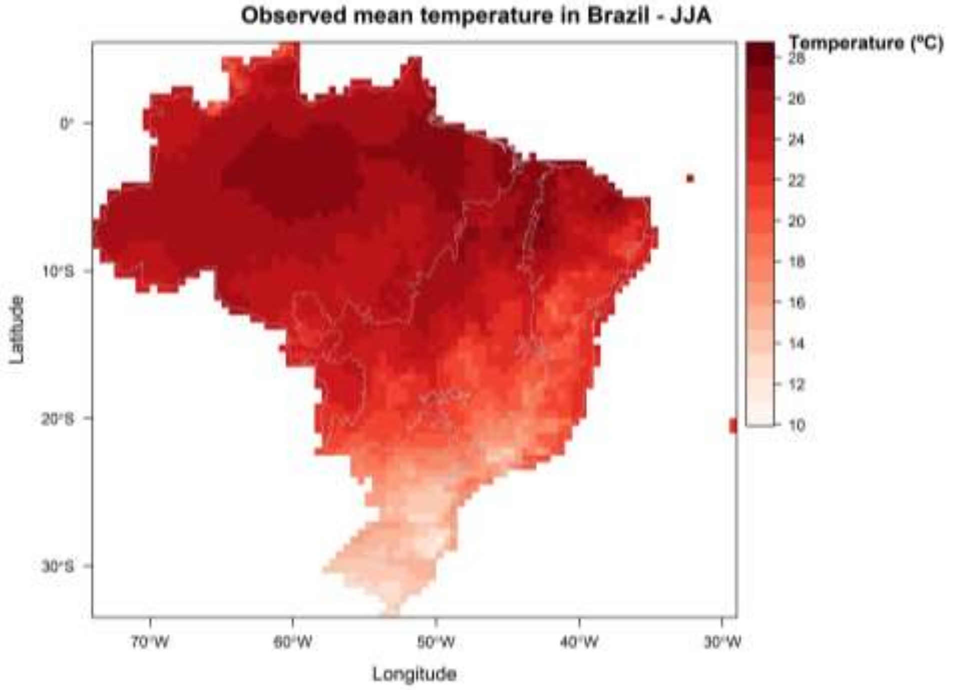


Figure 6: Observed mean temperature for winter season (June, July and August) in Brazil.

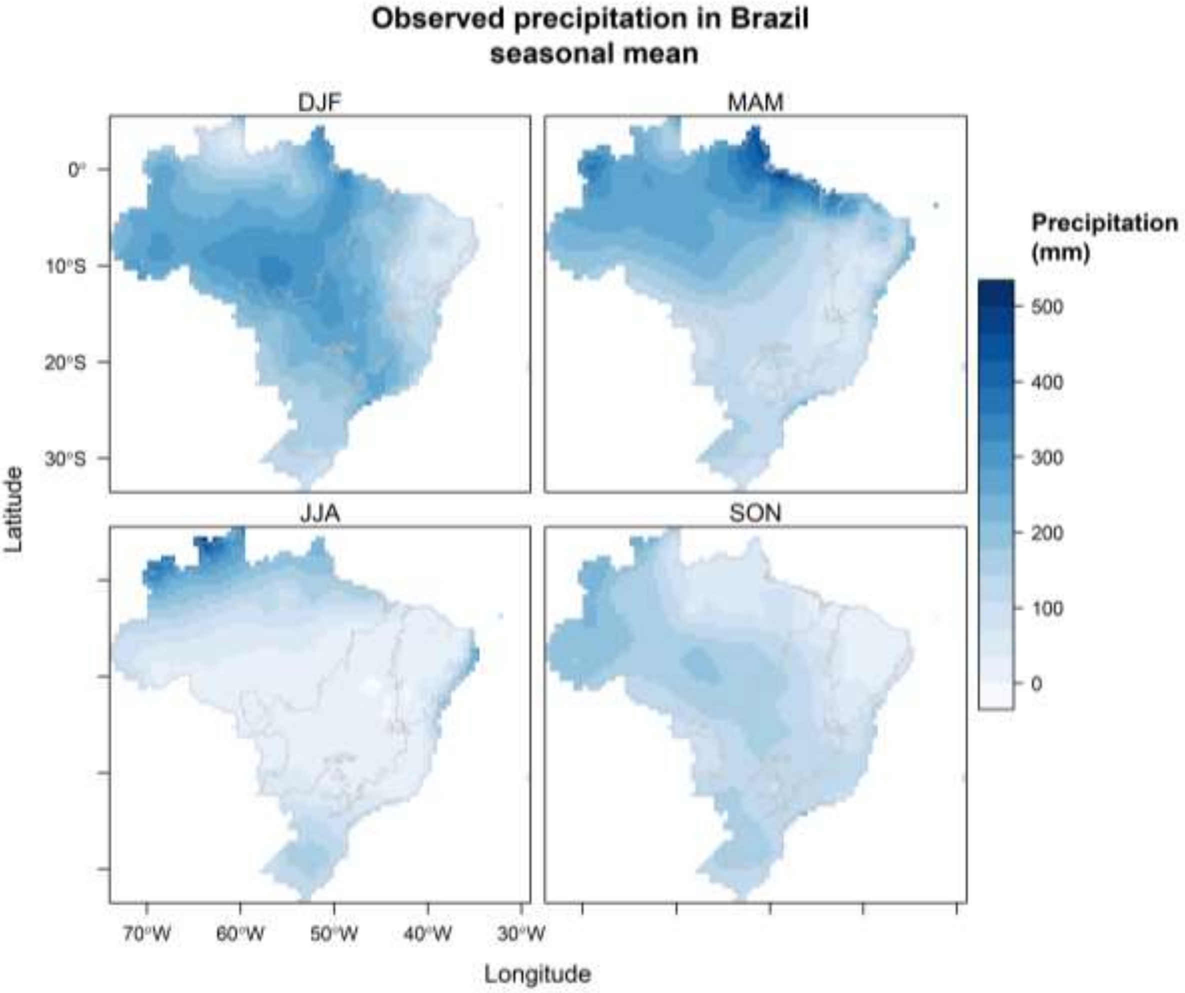


Figure 7: Seasonal mean of observed precipitation in Brazil for the period between 1961 and 1990. DJF – Summer months (December, January and February), MAM – Autumn months (March, April and May), JJA – Winter months (June, July and August), SON – Spring months (September, October and November).

Projected climate dataset

The pattern-scaled approach (used to create WI 'projected climate dataset' and the derived 'WI projected bioclimatic dataset' - used in chapter 3) has been validated by (Osborn et al. 2018) (as explained in chapter 2 section 2.b). A formal comparison between the WI 'projected climate dataset' for the Brazilian biomes and the plots and maps presented by the Intergovernmental Panel on Climate Change on its 5th Assessment Report – IPCC AR5 (IPCC 2013b) is scientifically improper because:

1. The IPCC used all 42 climate models of CMIP5, and the WI used a set of 21
2. The IPCC used 1986-2005 as baseline while the WI used 1961-1990

3. The WI climate data are downscaled to 20kmx20km, and the IPCC use 2.5º grid
4. The IPCC projected changes in precipitation for two halves of the year (October-March and April-September), while the WI projections were calculated seasonally (DJF, MAM, JJA, SON)
5. The IPCC used polygons that do not represent the Brazilian biomes and that go beyond the Brazilian boundaries.

b. WI-III biodiversity data for Brazil

The Wallace Initiative modelled the current and future potential geographical distribution of over 130,000 terrestrial species. As this modelling exercise was performed on a global scale, the number of species modelled to potentially be present (currently or in the future) in a specific region, biome, or country is not available in the database. Knowing the proportion of the Brazilian biota for which the WI has data on is important to validate the use of the WI datasets in analyses that aim to contribute to the planning of biodiversity conservation measures in Brazil. Therefore, to estimate the sample size that the number of species modelled by the WI to currently be in Brazil represents in relation to the country's biota richness, the current potential geographic distribution of each species in the WI-III database was analysed in this research.

First, the total number of species modelled by the WI-III to currently occur in Brazil and in each biome was calculated by counting the number of species which at least part of its current distribution was modelled to be in Brazil or in each biome (Table 1).

Table 1: Total number of species per studied taxonomic group modelled by the WI-III as currently suitable to be in Brazil and in its biomes.

	Amphibia	Aves	Mammalia	Plantae	Reptilia	Total
Brazil	**293**	**2432**	**367**	**19380**	**63**	**22535**
Amazon	267	2045	316	13242	58	15928
Atl. Forest	89	1381	239	10149	29	11887
Caatinga	44	1011	177	8081	15	9328
Cerrado	109	1589	290	11793	32	13813

Pampa	71	936	133	4277	21	5438
Pantanal	54	664	150	4307	12	5187

Following that, the number of threatened species according to the IUCN Red List data included the WI data for Brazil was assessed per biome and compared to the results using IUCN Red List data (Table 2).

Table 2: Comparison between a) number of species (total and threatened according to IUCN Red List data) included in the WI database for each Brazilian biome, and b) the number of species (total and threatened) included in the IUCN Red List database.

a. WI data	Amphibia		Aves		Mammalia		Reptilia		Plantae	
	Total	Threat.	Total	Threat.	Total	Threat.	Total	Threat.	Total	Threat.
Amazon	267	13	2045	77	316	15	58	1	13242	57
Atl. Forest	89	0	1381	52	239	10	29	0	10149	34
Caatinga	44	1	1011	30	177	3	15	0	8081	23
Cerrado	109	0	1589	56	290	13	32	0	11793	34
Pampa	71	0	936	25	133	6	21	0	4277	18
Pantanal	54	0	664	30	150	7	12	0	4307	17

b. IUCN data	Amphibia		Aves		Mammalia		Reptilia		Plantae	
	Total	Threat.	Total	Threat.	Total	Threat.	Total	Threat.	Total	Threat.
Amazon	362	10	1405	72	547	56	345	10	84	1
Atl. Forest	546	22	1030	103	391	57	291	15	158	28
Caatinga	130	3	719	54	244	24	197	12	114	15
Cerrado	288	3	1149	77	412	49	349	16	155	17
Pampa	79	4	596	29	177	17	89	7	71	15
Pantanal	70	0	627	25	180	9	160	2	69	2

Then, the WI-III total number of species modelled to currently be in Brazil was compared to the total number of species that are reported to currently occur in Brazil by the Taxonomic Catalogue of Brazilian Fauna (TCBF 2020), and to the number of species assessed by IUCN (IUCN 2020) accounted as occurring in Brazil (Table 3).

Table 3: Comparison between the number of species recorded in Brazil according to the Taxonomic Catalogue of Brazilian Fauna (BR – TCBF) and the number of species modelled by the WI-III as currently suitable to be in the country (WI-III), and the number of species assessed by IUCN with occurrence in Brazil (IUCN). The numbers in brackets show the proportion that the latter two datasets represents in relation to the BR-TCBF estimative. OBS: BR-TCBF and IUCN include non-terrestrial species and species with no geospatial data, while WI-III only considered terrestrial species with geospatial data.

Group	BR-TCBF (=100%)	WI-III (%)	IUCN (%)
Amphibia	1024	293 (27)	829 (81)
Aves	1924	2432 (126)	1805 (94)
Mammalia	722	367 (51)	676 (94)
Reptilia	763	63 (8)	492 (65)
Animalia	**4,180**	**3,155 (76)**	**3,802** (91)
Plantae	35,749	19,380 (54)	6,614 (19)
Total	**39,929**	**22,535 (56)**	**14,281 (36)**

In total the WI-III database includes a very good sample of the Brazilian biota (56% or 55% after correcting the number of birds' species to the maximum reported) and that is especially true for birds, mammals, and plants (the two latter taxa have at least 50% of the species known to occur in Brazil included in the WI-III database, and birds has more species in the WI-III database than the number reported for the country). The number of threatened species within Brazil included in the WI-III database can also be considered satisfactory for birds and plants (Table 2). However, reptilians and amphibians (total and threatened) within Brazil are underrepresented in the WI-III database and hence the results presented in this thesis for these taxonomic groups need to be interpreted with caution, as they could be reflecting the impacts of future climate change only on the most generic species.

The three main reasons for the difference between the number of species in the WI-III database and the species records from TCBF and IUCN shown in Tables 2 and 3 are: (i) only terrestrial species were considered by the WI-III, while TCBF and IUCN include aquatic species as well; (ii) only species that had good geospatial records could be included in the modelling exercise performed by the WI while TCBF and IUCN included species with poor or no geospatial records (e.g., endemic species that have a highly restricted range are listed in TCBF and IUCN but were not included in the WI); and iii) the use synonyms of the scientific name or inconsistencies in the taxonomies used by different organizations (as also noted by Jenkins et al. (2015)).

It is noteworthy that the WI-III data represents the potential current geographic distribution based on the species climatic suitability, not considering other factors that shape species’ geographical ranges such as habitats and biotic interactions (Pulliam 2000). Consequently, for a taxonomic group with very good and abundant geospatial records of its species in a region, such as birds in the tropics, the WI-III database could include a higher number of species than previously recorded and hence expected. For birds in Brazil, the WI-III projections showed that the country is climatically suitable for 2432 species, i.e., 508 species more than the total number of species listed on the TCBF. This higher number of species could also mean that these species might currently be in Brazil but have not been observed yet, or they were there in the past and were pushed away due to natural or anthropic actions (e.g., competition or land-use change).

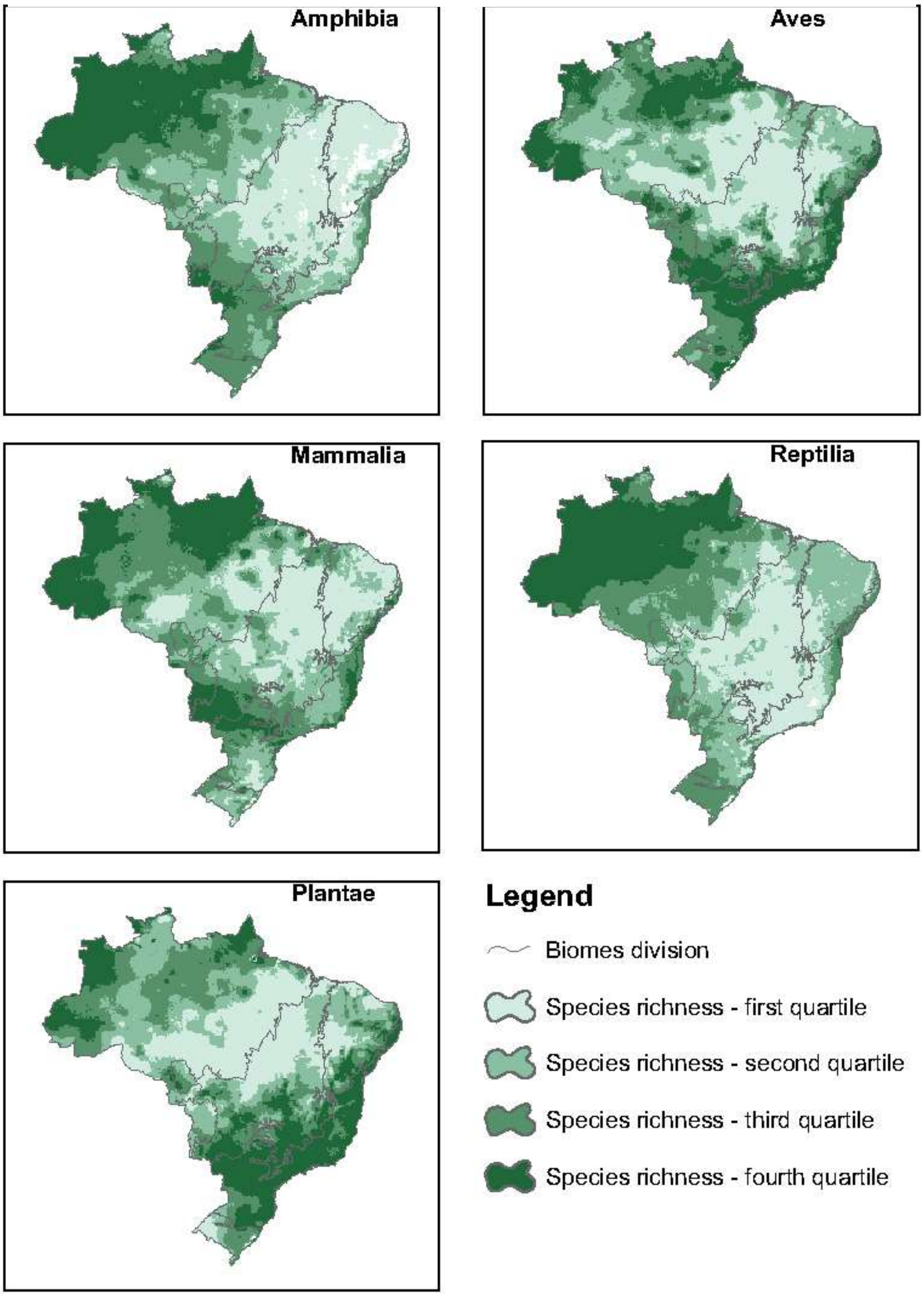
Furthermore, some species modelled to currently be in Brazil presented as the highest value of their probability of occurrence inside the country a very low (<0.05) or low (<0.25) value, which represented the lowest values of their global range (i.e., these species had higher probabilities in Central America or in other parts of South America). Probably these species potential current distribution included Brazil because not only the country has areas that are climatically suitable for them, but also these areas are in the same biogeographic realm and within the 2000 km buffer around the outermost occurrence records (buffer size used by WI during the modelling exercise – Warren et al. (2013a)).

For birds, for example, 98 species modelled to currently be found in Brazil by the WI-III had the highest probability of presence below 0.25. These bird species were mainly present in few pixels near the country’s northern border and accounted for the maximum of 25 species in the same pixel. When the threshold of the highest probability of presence was increased to 0.30 or 0.50, the number of bird species that met this criterion increased to 134 or 388, respectively. For the other taxa of animals, the maximum number of species that had highest probability of occurrence under 0.25 were very low both in total and in the same pixel: 8 in total and per pixel for amphibians; 5 in total and 1 per pixel for mammals; and 1 in total and per pixel for reptiles. This indicates that the WI-III database probably has included more bird species that are not reported to be there by TCBF than species of the other three taxa.

Although it might seem tempting to post-process the outputs of the WI modelling exercise creating a threshold for the probability of presence, this would not exclude commission errors. Any attempt to select just the species that WI modelled to be inside the country and were also recorded as currently there by an expert assessment (TCBF and IUCN) needs to be done species by species and cannot make use of generalisations. The example below with two bird species that presented the same probability of occurrence inside Brazil shows that a single value will not fit all cases and that avoiding commission errors might not be an easy (if feasible) task. The species *Vultur gryphus* had a maximum probability of occurrence of 0.25 in Brazil according to the WI-III current potential geographic distribution of this species. And although there is no observed record for this species in the country on the GBIF website (until the time of the writing of this thesis), it is listed in the TCBF's species list. On the other hand, the species *Tigrisoma mexicanum* also had a maximum probability of occurrence of 0.25 inside Brazil according to WI-III data, but neither GBIF website nor TCBF's species list reports that it occurs in the country. Applying a threshold on the probability of presence would put both species in the same category, thus not solving the issue.

Finally, it is important to emphasise that the WI-III database is the most comprehensive global database published so far in terms of number of species, taxa, future climate scenarios, GCMs, and dispersal scenarios; and that is specifically true for the data it has on Brazil. However, due to the scale in which the modelling was performed, it is not possible to identify microrefugia that might be especially relevant for the small PAs or OECMs in the mountainous parts of Brazil (e.g., Serra do Mar in Atlantic Forest) or to model impacts of future climate change on small ranged species (Akçakaya et al. 2006). This might affect particularly small-ranged amphibians that occur in the mountainous region of the Atlantic Forest (Jenkins et al. 2015) that probably are underrepresented in the WI. Nonetheless, maps of species richness derived from WI data (Figure 8) and the ones derived from IUCN data for Amphibia and Mammalia and from BirdLife data for Aves (Jenkins et al. 2015) show similar patterns of diversity for the country: two poles of really higher diversity in the south-east and north-west regions, corresponding to the Amazon and Atlantic Forest.

As a conclusion, the WI-III database is considered to have a highly satisfactory sample of species in Brazil and in its biomes that could act as surrogates in the design of area-based conservation planning that takes into consideration climate change impacts on the terrestrial biota of Brazil.



Current species richness per taxonomic group modelled by the WI

Figure 8: Current species richenss per taxonomic group (Amphibia, Aves, Mammalia, Reptilia, Plantae) modelled by the WI. Species richness is divided into quartiles to show areas modelled to currently have higher or lower number of species.

Chapter 3: Projections of bioclimatic variables for Brazil under future climate change

This chapter presents an analysis of future projected changes in the bioclimatic variables that are used on the modelling exercises that aim at identifying locations that will remain climatically suitable for species despite future changes in climate (i.e., refugia), and how these changes vary across the Brazilian biomes.

1. Introduction

The IPCC's fifth assessment report (IPCC 2013b)showed that each part of the world will experience different kinds and magnitudes of future climate change. Therefore, these climatic changes are and will continue to impact biodiversity differently throughout the world (IPCC 2014).

One way to assess future climate change impacts on biodiversity is through the changes that the projected future climate could cause on species potential geographical distributions created with the aid of species distribution models (SDMs) (Araújo and Peterson 2012). The Wallace Initiative (WI) has used this approach to model current and future potential geographical ranges of more than 130,000 terrestrial species globally (explained in detail in chapter 2 sections 2 and 3).

An SDM uses a set of bioclimatic variables to create a relationship between current species occurrence and observed climate data (explained in detail in chapter 2 section 2.a), based on the assumption that these two factors are at equilibrium (Elith et al. 2011). These bioclimatic variables are derived from monthly climatic variables to create variables that better represent biota's climatic needs and constraints (Ramírez-Villegas and Bueno-Cabrera 2009).

Although several studies have used SDMs and bioclimatic variables to project species potential geographic ranges (e.g., (Svenning, Normand, and Kageyama 2008; Rodrigues et al. 2015; Borges and Loyola 2020)), few have shown graphically or spatially the projected changes for these variables in their study areas (e.g., Ferro et al. (2014), Román-Palacios and Wiens (2020)).

It is believed that in the changes of the Quaternary, biota retreated to and persisted in refugia (Keppel et al. 2012; Gavin et al. 2014). Identifying and scrutinizing locations that could act as future climatic refugia for terrestrial biota is especially important for Brazil, a megadiverse country, home not only of the biggest part of the Amazon, but also of the largest tropical wetland (Pantanal), and of the richest Savannah (Cerrado).

To start this investigation of potential future refugia in Brazil, this chapter first unveils an analysis of the projected future changes in the bioclimatic variables used by the WI on its SDMs. Following that, this chapter presents four discussion topics: (section 6.a) how these projections could help understanding the robustness of SDMs exercises, (section 6.b) how these projections could help understanding and analysing the WI refugia data, (section 6.c) possible speculations regarding the impact of climate change on biota, and (section 6.d) limitations and caveats of using bioclimatic variables for SDMs exercises. Finally, key messages are presented highlighting the main projected changes in the bioclimatic variables throughout Brazil, and how projections presented in this chapter could help the identification and interpretation of areas identified as potential future climatic refugia in this country.

2. Objective

To analyse the future projected changes for eight bioclimatic variables derived from 21 General Circulation Models under six future levels of global warming for Brazil, and of how these changes vary across the Brazilian biomes.

3. Data

a. Data on bioclimatic variables

This research uses data from the WI ‘observed / projected bioclimatic datasets’ (explained in detail in chapter 2 section ‘WI climate database’).

The ‘observed bioclimatic dataset’ was generated by the WI from the monthly observations of temperature and precipitation of the period between 1950 and 2000. In a similar way, the projected dataset derived from monthly climate projections for temperature and precipitation made by 21 GCMs under six future climate change scenarios: 1.5, 2.0, 2.7, 3.2, 4.5 and 6.0ºC above pre-industrial levels (as explained in detail on section ‘projected climate dataset’ of chapter 2).

The same set of eight bioclimatic variables used by the WI for the species distribution modelling exercise is analysed in this research: (1) annual mean temperature – AMT, (2) temperature seasonality – TS, (3) maximum temperature of warmest month – MTW, (4) minimum temperature of coldest month – MTC, (5) annual total precipitation – ATP, (6) precipitation seasonality – PS, (7) precipitation of wettest quarter – PWQ, and (8) precipitation of driest quarter – PDQ. Apart from the precipitation seasonality, which is expressed as a percentage (%), all precipitation related variables are expressed in millimetres (mm), and all temperature related variables are expressed in degrees Celsius (ºC).

4. Post-processing

The data on observed and projected bioclimatic variables are post processed in four steps: (a) data extraction, (b) calculation of projected change, (c) calculation of GCMs consistency, and (d) calculation of averages, described in detail in the next subsections.

a. Data extraction

The data on observed and projected bioclimatic variables for Brazil were extracted from the WI ‘observed / projected bioclimatic datasets’. The data on observed bioclimatic variables extracted for Brazil are used to create the country maps of the observed values for each bioclimatic variable.

b. Calculation of projected change

Future projections for the set of eight bioclimatic variables were generated by the WI using 21 GCMs under six scenarios of future climate change and are part of the ‘projected bioclimatic dataset’. This research first calculates the ‘projected change’ as the difference between the projected absolute values and the observed values of each bioclimatic variable for each grid cell in Brazil under each scenario of future climate change.

c. Calculation of GCMs consistency

Following Hirabayashi et al. (2013), the GCMs consistency is calculated as the number of climate models (among the 21 considered) that agree on the direction of change projected for each bioclimatic variable in each land grid cell, i.e., the number of GCMs that have projected for each land grid cell an increase or decrease of a specific bioclimatic variable in relation to its observed value.

Levels of GCMs consistency

The GCMs consistency on the direction of projected change for each variable is then mapped for Brazil. This research adopts four levels of consistency based on the number of GCMs that agree on the direction of the projected change:

- No consistency: below 12 GCMs agree on the direction of change.
- Low: between 12 and 14 GCMs agree on the direction of change.
- Moderate: between 15 and 17 GCMs.
- High: between 18 and 21 GCMs.

d. Calculation of averages

All calculations were performed using the package ‘dplyr’ of the software R.

Observed mean per biome

The observed bioclimatic data for Brazil are used to calculate the ‘observed mean per biome’ for each combination of bioclimatic variable and biome, resulting on the average observed value of each variable over all land grid cells that fell within each biome’s boundaries.

Projected change

The calculated values of ‘projected change’ (i.e., the anomalies in relation to the observed values) for each variable for each future climate scenario are averaged in three different ways:

- Over the grid cells within each biome, across all GCMs – resulting in the multi-model mean projection of change for each biome under each future climate scenario (represented by the black line on the line plots).

- Over the grid cells within each biome, but separately for each GCM – resulting in each GCM mean projection of change for each biome under each future climate scenario (represented by the coloured lines on the line plots).
- Across all GCMs for each land grid cell – resulting in the multi-model mean projection of change for each grid cell under each future climate scenario (represented on the maps).

e. Note about plots and maps

Plots and maps were created using packages ‘raster’, ‘RColorBrewer’, and either ‘ggplot2’ (for plots) or ‘rasterVis’ (for maps) of the software R.

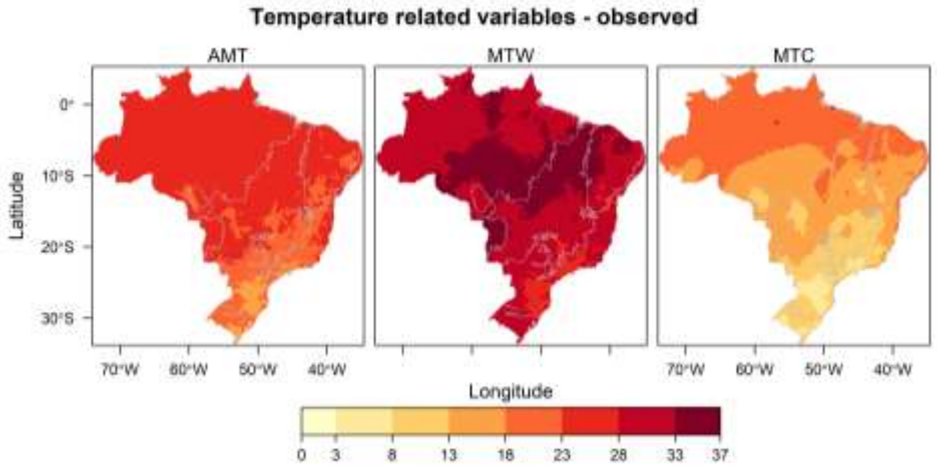
5. Analysis of bioclimatic variables

Although the bioclimatic variables were not created to classify climate regions, their observed values should give a general notion of the climate in the studied area. With that in mind, this section first presents the WI data on observed bioclimatic variables for Brazil and its biomes (Table 4, Figure 9, and Figure 10). Then, the changes projected for these variables by 21 GCMs under six scenarios of future climate change are shown in a series of plots and maps. Following that, this section presents a summary per Brazilian biome that shows: (a) how the WI observed values for the bioclimatic variables corroborate with the climate zones described in the literature for each biome (Alvares et al. 2013), (b) the projected changes throughout the country, and (c) the level of GCMs consistency on the direction of these projected changes (Figure 11 to Figure 32 represent items ‘b’ and ‘c’).

a. Observed values

Table 4: Observed values averaged per Brazilian biome for the studied set of eight bioclimatic variables derived from observed monthly data of the period between 1950 and 2000. Variables acronyms represent: AMT (annual mean temperature), TS (temperature seasonality), MTW (maximum temperature of the warmest month), MTC (minimum temperature of the coldest month), ATP (annual total precipitation), PS (precipitation seasonality), PWQ (precipitation of the wettest quarter), and PDQ (precipitation of the driest quarter). Values are expressed in degrees Celsius (ºC) for all temperature related variables, in millimiters (mm) for ATP, PWQ and PDQ, and in percent (%) for PS.

Biome/Var	AMT	TS	MTW	MTC	ATP	PS	PWQ	PDQ
	mean	mean	mean	mean	mean	mean	mean	mean
Amazon	25.9	0.51	32.8	19.2	2237	0.58	936	195
Atl. Forest	20.6	2.41	29.1	11.1	1419	0.48	561	190
Caatinga	24.6	1.21	32.0	17.2	761	0.89	421	26.1
Cerrado	24.2	1.25	32.2	14.8	1442	0.81	717	38.8
Pampa	18.8	3.86	30.2	8.8	1462	0.12	410	319
Pantanal	25.9	2.04	33.9	16.0	1276	0.65	585	80.5



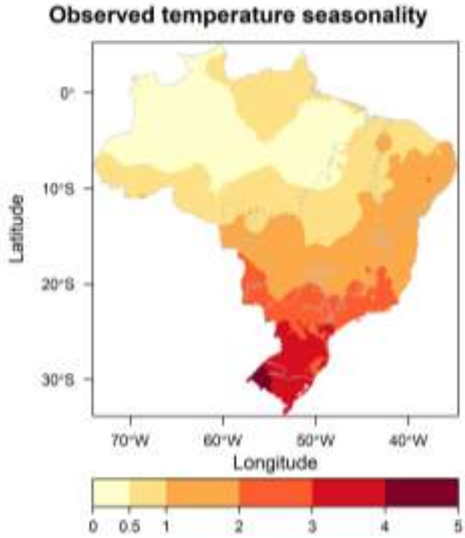
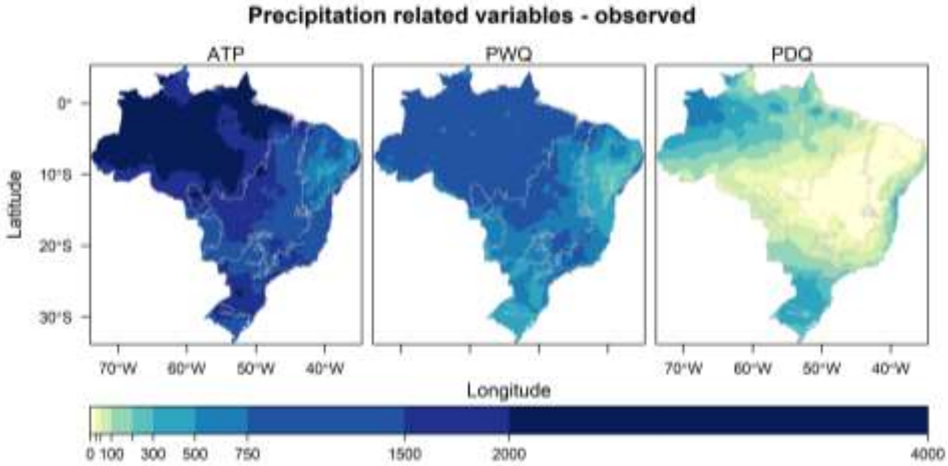


Figure 9: Calculated values from observed monthly data of the period between 1950 and 2000 for four bioclimatic variables related to temperature. Above for AMT (annual mean temperature), MTW (maximum temperature of the warmest month), and MTC (minimum temperature of the coldest month). And on the left for temperature seasonality (TS). Colour scale show values in degrees Celsius (ºC).



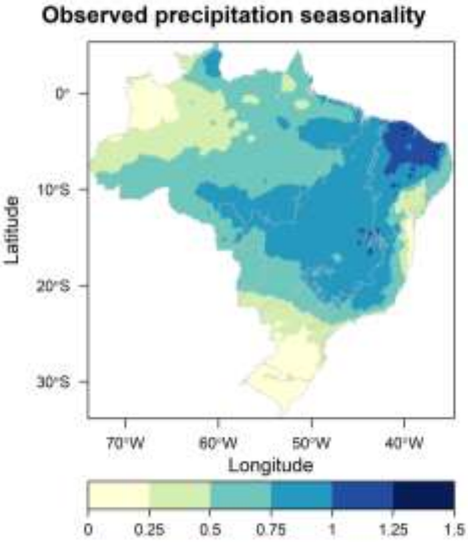


Figure 10: Calculated values from observed monthly data of the period between 1950 and 2000 for four bioclimatic variables related to precipitation. Above for annual total precipitation (ATP), precipitation on the wettest quarter (PWQ), and precipitation on the driest quarter (PDQ) with colour scale showing values in milimeters of rainfall. And on the left for precipitation seasonality (PS) with colour scale showing values as percentage

b. Future projected changes

Annual mean temperature (AMT)

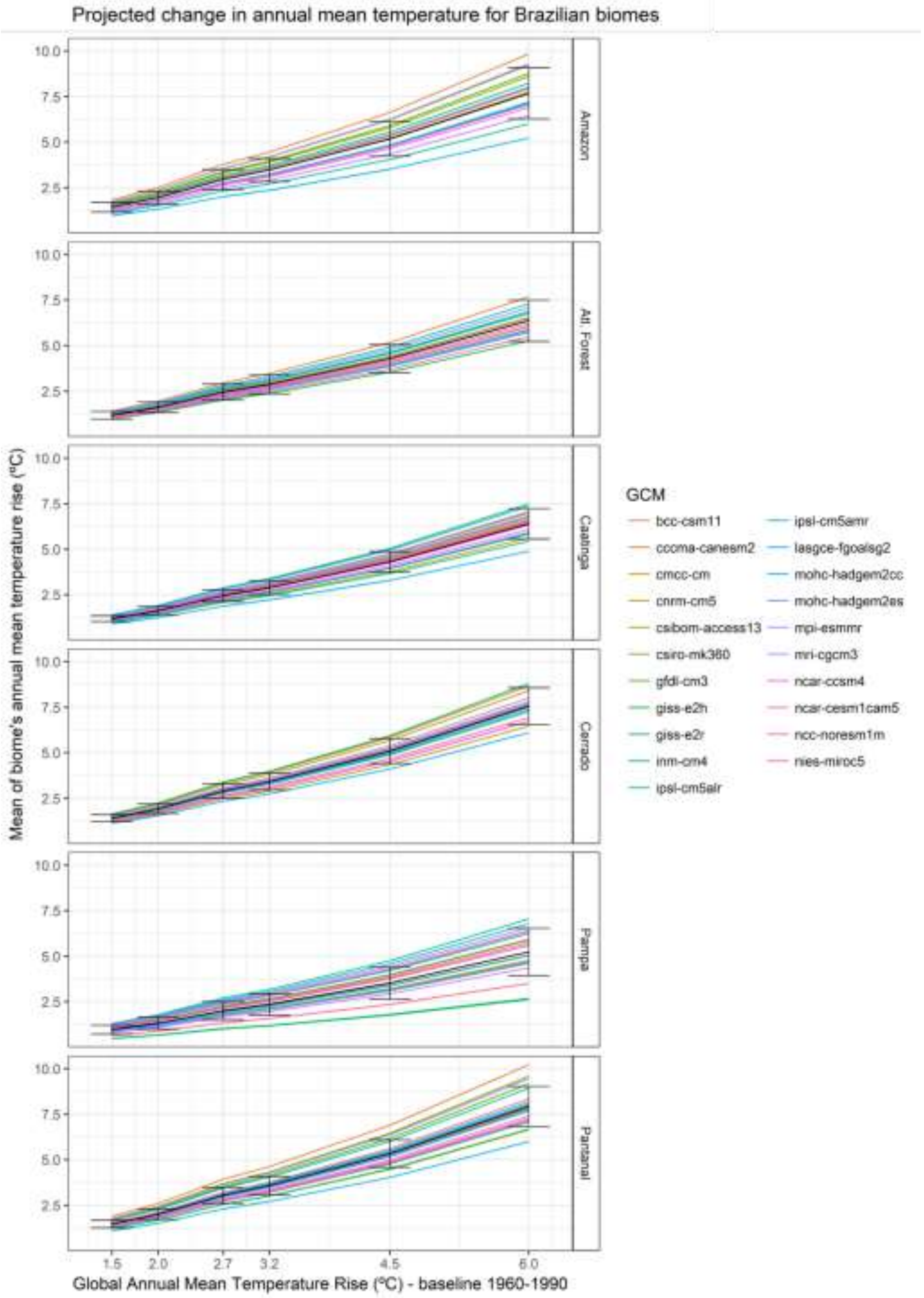


Figure 11: Projected change of annual mean temperature for each Brazilian biome forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

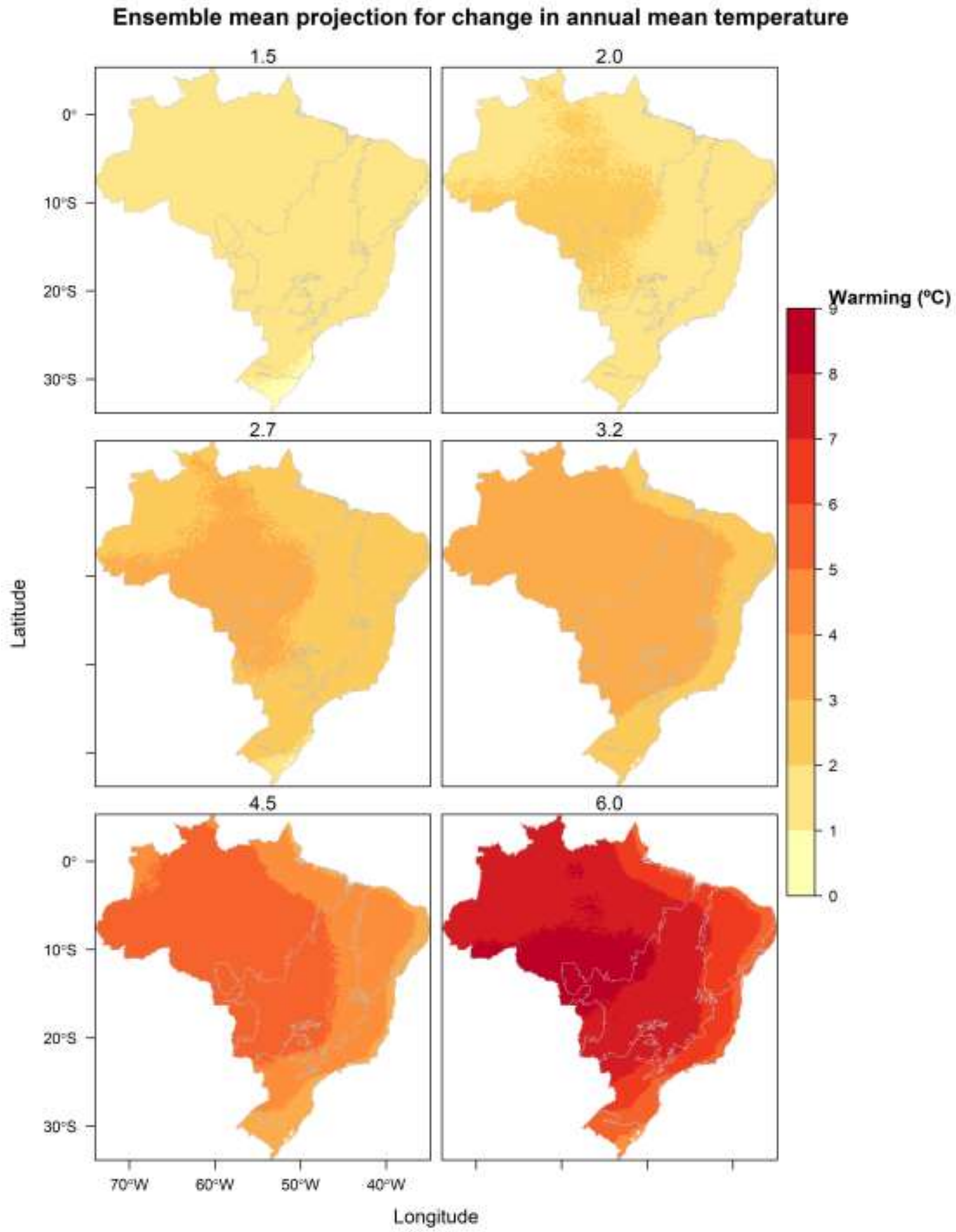


Figure 12: GCMs ensemble mean projection of annual mean temperature change relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

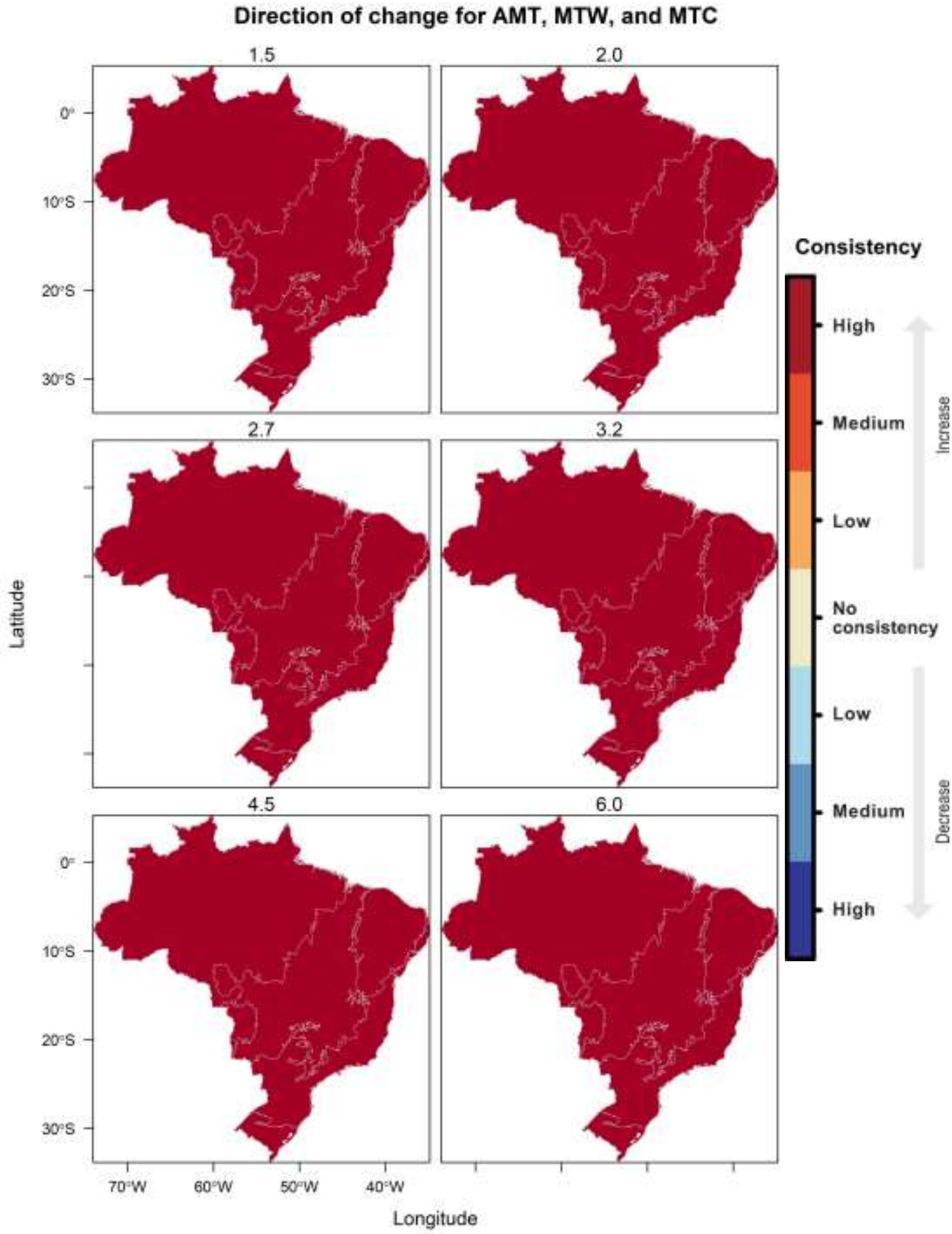


Figure 13: GCMs consistency on the direction of change (i.e., number of models projecting change in the same direction) of annual mean temperature (AMT), maximum temparature of warmest month (MTW), and minimum temperature of the coldest month (MTC). GCMs consistency represented by colour scale following Hirabayashi et al. 2013.

Maximum temperature of warmest month (MTW)

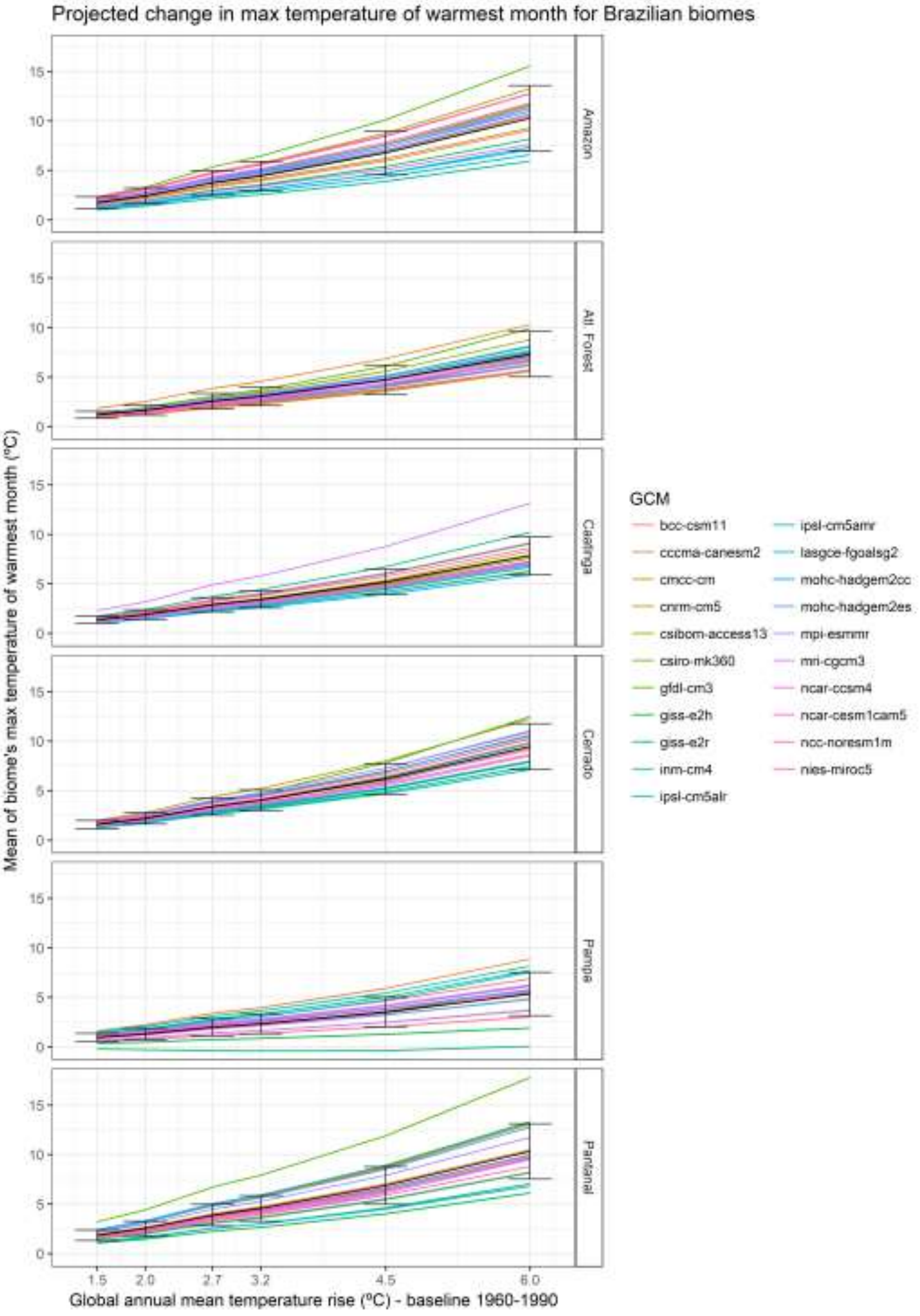


Figure 14: Projected change of maximum temperature of the warmest month for each Brazilian biome forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

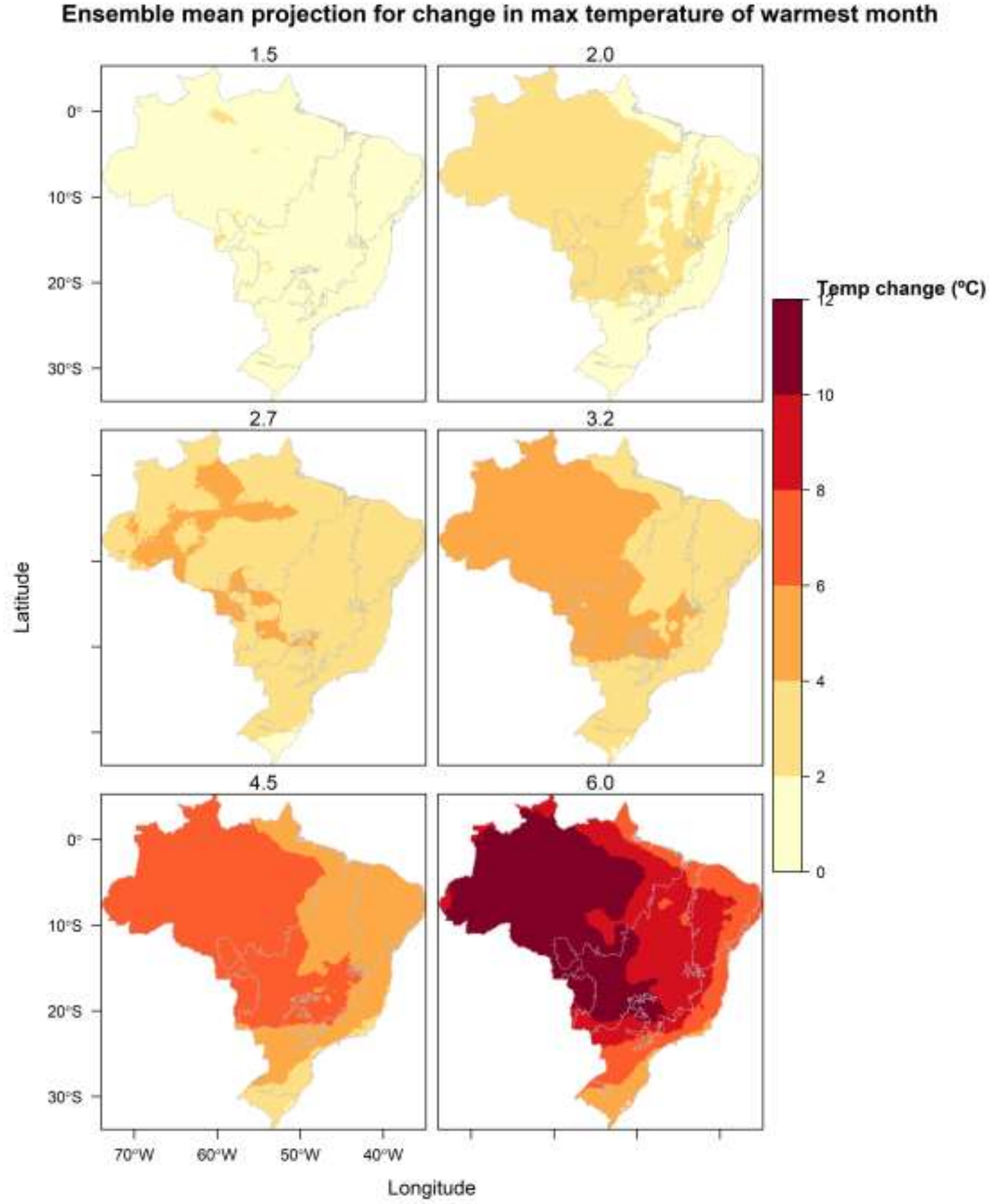


Figure 15: GCMs ensemble mean projection of change inmaximum temperature of the warmest month relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

Minimum temperature of coldest month (MTC)

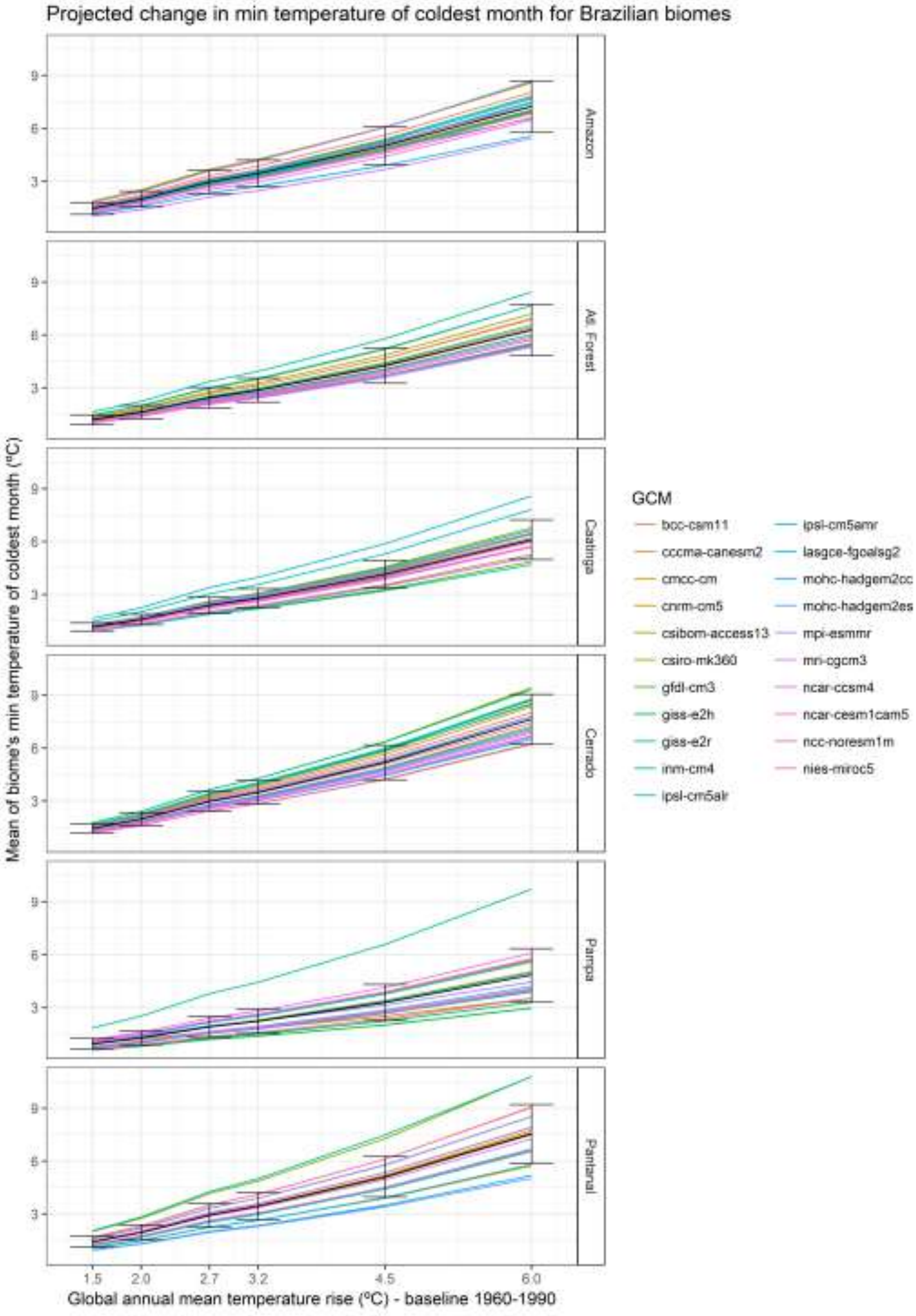


Figure 16: Projected change of minimum temperature of the coldest month for each Brazilian biome forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

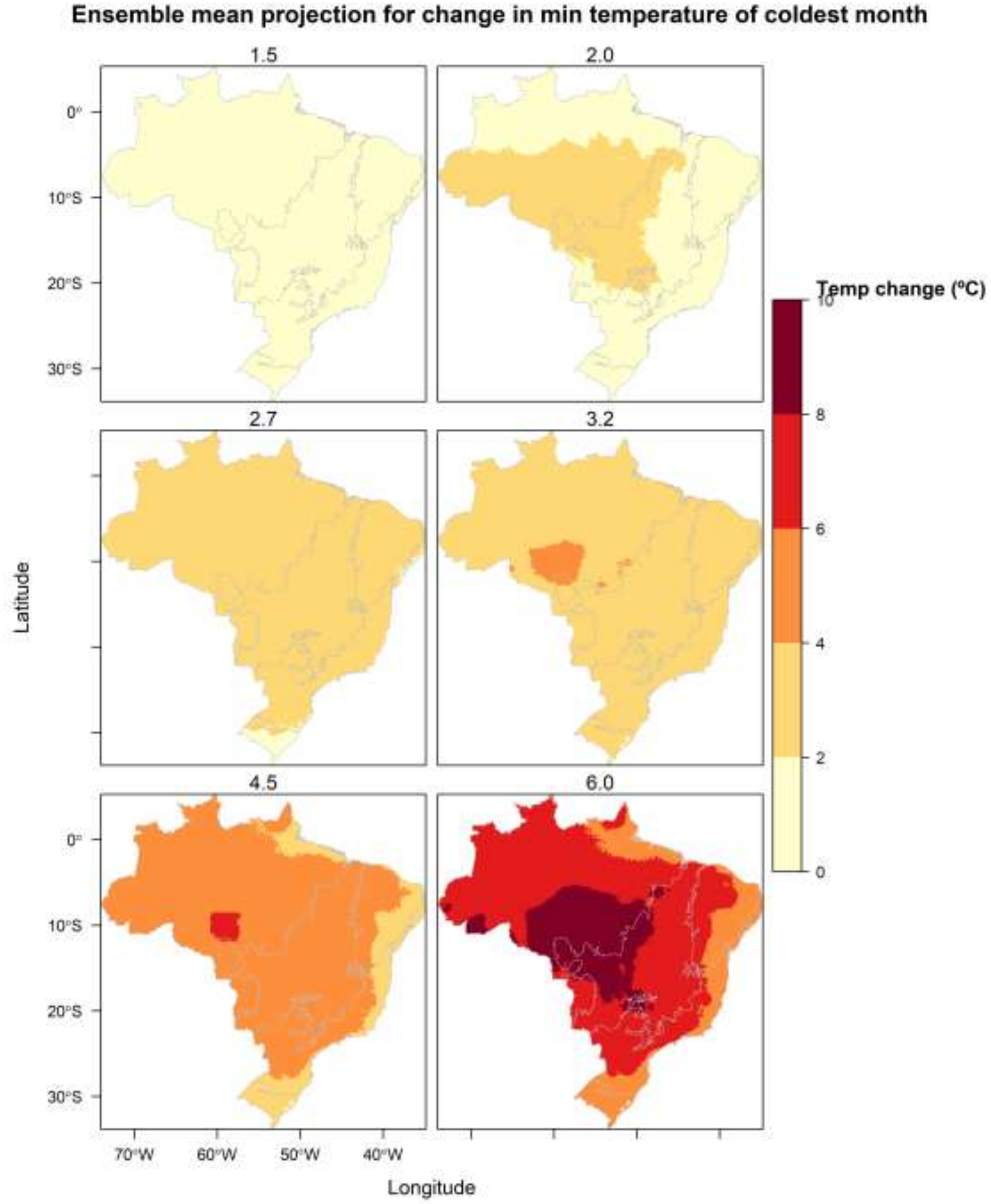


Figure 17: GCMs ensemble mean projection of change inminimum temperature of the coldest change relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

Temperature seasonality (TS)

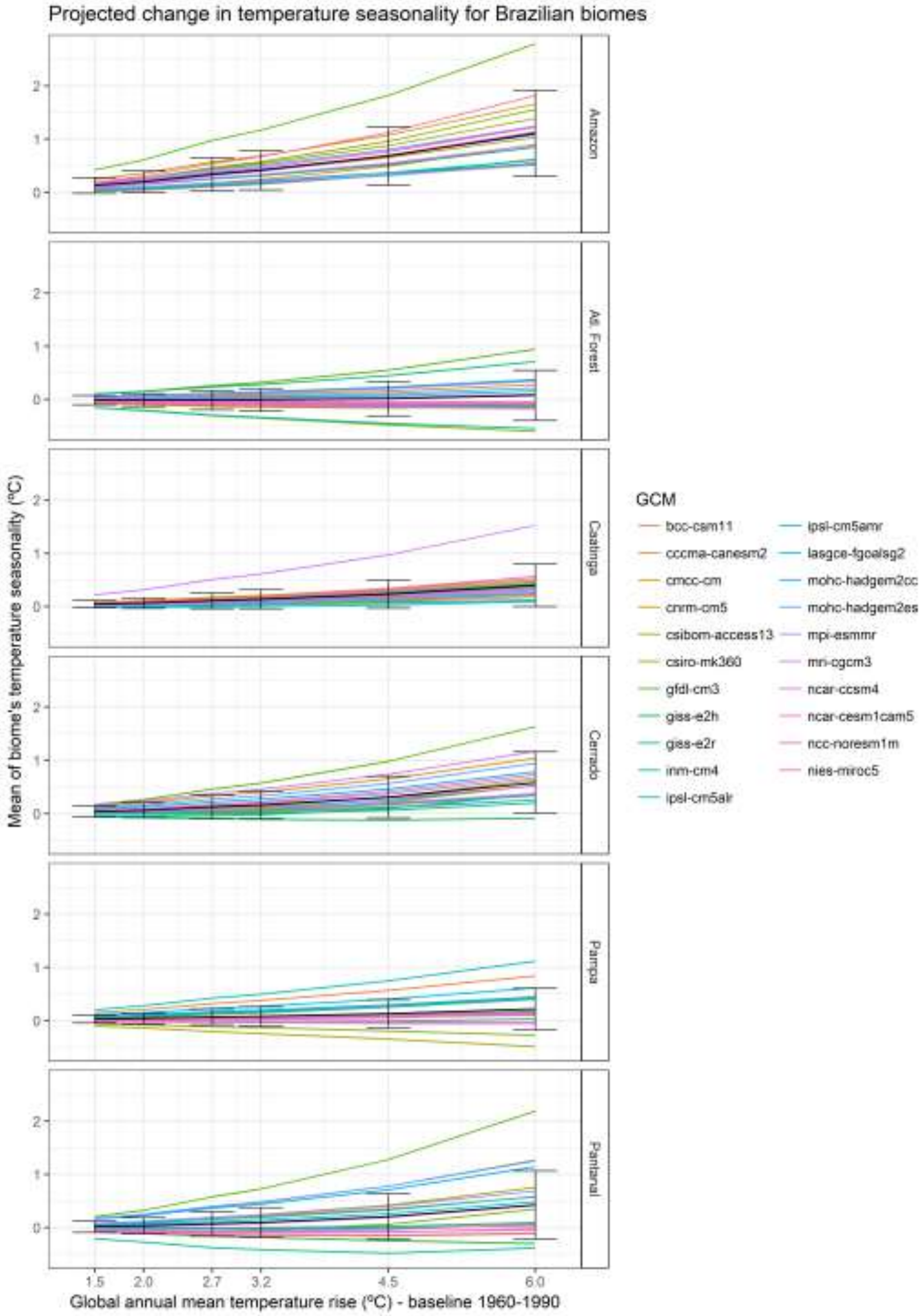


Figure 18: Projected change of temperature seasonality for each Brazilian biome forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

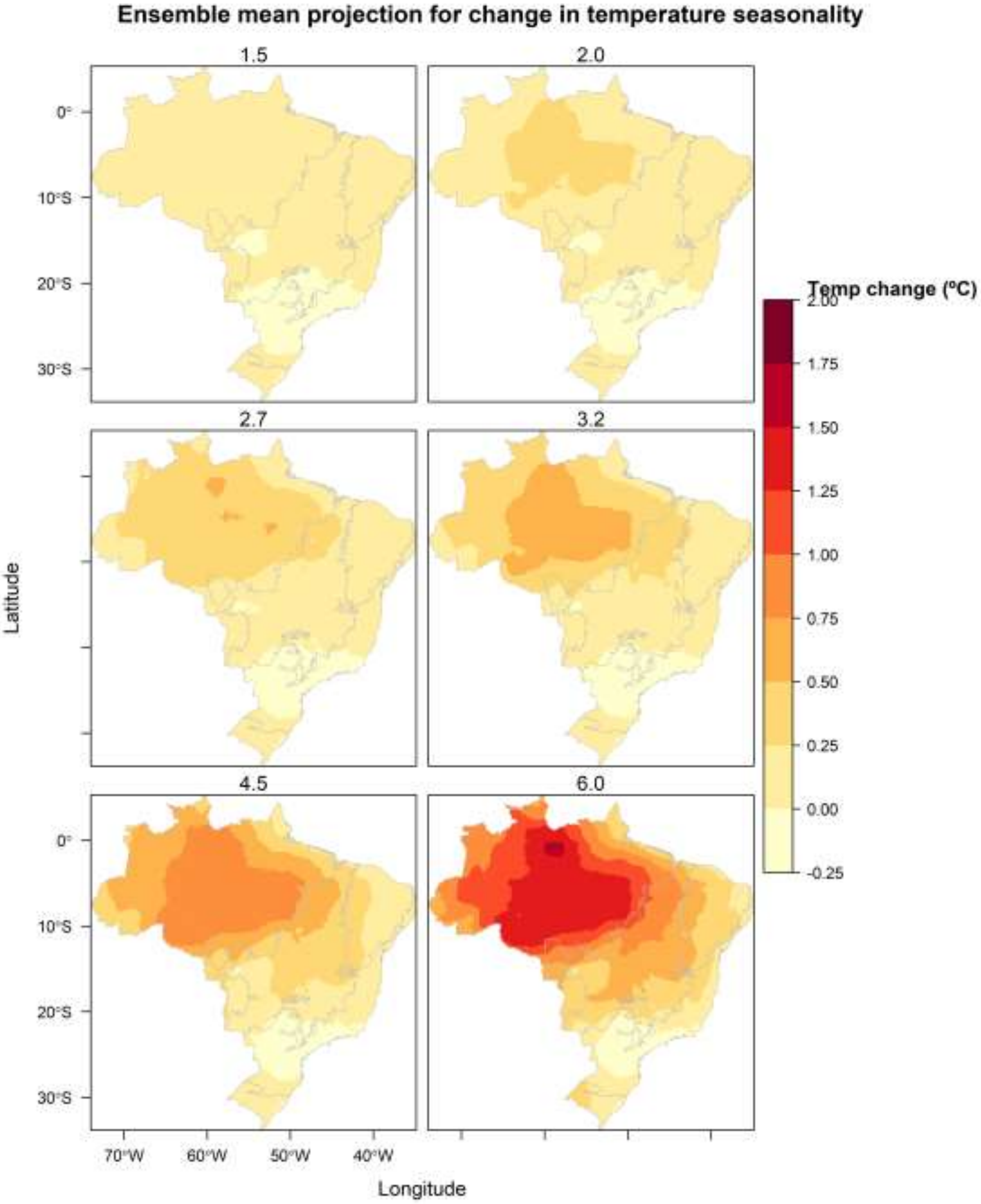


Figure 19: GCMs ensemble mean projection of change intemperature seasonality relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

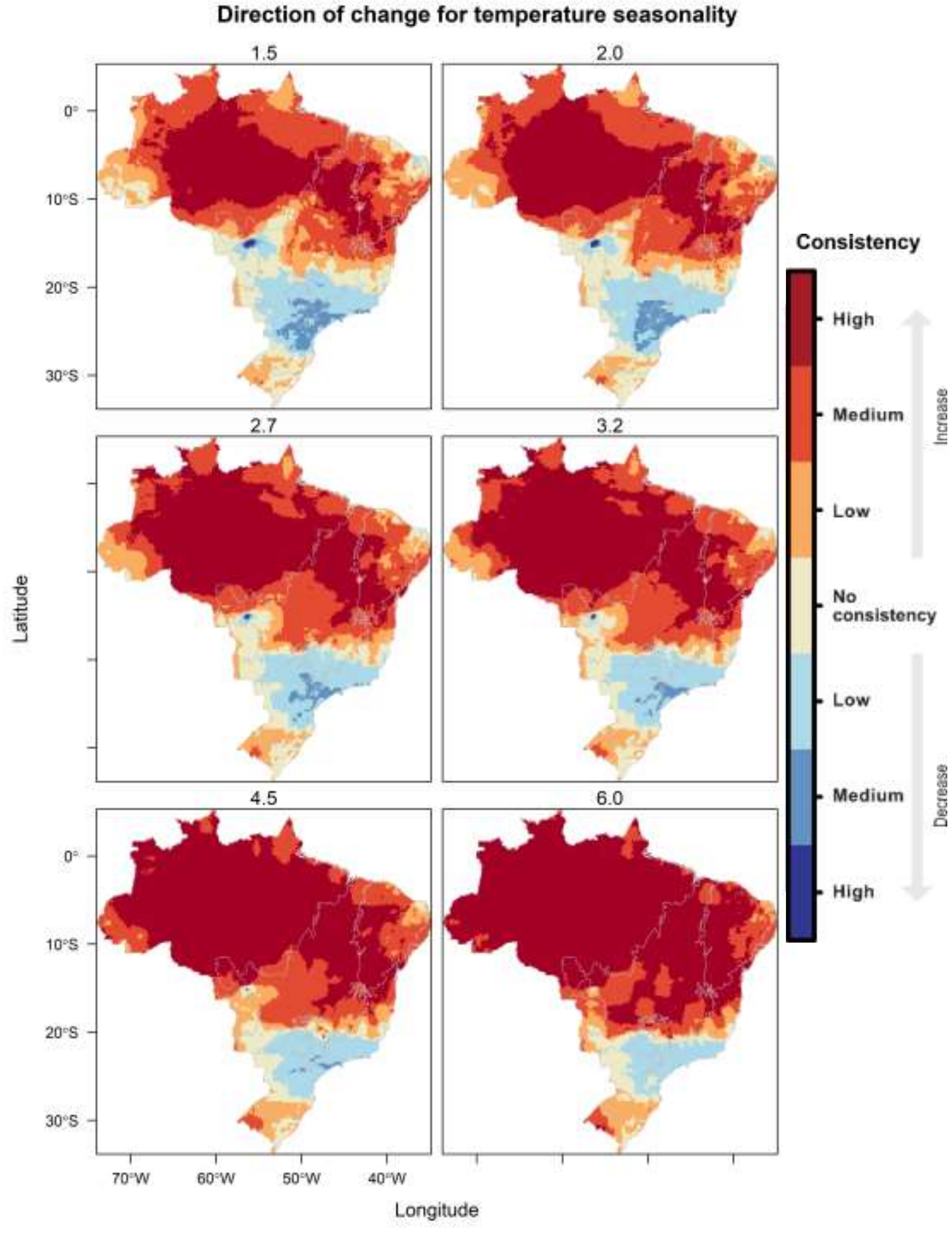


Figure 20: GCMs consistency on the direction of change (i.e., number of models projecting change in the same direction) of temperature seasonality (TS). GCMs consistency represented by colour scale following Hirabayashi et al. 2013.

Annual total precipitation (ATP)

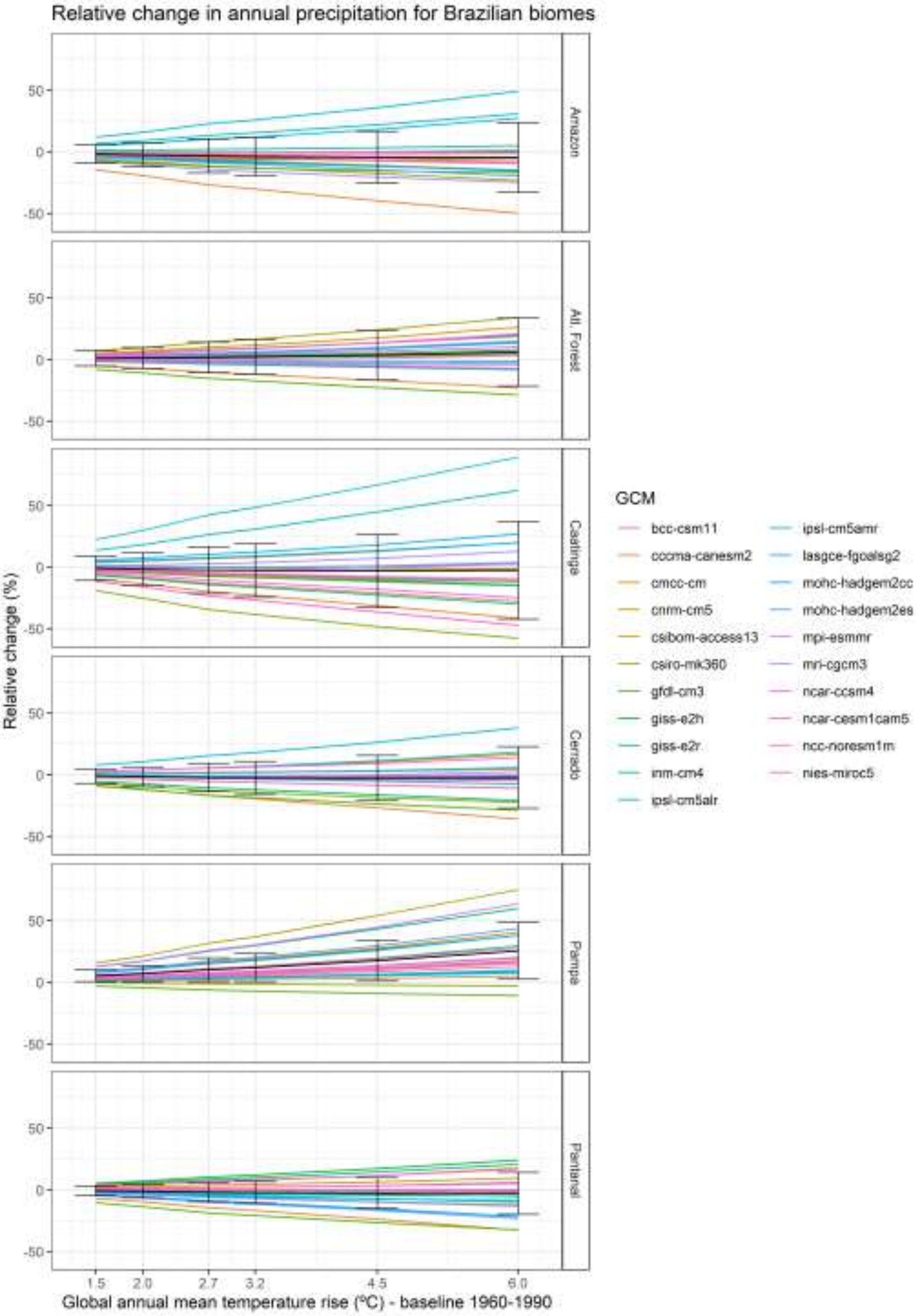


Figure 21: Projected change of annual total precipitation for each Brazilian biome in relation to observed mean values forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

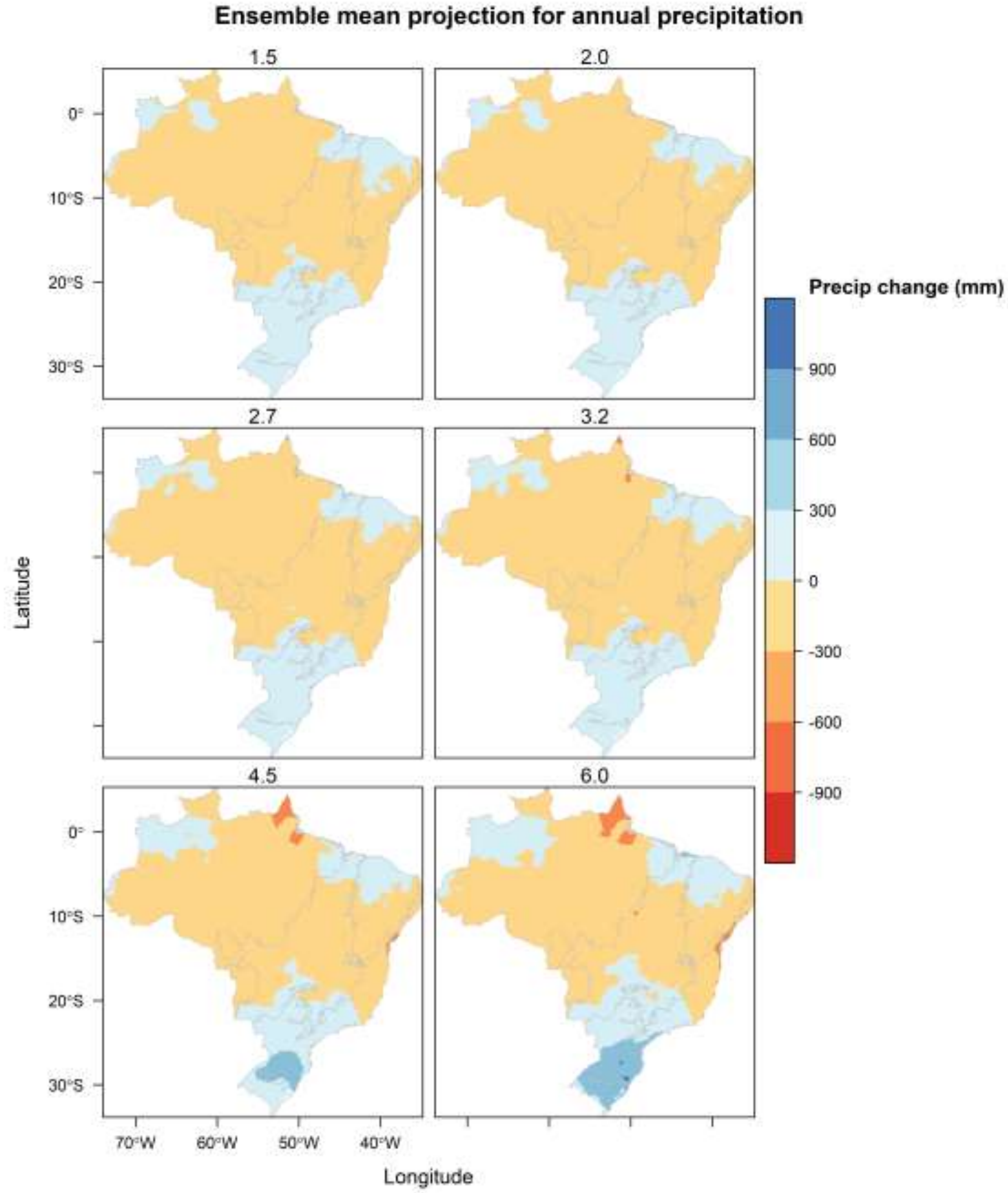


Figure 22: GCMs ensemble mean projection of change inannual total precipitaion relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

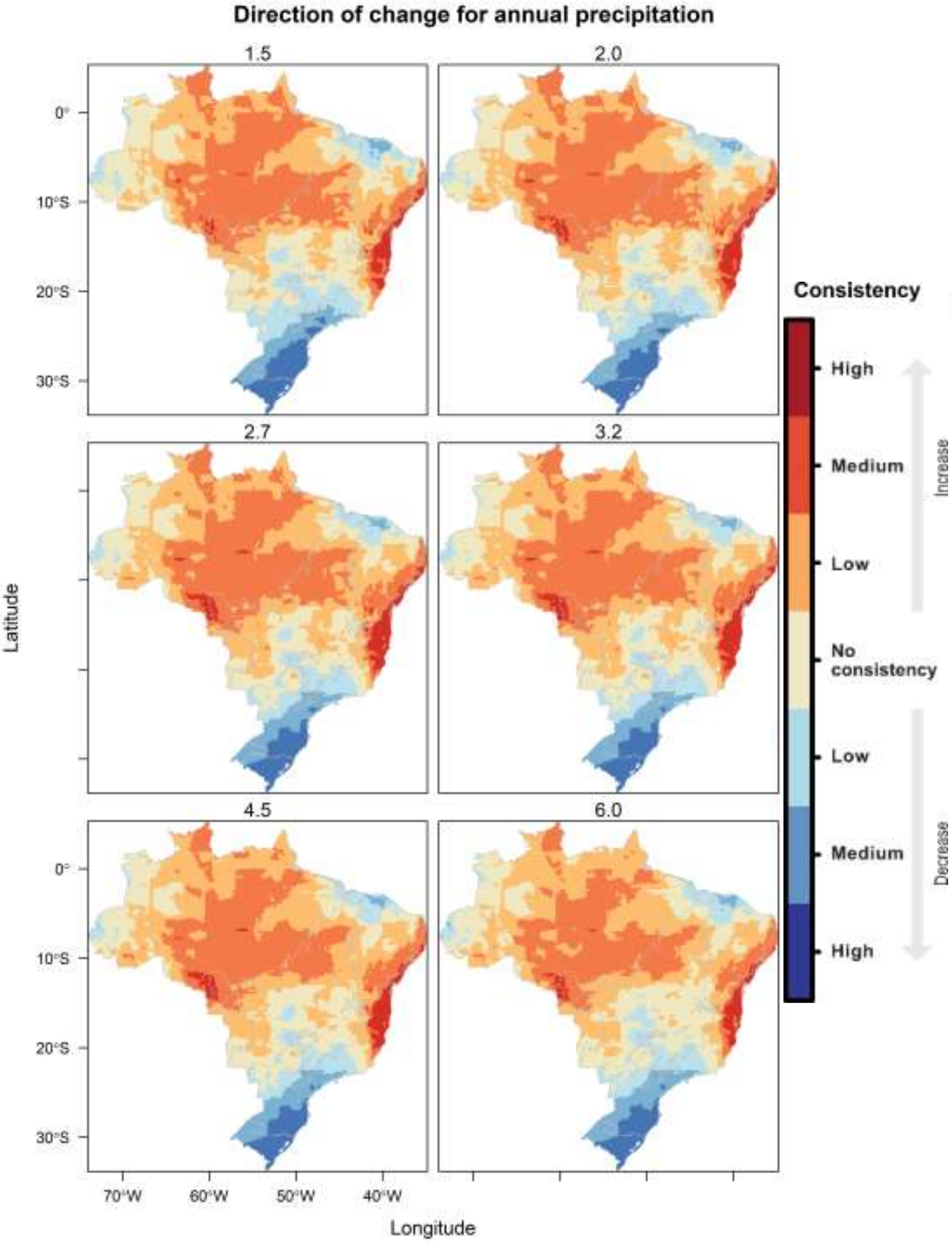


Figure 23: GCMs consistency on the direction of change (i.e., number of models projecting change in the same direction) of annual total precipitation (ATP). GCMs consistency represented by colour scale following Hirabayashi et al. 2013.

Precipitation seasonality (PS)

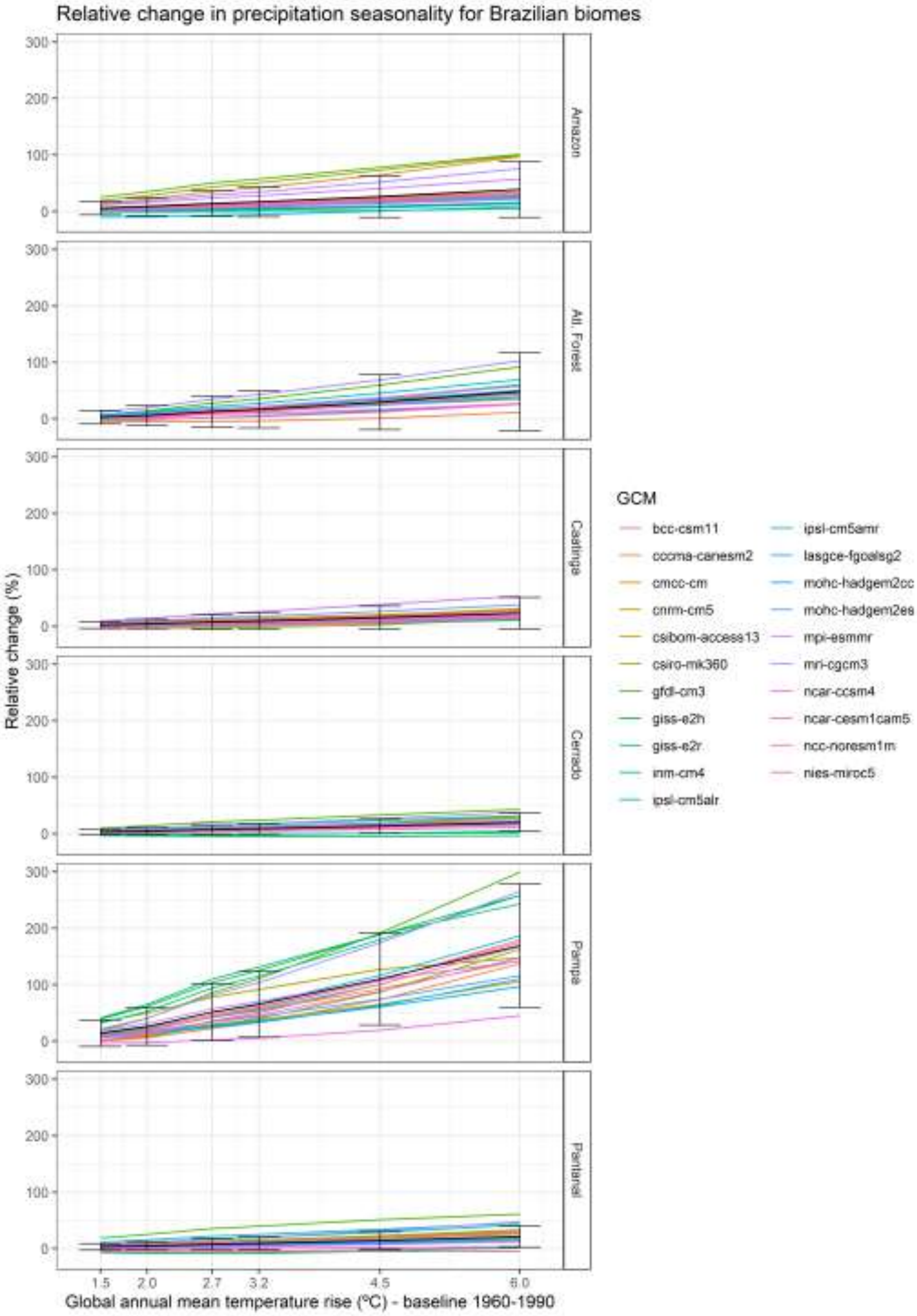


Figure 24: Projected change of precipitation seasonality for each Brazilian biome in relation to observed mean values forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

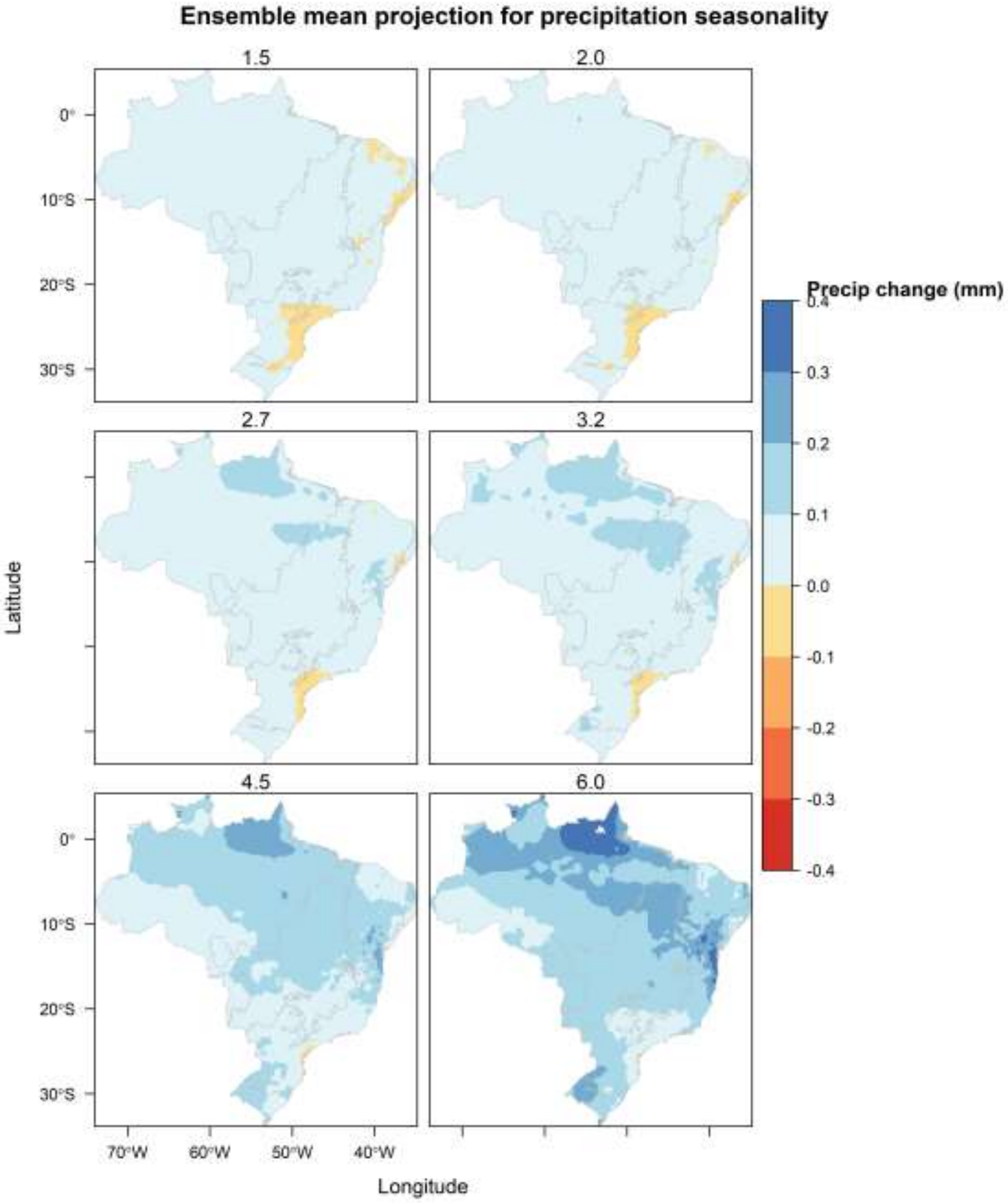


Figure 25: GCMs ensemble mean projection of change inprecipitation seasonality relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

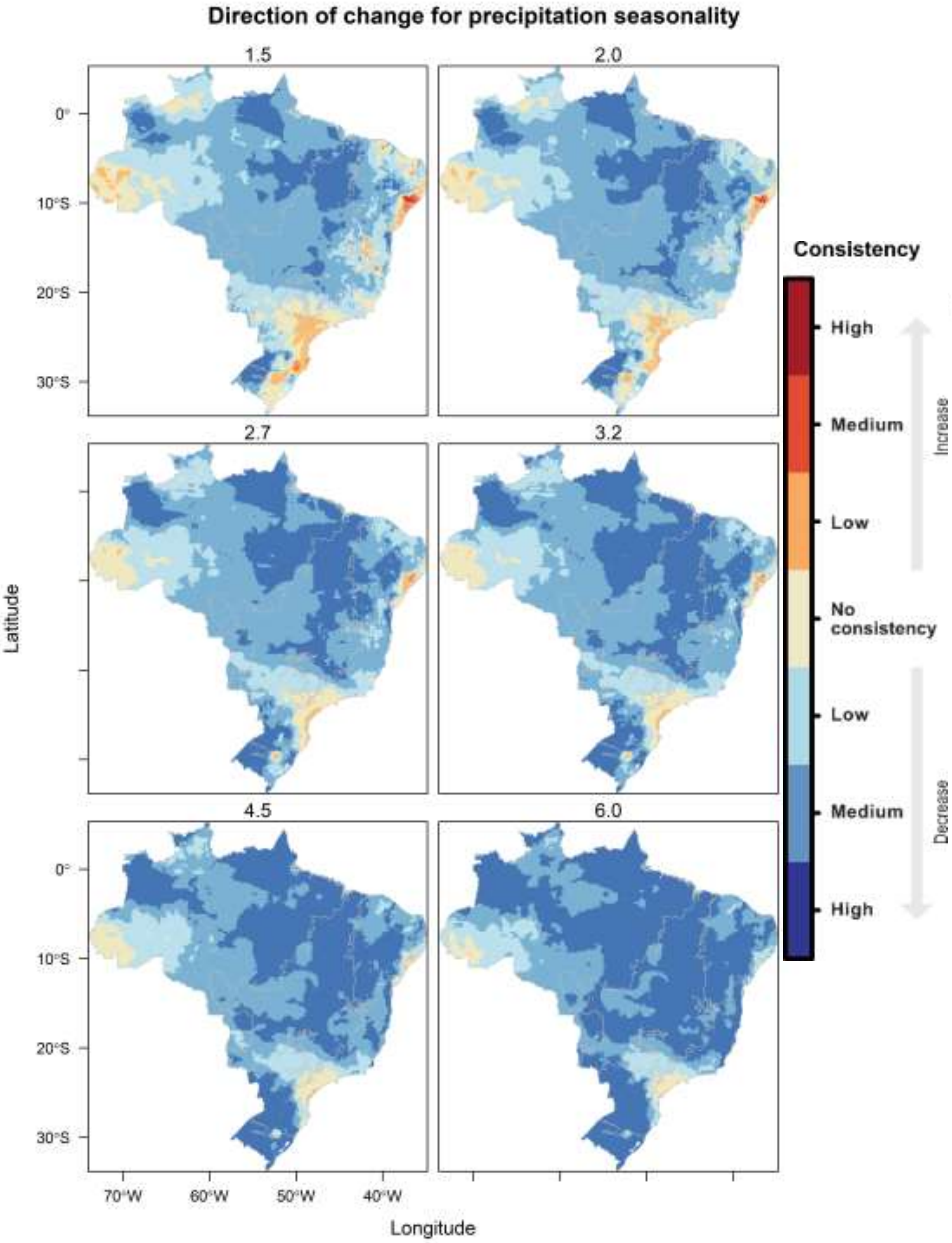


Figure 26: GCMs consistency on the direction of change (i.e., number of models projecting change in the same direction) of precipitation seasonality (PS). GCMs consistency represented by colour scale following Hirabayashi et al. 2013.

Precipitation of the wettest quarter (PWQ)

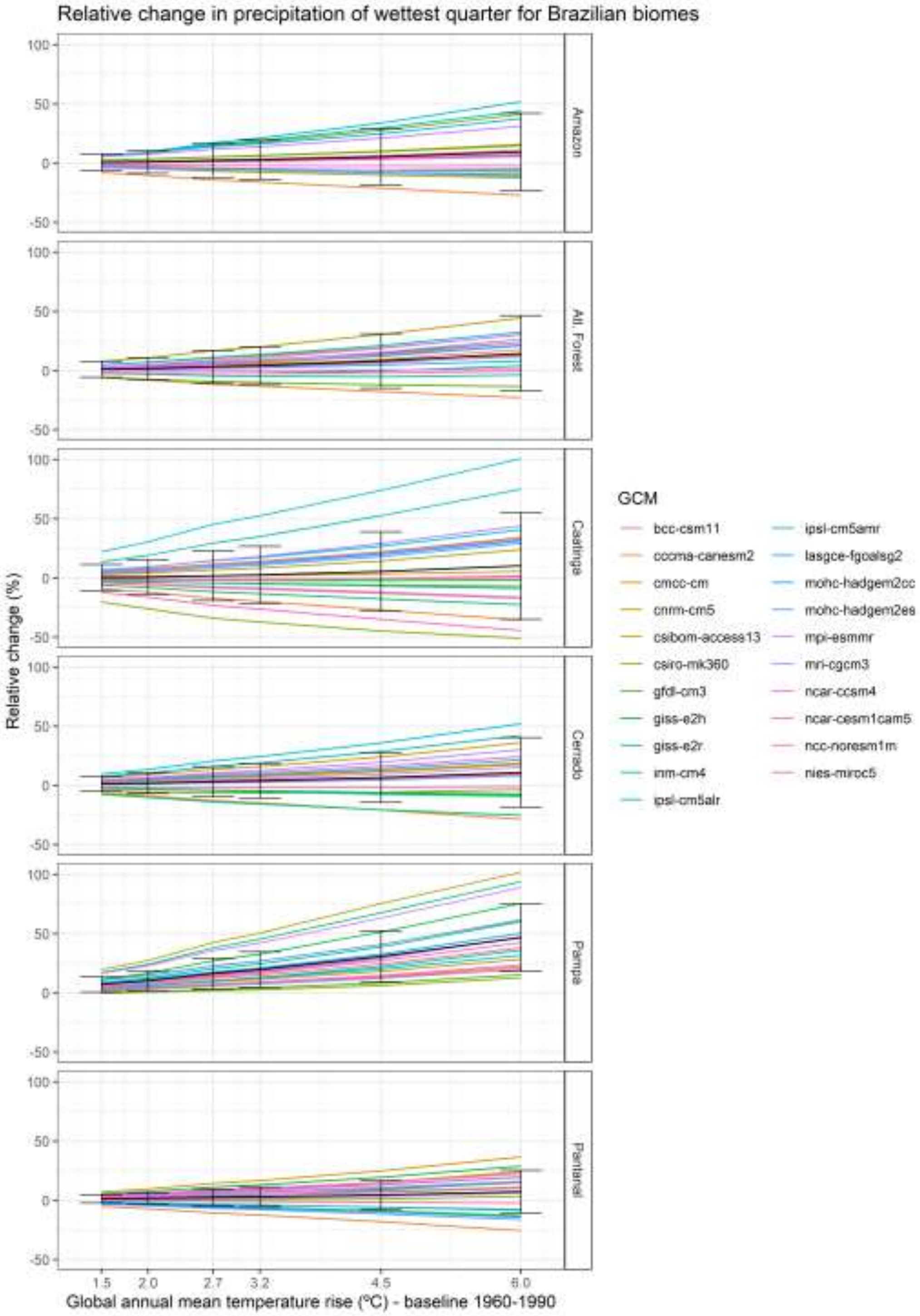


Figure 27: Projected change of precipitation on the wettest quarter for each Brazilian biome in relation to observed mean values forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

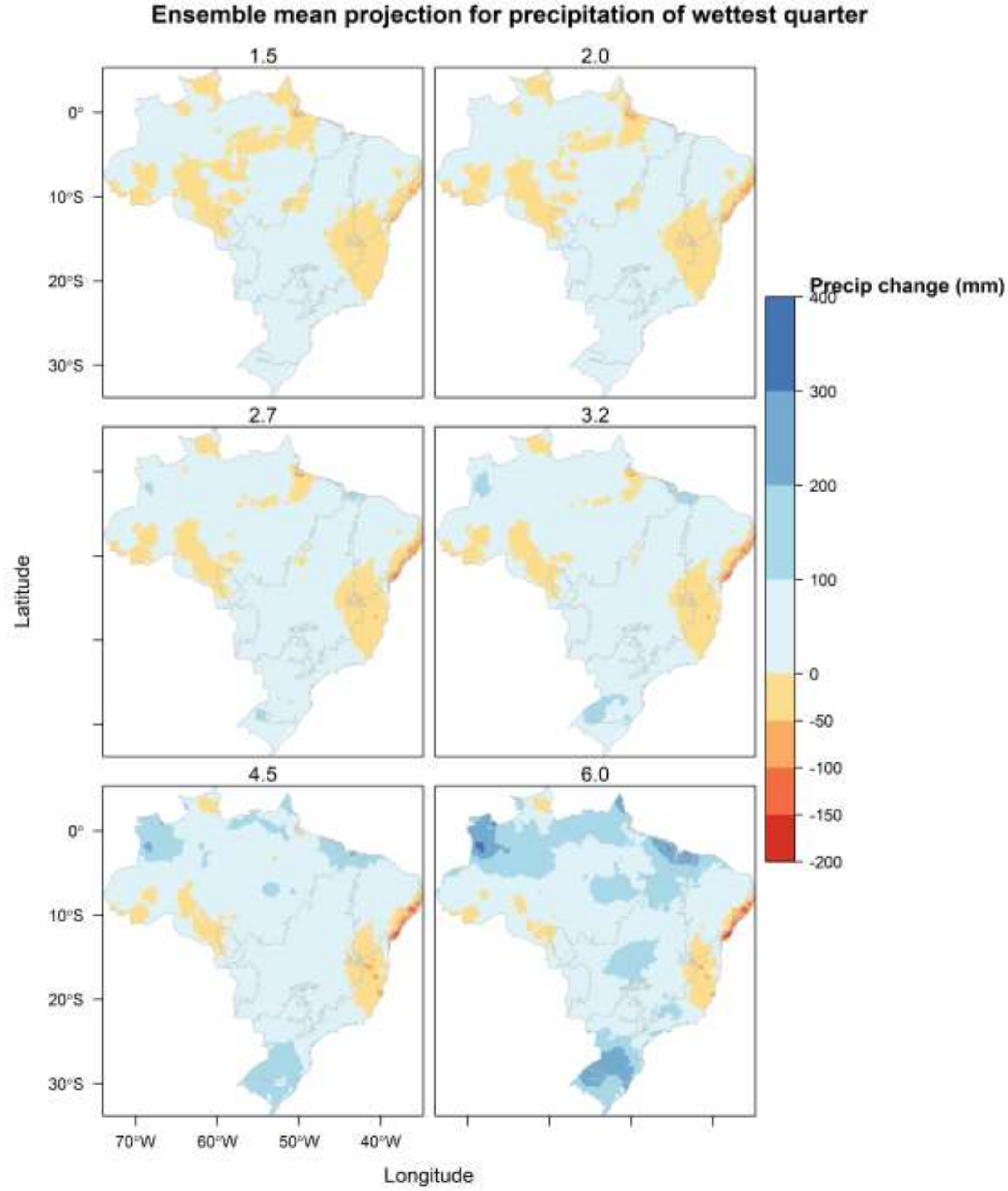


Figure 28: GCMs ensemble mean projection of change inprecipitation on the wettest quarter relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

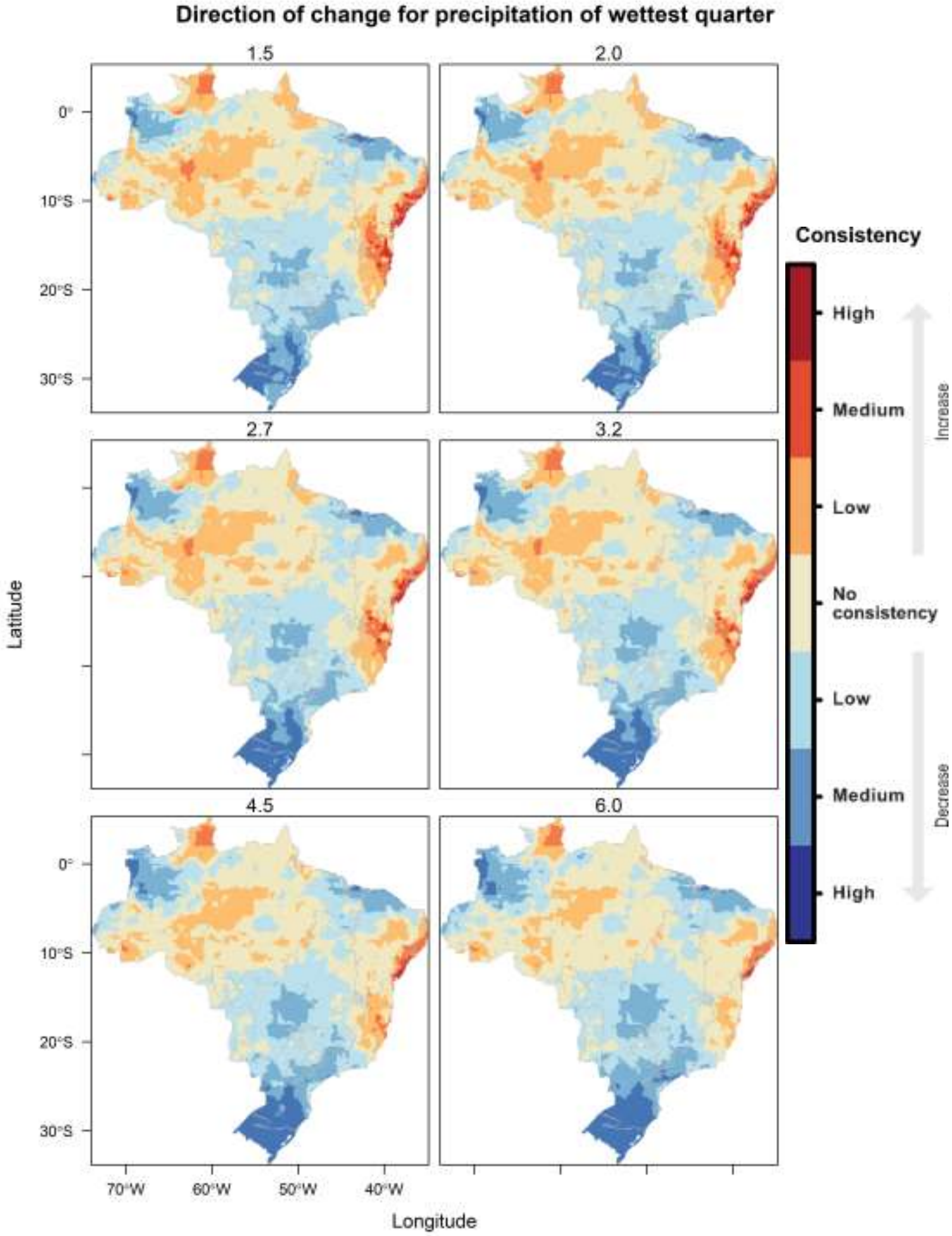


Figure 29: GCMs consistency on the direction of change (i.e., number of models projecting change in the same direction) of precipitation on the wettest quarter (PDQ). GCMs consistency represented by colour scale following Hirabayashi et al. 2013.

Precipitation of the driest quarter (PDQ)

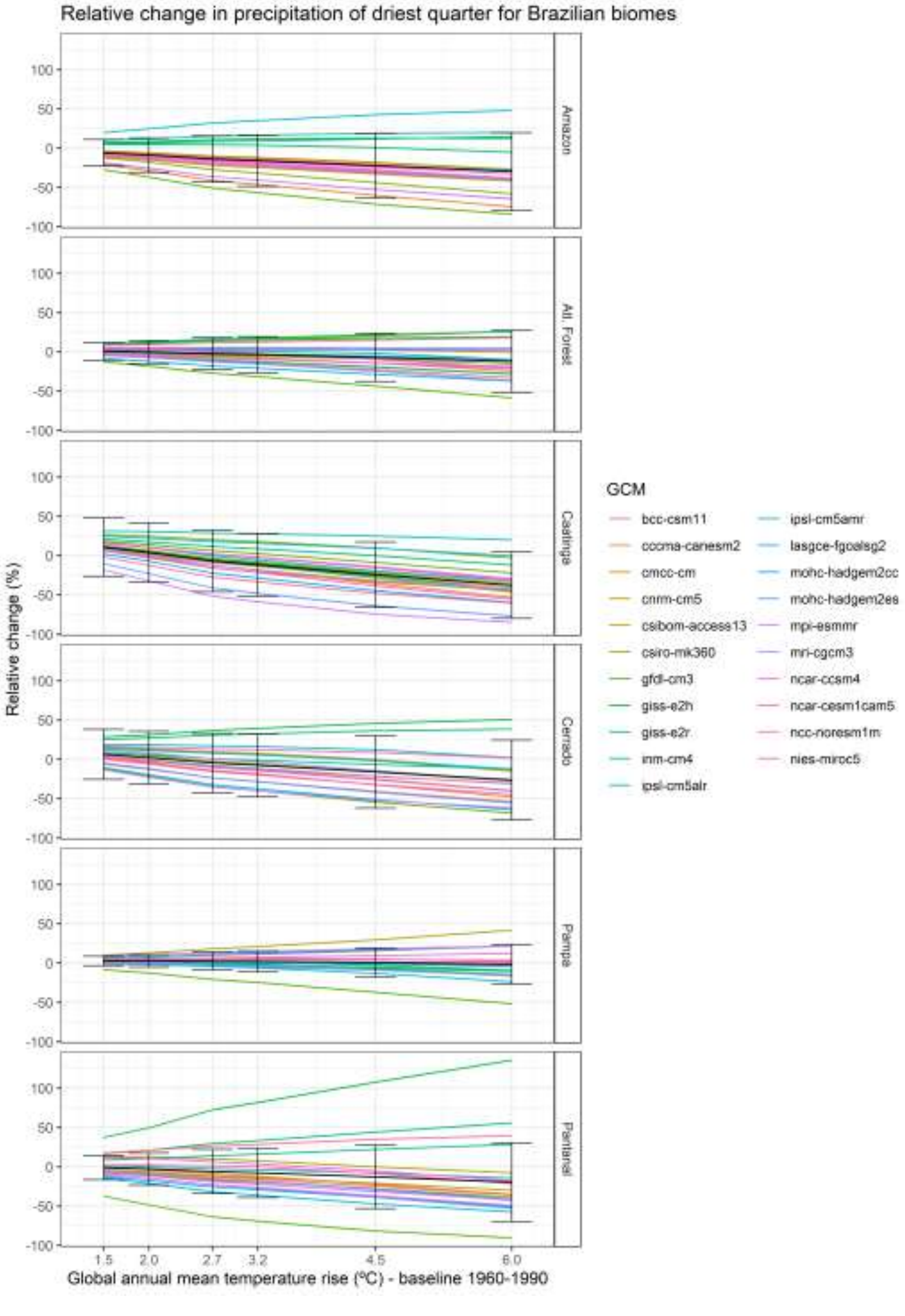


Figure 30: Projected change of precipitation on the driest quarter for each Brazilian biome in relation to observed mean values forced by 21 GCMs (coloured lines) under six scenarios of future climate change (1.5, 2, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels). The multi-model mean is represented by the black solid line and the standart deviation by the error bars.

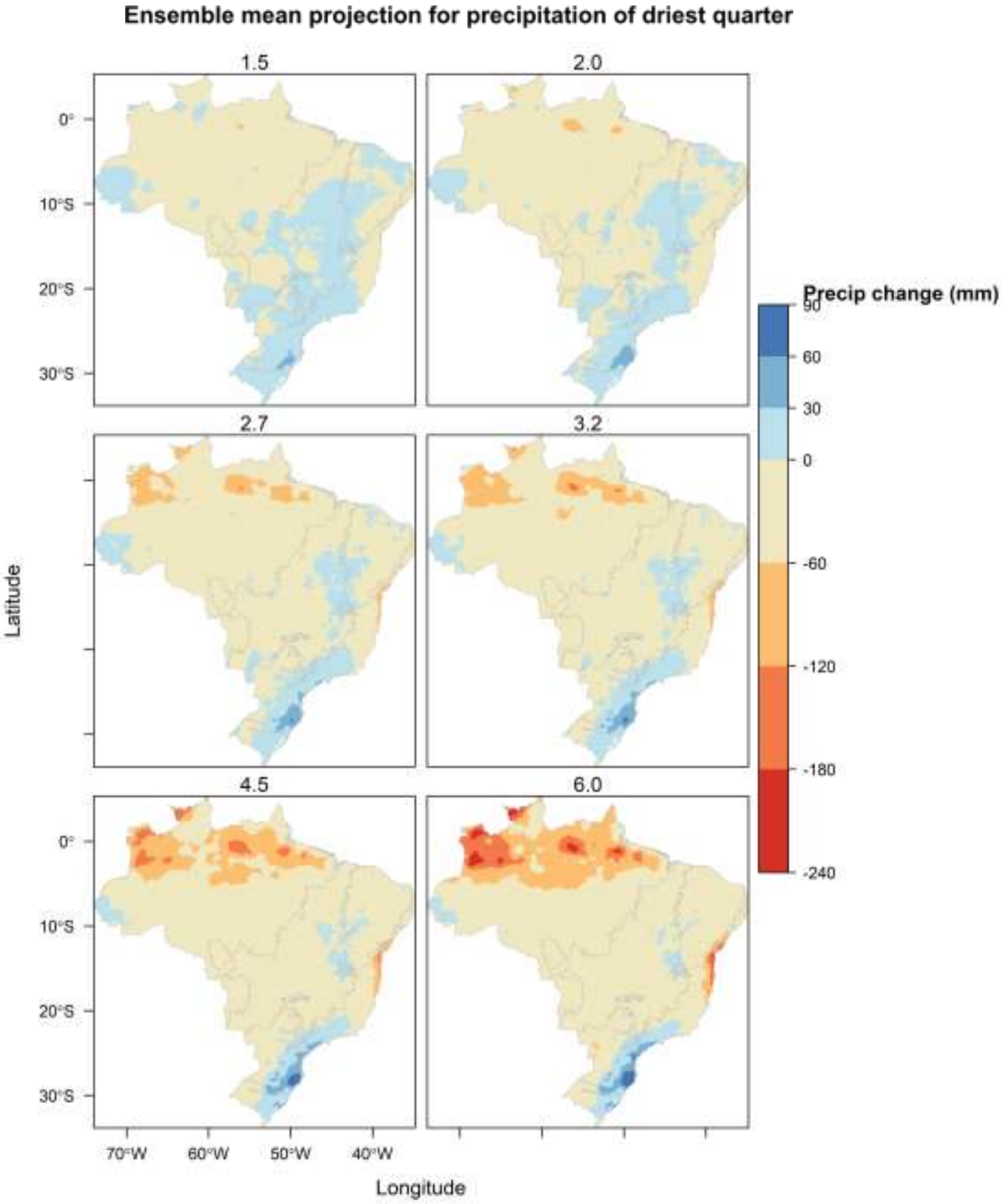


Figure 31: GCMs ensemble mean projection of change inprecipitation on driest quarter relative to 1950-2000 averaged over land grid points in Brazil under six future global warming scenarios (representing an increase of 1.5, 2, 2.7, 3.2, 4.5 and 6ºC on the global annual mean temperature with respect to pre-industrial levels).

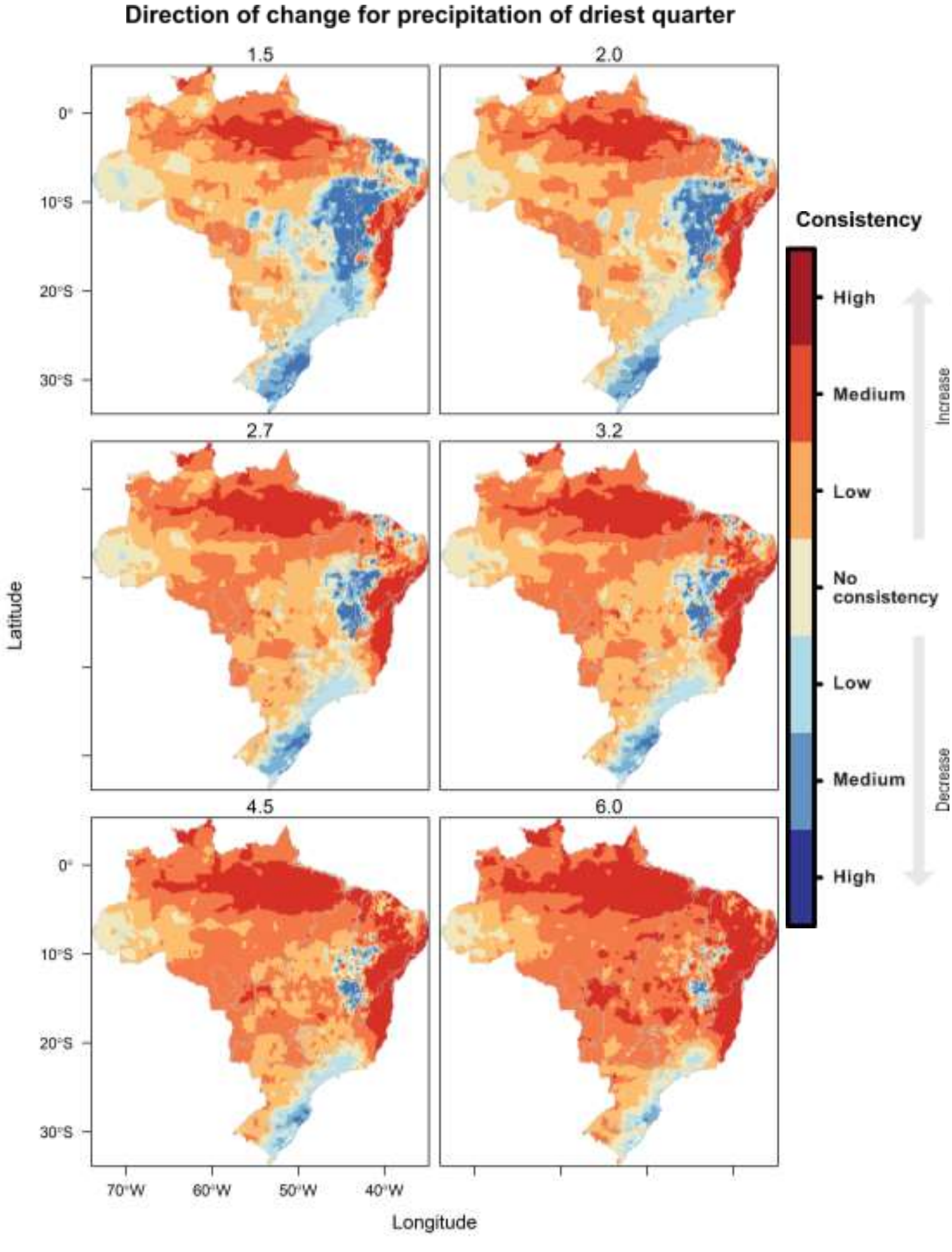


Figure 32: GCMs consistency on the direction of change (i.e., number of models projecting change in the same direction) of (). GCMs consistency represented by colour scale following Hirabayashi et al. 2013.

c. Amazon

As expected, the observed values averaged over all land grid cells within the Amazon show that overall, this biome is always warm (AMT 26ºC, TS 0.51ºC – Table 4) and always humid (ATP 2237 mm, PDQ 195mm – Table 4). In addition, the observed values for each land grid cell show that the south region that borders Cerrado and Pantanal has a dry season (PDQ under 180mm – map PDQ in Figure 10).

In general, the projected changes in the eight bioclimatic variables suggest that the Amazon will get warmer (Figures 13, Figure 15, Figure 17 and Figure 19), especially on the southern part (Figure 14), and drier (Figure 22, Figure 25, Figure 28 and Figure 31), especially on the northern part (Figure 13) under future scenarios of climate change. These projections are in line with the ones presented on chapter 27 of the IPCC's Fifth Assessment Report (Magrin et al. 2014) and references therein.

Considering future projections for bioclimatic variables related to temperature, there is a very high consistency that throughout this biome all variables will increase in relation to their observed levels due to future climate change (Figure 13, except for temperature seasonality, that is projected to increase throughout the biome but only has a high consistency in most of the biome – Figure 20). Moreover, the projections presented here corroborate that temperature increase in the Amazon is projected to happen at higher rates than the global mean temperature rises (Marengo et al. 2012; Magrin et al. 2014), e.g., if global annual mean temperature reaches 2.7ºC above pre-industrial levels, the projected changes in the annual mean (AMT), maximum temperature of the warmest month (MTW) and minimum temperature of the coldest month (MTC) averaged for this biome are of 2.96ºC, 2.96ºC, and 3.74ºC, respectively (Figure 11, Figure 14, and Figure 16). Likewise, in the 4.5ºC scenario almost the complete extent of the Amazon is projected to undergo an increase between 4.5-6.0ºC on the annual mean and minimum of coldest month (panel 4.5ºC of Figure 12 and of Figure 17), and of 6-8ºC on the maximum of warmest month (panel 4.5ºC of Figure 15), both in relation to the observed levels.

Regarding the precipitation related variables, for a great part of the Amazon, there is moderate consistency on the direction of change of the projections for the annual total precipitation (ATP) under future scenarios of climate change, indicating that for most part of this biome between 15 and 17 out of the 21 GCMs project a decrease of this variable as the world mean temperature rises (Figure 23). Moreover, the projections here presented suggest that ATP will decrease up to 13% in relation to the observed mean (roughly up to 300mm decrease in annual rainfall) regardless of the future scenario of warming under analysis (Figure 22). Both the direction and magnitude of change presented here support previous findings for the Amazon summarised by the IPCC (Magrin et al. 2014). In addition, the projections presented here show that for most part of this biome, there is a moderate to high consistency that the driest quarter will get drier (Figure 32), and moderate to high consistency that precipitation seasonality will increase (Figure 26). Considering the wettest quarter, although the multi-model mean for the biome (black line in Figure 27) suggests that the Amazon will in general get wetter on the wettest quarter, the multi-model mean per grid cell shows divergent trends for different portions of the Amazon and no consistency on the direction of change for most part of the biome (Figure 28 and Figure 29).

d. Atlantic Forest

The Atlantic Forest has a geographical location that is unique: this biome extends along the Brazilian coast, with latitudes ranging from 6ºS to 30ºS (it is the only one to have significant land surface in latitudes that are either close to the Equator or higher than the Tropic of Capricorn); and has a very wide elevation range (from sea level up to 2892 metres – the third highest point of the country). This particularity makes the values of the temperature related variables to vary throughout its extension (e.g., the northern part of the biome has AMT ranging between 23-28ºC while the southern part between 13-18ºC - map AMT in Figure 9), resulting in a biome with tropical and subtropical climates.

Projections of change in annual mean temperature (AMT) show that the Atlantic Forest along with Pampa will get warmer in a slower rate than the rest of Brazil as the global mean temperature rises (Figure 12), corroborating with previous projections (Nunez, Solman, and Cabré 2009; Marengo et al. 2012; Ferro et al. 2014). Moreover, the multi-model mean of the projected change for this biome indicates that under future warming conditions the Atlantic Forest will experience the lowest change in temperature seasonality (black line in Figure 18), second lowest increase in the mean annual temperature and maximum temperature of the warmest month (black lines in Figure

12 and Figure 14), and third lowest increase in minimum temperature of coldest month (black line in Figure 16) among all Brazilian biomes.

Considering the future projections for precipitation related variables under future scenarios of global warming, in general, the northern part of the Atlantic Forest will get drier while the southern part will get wetter, corroborating with projections presented by Ferro et al. (2014) and on IPCC's Fifth Assessment Report (Magrin et al. 2014). There is medium to high GCMs consistency that the northern part of this biome will experience a decrease in the total annual precipitation, while the southern part will experience an increase in this variable (Figure 22 and Figure 23). There is no consistency on the direction of change of the total annual rainfall for the central part of the Atlantic Forest (Figure 22 and Figure 23). This lack of agreement on the direction and magnitude of the projected change for total annual precipitation throughout the Atlantic Forest can also be observed on results from Ferro et al. (2014); (Buisson et al. 2010; Araújo and Peterson 2012), despite the low number of GCMs (three) used in that study. In addition, there is medium to high consistency (Figure 29 and Figure 32) on projections that suggest that the most northern part of the Atlantic Forest will get less rainfall and that the most southern part will get more rainfall during wettest and driest quarters (Figure 28 and Figure 31). Regarding precipitation seasonality under increased global warming levels, projections for this variable do not show consistency on the direction of change for the majority of the biome (Figure 26).

e. Caatinga

Regarding the Caatinga, as all semi-arid regions, it has high temperature throughout the year (AMT 25ºC, TS 1.21ºC – Table 4) and low precipitation even on the wettest period (ATP 761mm, PWQ 421mm – Table 4).

Future projections for temperature related variables under increased levels of global warming show that the western part of Caatinga will get warmer than the eastern part of this biome (Figure 12). Regarding future trends for precipitation related variables under future climate change, small parts of this biomes show different patterns. For a small part of the south-western region the precipitation of the driest quarter is projected to increase up to 30mm (medium to high consistency – Figure 31 and Figure 32), whilst projections suggest a decrease of up to 50mm on the rainfall of the wettest quarter (medium to high consistency – Figure 28 and Figure 29). As a result of this reduction in rainfall on the wettest quarter and probably in another period of the year, projections for the total annual precipitation for this patch show a decrease of up to 110mm (medium to high consistency – Figure 22 and Figure 23). A different picture is painted for a small patch on the north-western region of Caatinga: all precipitation related variables are projected to increase in all future climate scenarios (medium consistency – Figure 22 and Figure 32), except for rainfall on the driest quarter, which is projected to increase only in low or medium warming levels (1.5 to 3.2ºC above pre-industrial times – Figure 31 and Figure 32). And for the eastern part of Caatinga, there is medium consistency that the annual total precipitation will decrease up to 110 mm (Figure 22 and Figure 23) maybe driven by the projected decrease of up to 60mm on the rainfall for the driest period (high consistency – Figure 31 and Figure 32). It is worth noting that the northeast of Caatinga is the only part of this biome for which the IPCC's projection presented a decrease in total annual precipitation with strong agreement on the direction of change among the GCMs used, while projections for the rest of the biome did not agree on the direction of change (Magrin et al. 2014).

f. Cerrado

The observed values presented here for Cerrado, the Brazilian savannah, corroborate its status as a tropical climate (AMT 24ºC, TS 1.25ºC – Table 4) with dry winter (PDQ 39mm, PS 0.81 – Table 4).

Considering the future projections for all temperature related variables under scenarios of future climate change, the central and central-western parts of Cerrado will undergo a higher level of warming than the rest of the biome (Figure 12 and Figure 20). Moreover, the multi-model mean projections of change for the total annual precipitation and precipitation of the driest quarter averaged for Cerrado suggest that these variables will decrease under scenarios of future warming (Figure 21 and Figure 30, respectively), while the precipitation of the wettest quarter and precipitation seasonality will slightly increase (Figure 27 and Figure 24, respectively).

However, the multi-model mean projections of change for each grid cell for the precipitation related variables show that different parts of Cerrado will undergo changes in opposite directions, expect for precipitation seasonality, which is projected to increase throughout this biome (medium to high consistency – Figure 25 and Figure 26). For the most northern part of Cerrado, there is medium to high consistency that wettest quarter will get wetter (Figure 28 and Figure 29), while there is medium to high consistency that driest quarter will get drier (Figure 31 and Figure 32), but probably not enough to cause a decrease in the total annual precipitation, that is projected to increase (Figure 22 and Figure 23 – but note that there is low consistency on this projection, corroborating with the 'divergent changes' projected for this biome by the IPCC – (Magrin et al. 2014)). For the most southern part of Cerrado (border with Atlantic Forest), there is medium consistency of increase in total annual precipitation (Figure 22 Figure 23) probably driven by the projected increase in rainfall in the wettest quarter (low to medium consistency – Figure 28 and Figure 29). For this region there is no or low consistency on the direction of change for the precipitation of driest quarter (Figure 31 and Figure 32). Moreover, for the central-east part of this biome, there is a high consistency that future climate change will increase the rainfall on the driest quarter (Figure 31 and Figure 32), but medium to high consistency that it will decrease the total annual rainfall of this region (Figure 22 and Figure 23), and no consistency on the direction of change for the wettest quarter (Figure 28 and Figure 29). And for the western part of this biome (border with the north of Pantanal) there is medium to high consistency that both total annual and driest quarter will get drier (Figure 22 and Figure 23; and Figure 31 and Figure 32, respectively), and no or low consistency on the direction of change for the wettest quarter (Figure 28 and Figure 29).

g. Pampa

Pampa, the biome located in the most southern part of Brazil, is the only biome completely in a subtropical zone and climate. The observed values for temperature related variables show that this biome has not only the lowest temperatures of the country, but also the highest variability between cold and warm months (AMT 19ºC, MTC 9ºC and MTW 30ºC, TS 3.16ºC – Table 4). Considering precipitation, this biome is humid and does not present a dry season (ATP 1462mm, PDQ 319mm, PWQ 410mm, PS 0.12 – Table 4).

Regarding projections for bioclimatic variables for Pampa under future climate change, there is a high consistency that all variables related to temperature will increase in higher levels of future warming but at lower rates than the rest of the country (Figure 12 and Figure 20), what is also represented on the projections made by the IPCC (Magrin et al. 2014). Considering the projections for the precipitation related variables under future levels of global warming, there is medium to high consistency that the wettest quarter will get wetter (Figure 28 and Figure 29) and that the total annual precipitation will increase (Figure 22 and Figure 23) throughout Pampa, corroborating with IPCC's projections for this biome (Magrin et al. 2014). On the other hand, there is low to medium consistency that the driest quarter will get drier on the western part and wetter on the eastern part of this biome (Figure 31 and Figure 32). These opposite projections for different and almost equally sized regions of the biome partially explain the 'no change' projected for precipitation of the driest quarter by the multi-model mean averaged for this biome (Figure 30).

h. Pantanal

The observed values for some temperature related variables for Pantanal, the smallest of the six Brazilian biomes, are as high as for the Amazon (AMT of 26ºC, MTW of 34ºC – Table 4). While the observed values for the precipitation related ones for this biome show patterns similar to the ones presented for Cerrado (PDQ of 81mm, PS of 0.65 –Table 4Table 4).

Future projections for temperature related variables under future climate change for Pantanal suggest that this biome will get warmer at the same rate as the western part of the Amazon, higher than the rest of the country (Figure 12 and Figure 20). This higher level of warming is more pronounced in higher levels of global mean temperature, a difference that is also represented on projections under RCPs 2.6 and 8.5 made by the IPCC (Magrin et al. 2014). Regarding future projections for precipitation related variables, there is low to medium consistency that the precipitation seasonality will increase in Pantanal (Figure 25 and Figure 26) and that this biome will get drier in the driest quarter (Figure 31 and Figure 32). Moreover, there is no to low consistency that this biome will get wetter in the wettest quarter (Figure 28 and Figure 29) and that its total annual precipitation will decrease (Figure 22 and Figure 23). It is worth mentioning that under both RCPs 2.6 and 8.5 less than 2/3 of the models used by IPCC projected change for total annual precipitation greater than the baseline variability for the Pantanal (Magrin et al. 2014).

6. Discussion points

a. Implications for species distribution modelling robustness

Species distribution modelling (SDM) exercises that analyse the impact of future climate change on biodiversity rely on how well the projections of change in the adopted bioclimatic variables can predict the future climate (Buisson et al. 2010; Araújo and Peterson 2012). Therefore, the choice of GCMs used in the modelling approach and how this approach is developed have a direct impact on the modelling outcome and can jeopardize the biological meaning of the exercise (Porfirio et al. 2014).

For Brazil, the analysis of future projections for changes in bioclimatic variables from a wide range of GCMs instead of from just one or few, shows the inter-model variability (i.e., large spread among models' projections) regarding how temperature and precipitation patterns could change in the future throughout the country due to climate change. Even though the projections of change in temperature related variables show a higher level of GCMs consistency about the direction of change (i.e., all models show an increase in relation to the observed values) than the projections of change in precipitation related ones, the GCMs projections do not completely agree on the magnitude of change (i.e., the amount of degrees Celsius or of millimetres of rain) for both types of variables. Consequently, using projections from a wide range of GCMs makes the SDM approach more robust (and more likely to include the accurate projection).

Moreover, it is worth noting that the multi-model mean projection for precipitation related variables for each grid cell in each biome (shown by the maps of projected change) does not always show the same direction of change throughout the biome that the multi-model mean averaged for all grid cells within the same biome (represented by the black line in all line plots). Hence, the latter should be used with caution to describe the climatic changes that each biome is likely to undergo, as projections might show divergent changes for different parts of the same biome. Accordingly, the projections presented here suggest that an SDM exercise that is developed model by model and cell by cell will capture the climate change impacts on biodiversity derived from each GCM's projection specifically for each grid cell, as well as the overall projection of change and consequent impact on the biota. Therefore, the findings of this chapter support the recommendations previously made by several other studies (Buisson et al. 2010; Porfirio et al. 2014; Araújo et al. 2019) about the 'good practices' while performing SDMs analysis to investigate the potential impacts of future climate change on biota.

In conclusion, the projections presented on this chapter support that a species distribution modelling exercise that uses a big set of GCMs and is performed model by model and cell by cell, such as the one performed by the WI, is very robust as it captures both the inter-model variability on future projections for Brazil and the natural variability of climate patterns in the country.

b. Implications for the analysis of the WI 'future climatic refugia' dataset

As future climatic refugia are the cornerstone of the research presented in this thesis, it is important to understand the implications of the bioclimatic projections on the analysis of the WI 'future climatic refugia' dataset. This dataset (explained in detail in chapter 2 section 3.c) shows the grid cells around the world that are projected to remain climatically suitable for at least 75% of the species included in the WI database and modelled to currently be in there (hereafter referred as refugia). In addition, this dataset shows for each grid cell identified as potential refugia the number of GCMs agreeing on this projection.

In addition, the studied GCMs present a large spread of future projections of the bioclimatic variables for the Brazilian biomes (including projections suggesting divergent changes for the precipitation related variables). If too many climate models' projections are included, the identification of refugia is constrained by regional climate projections that are outliers (in terms of climate projection). On the other hand, if too few models' projections are included, the refugia are not based on a full understanding of uncertainties on climate projections.

Therefore, three different thresholds on the number of models agreeing that a cell is a potential refugia are considered for exploration: 2, 11, and 19 models.

- If grid cells are identified as potential refugia selecting only 2 climate models (2 out of 21 modes, i.e., only requiring 10% agreement) – refugia are based mainly on projected changes in the temperature related variables.

Because the range of precipitation projections across the 21 climate models is so great, including both negative, zero and positive trends, selecting only 2 models out of the 21 means that precipitation is much less of a constraint when identifying refugia. This means that refugia are largely determined by temperature related variables only.

- If grid cells are identified as potential refugia by 11 climate models (50% agreement) – show the combined effects of the projected changes in all variables

The grid cells identified as potential refugia by 11 models are likely to represent the multi-model mean projection for change in all temperature and precipitation related variables, and thus is the threshold that is more likely to include the impacts of both types of variables. Moreover, a recent analysis of the performance of past climate models projections developed by (Hausfather et al. 2020) showed that most (10 out of 17) models examined have accurate projected global warming levels for the years after their publication, with the remaining models projecting more (4 models) or less (3 models) warming. Therefore, considering the grid cells identified as potential refugia by most of the climate models adopted in this research, i.e., 11 models, is a good compromise between maintaining robustness and accounting for the uncertainties of the climate modelling without narrowing too much the options of land that could be used in conservation planning.

- If grid cells identified as potential refugia by 19 climate models (90% agreement) – refugia are based on too high a threshold that could include projections of extreme change

The maps of GCMs consistency on the projected change for precipitation related variables (Figures 24, 27, 30, 33) show that few areas in Brazil present 18 or more climate models agreeing on the direction of change for these variables. Moreover, although the range of individual models' projections was not analysed per cell (only for the models' mean per biome), a similar discrepancy to the ones shown on the line plots (Figures 22, 25, 28, 31) can be expected. Selecting 19 models as a threshold would result identifying refugia based on outliers for climate projections and the exclusion of areas that might perform well as refugia in the future.

For the Amazon, the multi-model mean projection of change for the precipitation of the driest quarter (PDQ) averaged for the biome suggests a decrease in rainfall in this period. At the same time, different models have projected that in a 6ºC warmer world PDQ could either increase by 126mm or decrease by 169mm in relation to the observed 195mm (Amazon – Figure 30). As a humid biome, a decrease in rainfall is likely to be more disruptive for its biota. Yet, even if the two projections suggesting the most extreme reductions on precipitation (-169mm and -160mm) are not considered (i.e., 19 models remaining), there is still a model projecting a decrease of 132mm on PDQ in relation to the 195mm observed. Therefore, for this biome, using 19 models as a threshold would include projections of change in the precipitation on the driest quarter that are opposite in direction and in quantity, and would only identify as refugia cells that have 75% of their biota with a very broad climate envelope (in order to 'accept' both changes).

In conclusion, the adoption of 19 models as a threshold to analyse the WI 'future climatic refugia' dataset will include projections on opposite directions, might also include projections of extreme change and could excessively narrow the options of land that could be used in conservation planning. Hence, this study considers this threshold as too high and even unattainable for some combinations of biomes and future climate scenarios.

Final consideration

It is worth highlighting that this explanation about the implications of adopting different numbers of climate models' projections to identify refugia is only based on the projections of change for the bioclimatic variables under future climate change and does not include the modelled impact of climate change itself on the species' ranges. With that in mind, the next chapter of this thesis presents a sensitivity analysis of the adoption of three different values (GCMs thresholds) in relation to the geographical location and size of the locations identified as refugia in the Brazilian biomes.

c. Speculations about the impact of projected climatic changes to biodiversity

Under future climate change scenarios, all 21 GCMs included in this research individually project an increase in the levels of all temperature related bioclimatic variables throughout Brazil as the global mean temperature rises (Figure 11 and Figure 20). The only exceptions are the southeast part of the Atlantic Forest and western part of Cerrado where there is a moderate and high model's consistency (respectively) that the temperature seasonality will decrease up to 0.25ºC in relation to observed levels (Figure 19 and Figure 20 – but note that still corroborating with the projected increase in the other temperature related variables). Moreover, some parts of the country are projected get warmer at a faster rate than the global annual mean temperature increase (Figure 12, Figure 14, and Figure 16).

Assuming that the current set of species in a place is at equilibrium with the place's observed climate, the projected warming could possibly expose the Brazilian biota to temperatures beyond the ones that the species are adapted to (based on the assumption that the vulnerability and resilience of ecosystems to future climate change are connected to the observed climate variability (Seddon et al. 2016; Newbold et al. 2020)). This might be especially true for endemic species of biomes that have their observed mean AMT and MTW closer to their observed maximum AMT and MTW, as even a small increase in these variables might turn this biome climatically unsuitable for its endemic species. At the same time, biomes that have their observed mean AMT and MTW closer to the country observed max AMT and MTW could become climatically unsuitable for generalist species / species endemic to the country (i.e., species that may occur in more than one Brazilian biome). On the other hand, the opposite should also be true: biomes that have their observed mean AMT and MTW further to their observed max AMT and MTW should be able to remain climatically suitable for endemic species; and further to the country observed max AMT and MTW should be able to remain climatically suitable for generalist species.

In the tropics, what mainly differentiate one climate zone from the other is the annual and seasonal amount of precipitation (Kottek et al. 2006).Assuming again that current species and climate are at equilibrium, the current species distribution in the tropics also heavily relies on the quantity of precipitation and its patterns. Moreover, water availability has been pinpointed as the main driver of climate sensitivity for Caatinga (Seddon et al. 2016). Therefore, investigating how the projected changes in the precipitation patterns could impact biodiversity is needed. Although the climate models' projections do not show the same level of confidence on the direction or magnitude of changes that future climate change could cause on the precipitation related variables as the one presented for temperature related variables, any change in the current precipitation patterns that would cause the current climate zones to shift, could possibly have large effects on the current distribution of species in the Brazilian biomes.

This might be the case of regions within the humid biomes that are projected to experience a decrease in precipitation related variables in relation to the observed levels. The projected changes for regions such as the central east part of the Atlantic Forest and the eastern part of the Amazon could lead to a phytophysiognomy changes there. For the former region, there is a high confidence that ATP, PWQ and PDQ are projected to decrease (Figures 15, 21, 24), what could lead to an expansion of the semideciduous forest upon the dense and humid forest. And the Amazon, where projections have low to moderate confidence that ATP and PDQ will decrease, could experience the retraction of its dense and humid forest towards its Brazilian western border, and consequently an expansion of formations that tolerate a dry season (e.g., semideciduous forest, campinarama, and savanna like formations), that currently occur in its eastern side (similar predictions have been made for south-western part of the Amazon regarding the expansion of the areas dominated by bamboo due to future changes in climate – see Ferreira, Kalliola, and Ruokolainen (2020))

Finally, it is important to emphasize that changes in precipitation and temperature to any direction could benefit some species of current assemblage, but be a detriment to others, possibly disrupting the interactions (trophic and spatial) of that ecosystem. As an example, an increase in precipitation on the driest quarter in Pantanal could favour species of amphibians that have breeding activity in rainy days (Prado, Uetanabaro, and Haddad 2005) and, at the same time, could negatively impact seasonal aquatic bird species that are attracted by the abundance of easy preys caught in pools or mud (Figueira et al. 2006).

d. Caveats of the adoption of bioclimatic variables

Limits related to the measuring units

Measurements and consequently the projected changes in precipitation related variables are shown in millimetres and, therefore, have a bottom limit (0mm). Meanwhile, measurements and projected changes in temperature are shown in degrees Celsius and hence can increase or decrease without limits. E.g., dry areas that have precipitation of the driest quarter close to zero cannot get any drier so a projection of ‘no change’ on this variable on those regions might not mean that the region is not getting overall drier, what could be captured by another variable (annual total can decrease; wettest quarter can decrease) or not (annual total can remain the same if the wettest quarter increases and other period of the year gets drier).

Extreme weather events

Projected changes in the frequency or duration of extreme weather events (IPCC 2012), such as severe drought, and projected changes in El Niño (Magrin et al. 2014), affect biodiversity in Brazil (Marengo et al. 2016; Correia Filho et al. 2019; Jimenez et al. 2019) and is not captured by the bioclimatic variables (as even the variables that represent maximum values are an average of all years).

Possible impacts of a prolonged drought are not captured by the SDMs as the bioclimatic variable that represents the precipitation on the driest quarter (PDQ) consists of the 3 consecutive driest months. Therefore, this bioclimatic variable is not fit to show if the dry period of a region is projected to get longer due to future climate change. On the other hand, in some cases, if future climate change is leading to a long-term trend of longer dry seasons, this could be partially inferred by analysing projections for precipitation on the driest and wettest quarters and total annual precipitation.

7. Key messages

The projections of changes in the studied bioclimatic variables under scenarios of future climate change vary in magnitude and in the number of climate models agreeing on the direction of change (confidence) throughout the Brazilian biomes. There is high concistency on the projections showing that all temperature related bioclimatic variables will increase in all Brazilian biomes (except for the temperature seasonality on the south of Cerrado and central-southern part of the Atlantic Forest that is projected to decrease – low to medium consistency). Yet, the magnitude of this increase is projected to be higher in the western part of the country (Amazon, western Cerrado, and Pantanal) and lower in the south (southern Atlantic Forest and Pampa). Regarding the precipitation related variables, there is medium to high consistency that the total annual precipitation, and the precipitation of the wettest and driest quarters will decrease in small parts of the north of the Amazon, and north and central-east of the Atlantic Forest, and will increase in the south-eastern Atlantic Forest and eastern Pampa. As for the precipitation seasonality, there is medium to high confidence that most parts of Brazil will experience an increase in this variable.

The confidence on the future projections varies depending on the grid cell or biome, bioclimatic variable, and future climate scenario under analysis. Considering that this confidence is used in the interpretation of the WI ‘future climatic refugia’ dataset, this chapter shows that from the climate perspective, adopting the threshold of 11 models to analyse future potential refugia reflects the combined effects of the projected changes in temperature and precipitation bioclimatic variables on the future potential species distribution for all biomes in the country. Therefore, the next chapter explores how the adoption of this threshold affects the areas identified as potential future climatic refugia for terrestrial biota in Brazil.

Finally, this chapter suggests that areas that are projected to experience changes in the bioclimatic variables that do not exceed the maximum observed levels of the biome or country might be identified as future climatic refugia for biodiversity (explored in chapter 4). And conversely, areas that are projected to experience a greater change (exceeding the biome’s or country’s maximum observed levels) on the bioclimatic variables, would not be expected to be refugia. Despite that, these locations would still be important for long-term biodiversity conservation under future climatic changes. Since these locations would probably be the first to experience the impacts of these changes in their biota, they would be suitable areas to monitor and to test adaptation measures.

Chapter 4: Future climate change refugia for terrestrial biota in Brazil

This chapter presents an analysis that takes into consideration the locations projected as potential future refugia for a taxon to identify and assess locations that are projected to be refugia simultaneously for at least two taxa, i.e., future climatic cross-taxon refugia, in Brazil and its biomes.

1. Introduction

Recent climate change has been affecting different levels of biodiversity, from organisms to biomes (Bellard et al. 2012), already causing observed impacts (Parmesan and Hanley 2015; Settele et al. 2014). Previous analyses of climate change impacts on biodiversity have shown that the trends of species range shifts are matching climate change predictions, with ranges shifting towards higher latitudes (Parmesan and Yohe 2003; Franco et al. 2006), or towards higher altitudes (Franco et al. 2006; Chen, Hill, Ohlemüller, et al. 2011) and sometimes both (Parmesan 1996; Parmesan, Ryrholm, Stefanescu, Hill, Thomas, Descimon, Huntley, Kaila, Kullberg, Tammaru, et al. 1999), following a suitable climate. Furthermore, studies that analysed possible future impacts of different climate change scenarios on biodiversity (Jetz, Wilcove, and Dobson 2007; Pimm 2008; Bellard et al. 2012; Warren et al. 2013a) have reached the conclusion that even in the best-case scenario (that usually means that greenhouse gas –GHG– emissions would immediately stop or would be negative) biodiversity will still be affected.

In previous periods of climate instability (e.g., cyclical warming and cooling in the Quaternary), species have "retreated to, persisted in and expanded from" areas called refugia (Keppel et al. 2012). Although projected changes in future climate do not suggest a return to pre-industrial levels in this century under any explored scenario (IPCC 2014), the concept of refugia as areas where species could survive despite future climate change is still considered valuable for biodiversity conservation (Keppel et al. 2012; Morelli et al. 2020). Therefore, a growing body of research has aimed at identifying future refugia (Keppel et al. 2012; Baumgartner, Esperón-Rodríguez, and Beaumont 2018) and planning their conservation and protection (Keppel et al. 2015; Morelli et al. 2016; Graham et al. 2019). However, most proposals are usually targeted at one or few species of the same taxonomic group (e.g., Monsarrat, Jarvie, and Svenning (2019), Ribeiro, Sales, and Loyola (2018), Borges and Loyola (2020)) and are mainly not at scales most pertinent to biodiversity conservation (Selwood and Zimmer 2020).

Identifying future refugia for a species is important and should be included in the conservation planning of critically endangered species. Despite that, as resources for conservation are often scarce, conservation planning aimed at the ecosystem level would greatly benefit from the identification of locations that are projected as potential future refugia simultaneously for more than one taxon, i.e., cross-taxon refugia. This thesis adopts the simplistic assumption that cross-taxon refugia are more likely to retain their current ecosystem structure and function due to their higher number of species and taxa in comparison with non-refugia locations (but note that ecosystem resilience is much more complex and likely to be determined by several other factors in addition to the ones considered here as explored by Tom (2015), and that there are still several questions related to the role of biodiversity on ecosystems functioning unanswered as pointed out by Hooper et al. (2005)). Hence, identifying cross-taxon refugia is useful for long-term conservation measures that aim to protect currently healthy ecosystems (creation of new PAs) or to recover the functionality of degraded ecosystems (restoration actions). Moreover, cross-taxon glacial refugia for birds and mammals during the Last Glacial Maximum in the sub-Saharan Africa matched the locations previously suggested as refugia for individual species or taxonomic group within those clades (Levinsky et al. 2013), supporting the representativeness of cross-taxon refugia.

Considering the key role that cross-taxon refugia have in conservation planning under future climate change, the aim of this chapter is to address the question: what proportion of Brazil and its biomes is projected to remain climatically suitable for most of the biodiversity they presently contain, by acting as future climatic cross-taxon refugia?

To achieve that, the research presented in this chapter uses output taken from the existing Wallace Initiative database to determine the location of future climate change refugia for terrestrial species of five taxa (Amphibia, Aves, Mammalia, Plantae, and Reptilia) under six different future climatic scenarios (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels) mapping them to individual grid cells at a scale of 20x20km.

The process of determining the refugia's location involves the selection of two thresholds which influence the extent and location of the refugia. Therefore, this chapter first presents two important sensitivity analyses that compare the effects of changing these two thresholds that are embedded in the identification of refugia: (a) climate model consistency, i.e., the number of Global Climate Models (GCMs) in agreement that a grid cell is a refugium, and (b) the minimum percentage of species currently present which are projected to remain in that grid cell under future climatic conditions for it to be considered a refugium. These sensitivity analyses are performed on single taxon refugia.

On the basis of these sensitivity analyses, an informed choice can then be made on the appropriate values of the thresholds to use in the creation of the future climatic cross-taxon refugia for Brazil under the six future climatic scenarios explored. Moreover, based on the results of the sensitivity analysis on the single taxon refugia, the location and size of these cross-taxon refugia are analysed for Brazil and its biomes. Following that, the importance of meeting the Paris Agreement targets for biodiversity conservation is explored along with the limitations and caveats related to species distribution modelling and the approaches adopted by this research. To finalize, key messages about Brazil's and its biomes' potential to act as future climate change refugia are presented.

2. Objective

Main objective of the research presented in this this chapter is to analyse the proportion of Brazil and its biomes that is projected to remain climatically suitable for most of the terrestrial biodiversity they presently contain, by acting as future climatic cross-taxon refugia.

3. Use of Wallace Initiative data

a. Biodiversity data

The Wallace Initiative database provides projections the future potential geographical distribution for terrestrial species of five taxa (Amphibia, Aves, Mammalia, Reptilia, and Plantae) under six future climate change scenarios: 1.5, 2.0, 2.7, 3.2, 4.5 and 6.0ºC above pre-industrial levels. WI also summarises these projections into two derived products ‘future species remaining richness’ and ‘future climatic refugia’.

The analyses in this chapter are based on data for Brazil extracted from the two abovementioned WI derived products under the non-dispersal scenario. Both datasets are explained in detail in section ‘Wallace Initiative biodiversity database’ in chapter 2.

The ‘future climatic refugia’ dataset shows globally the grid cells that are projected to remain climatically suitable for at least 75% of species currently present and included in the WI database, for each studied taxon (total 5 taxa), under each considered future climate change scenarios (total of 6 scenarios).Each grid cell has an index ranging from 0 to 21 (hereafter called GCMs consistency) that represents the number of GCMs that have projected a future climate (under each climate change scenario) that allows this grid cell to remain climatically suitable for most of its modelled current biota. Therefore, the ‘future climatic refugia’ dataset does not contain a map of climate refugia, it rather provides information about the degree to which each grid cell can act as a refugium, by counting the number of GCMs in agreement that the grid cell is a refugium (this information which is used in this chapter to derive the location of the refugia in Brazil). Data from ‘future climatic refugia’ dataset is first used for comparison (a) which considers the influence of the threshold relating to climate model consistency, i.e., the number of GCMs that are in agreement when identifying refugia, and then to create the future climatic cross-taxon refugia. The complete WI ‘future climatic refugia’ dataset for Brazil is presented in section 1.b of this thesis’ Appendix.

The ‘future species remaining richness’ dataset has global data on the proportion of species of each studied taxon (total 5 taxa) for which each grid cell is projected to remain climatically suitable under each considered future climate change scenarios (total of 6 scenarios), with a GCMs agreement of 11 (out of 21 climate models). It ranges from 0-100% reflecting the proportion that the projected future number of species in a grid cell represents in relation to the modelled current number of species in the same grid cell. Data from the ‘future species remaining richness’ dataset was post-processed to generate a subset only with the grid cells that are projected to remain climatically suitable for at least 50% of the species modelled to currently be there. This subset is used in the comparison (b) to explore the influence of changing the threshold on the minimum percentage of species remaining in a grid cell for it to be considered a refugium. Locations projected to remain climatically suitable for different proportions of their modelled current species are presented on the maps in section 1.c of this thesis’ Appendix.

Table 5 summarises the information included in each WI dataset and how it was used in this chapter.

Table 5: Summary of the Wallace Initiative biodiversity data considered in this chapter.

Dataset	Percentage of species remaining represented (%)	Used in this chapter to
Subset of ‘WI future species remaining richness’ dataset	50-100	Sensitivity analysis (b): effect of selected percentage of species remaining.
WI future climatic refugia	75-100	Sensitivity analysis (a): effect of GCM model consistency threshold. Sensitivity analysis (b): effect of selected percentage of species remaining. Creation of future cross-taxon refugia dataset.

b. Note about plots and maps

All plots and maps presented in this chapter were created using packages ‘raster’, ‘RColorBrewer’, and either ‘ggplot2’ (for plots) or ‘rasterVis’ (for maps) of the software R.

4. Sensitivity analyses of single taxon refugia

a. Analysis related to climate model consistency

When identifying the locations with the most resilient biota to future climate change, it is important to reach a compromise between having a high robustness despite climate modelling uncertainties, and yet not underestimating the extent of land which could in the future act as refugia. Chapter 3 results show that projections for bioclimatic variables under future climate change in Brazil derived from different Global Climate Models (GCMs) vary in magnitude and sometimes in direction (increase / decrease) in relation to the baseline. Therefore, this section addresses how the threshold on GCMs agreement affects the locations in Brazil identified as refugia. This analysis is performed by comparing the number and the geographical locations of the grid cells projected as refugia for each studied taxon in Brazil and in each biome, under each future climate scenario included in this research. Three alternative levels of consistency are explored: one in which only 2 GCM agree that a grid cells is projected to act as a refugium, and alternatively requiring 11 or 19 GCMs to be in agreement (the three thresholds proposed and discussed on section 6.b "Implications for the analysis of the WI 'future climatic refugia' dataset" of the previous chapter of this thesis – for maps of refugia for each taxonomic group with GCMs agreement from 1 to 21, see Appendix 1.b). Refugia sizes are measured as the proportion that the land area projected to act as future refugia for each studied taxon in relation to the total land area of Brazil and each of its biomes (Figure 33). Moreover, the geographical locations of refugia are shown separately for each taxon and for each future warming scenario in the maps of Figure 34 to Figure 38 (Figure 34-Amphibia, Figure 35-Aves, Figure 36-Mammalia, Figure 37-Plantae, Figure 38-Reptilia).

Generally, the proportion of the country or biome land area identified as refugia decreases as the level of global warming increases and with higher levels of GCMs agreement. In Brazil, considering all combinations of the studied taxa and future warming scenarios, the proportional amount of land area identified as refugia that is discarded by increasing the level of GCM agreement from 2 to 11 is smaller than the proportional amount that is unconsidered when the GCMs agreement is increased from 11 to 19 (with the exception of amphibians under 2.7 and 3.2ºC of warming, birds under 6.0ºC of warming, and plants under 2.7 and 3.2ºC of warming). Likewise, when analysing refugia for each taxon, per biome, and future warming scenarios, the difference in size between the refugia identified by at least 2 and 11 models is smaller than the difference in size between the refugia identified by at least 11 and 19 models, for all combinations of taxon, biome, and future warming scenario (with the exception of refugia in the Amazon for amphibians at 2.7 and 3.2ºC, for reptiles at 6.0ºC, and in Cerrado for plants at 2.0ºC, and for amphibians at 2.7ºC of warming).

As for the refugia's geographical locations, in general, refugia identified by at least 19 climate models are surrounded by refugia identified by at least 11 models, that are surrounded by refugia identified by at least 2 models for almost all combinations of taxon, biome, and future warming scenario. However, there are some exceptions in which refugia identified by at least 2 GCMs do not have refugia under a higher level of agreement (i.e., refugia under 11 or 19 GCMs) at their core. This is case of refugia identified by at least 2 models under intermediate global warming levels (2.7 and 3.2ºC above pre-industrial levels) for amphibians (at the border of Amazon and Cerrado), birds (in Pantanal), and plants (in the Amazon and Caatinga). Conversely, adopting 11 models as a threshold would result in more evenly distributed refugia throughout the country in the lower levels of global warming (1.5 and 2.0ºC above pre-industrial levels), especially including locations in the Amazon, than adopting 19 models as threshold.

These comparisons suggest that, for Brazil and for its biomes, increasing the model consistency threshold on the refugium identification from 2 to 11 climate models increases the robustness of the findings without disregarding a large extent of land that might still be available for biodiversity conservation. On the other hand, increasing the GCMs consistency from 11 to 19 climate models leads to a steep decline in the refugia size which are mainly concentrated on the south part of the country, probably underestimating the extent of land area in Brazil with potential to act as future climate change refugia for terrestrial biota. Hence, adopting the medium threshold maintains a good robustness in climate projections without excessively restricting the options of locations that could be targeted for long-term conservation measures, such as the creation of new protected areas, and other nature-based solutions focused on climate change mitigation and adaptation. That is especially important for regions such as the Amazon, where increasing the number of GCMs agreement leads to including future bioclimatic projections that are discrepant in direction and value (as explained in chapter 3 section 5.a and section 6.b), and therefore the refugia size for this biome under the higher GCMs agreement is limited not only by the negative impacts of climate change on terrestrial biota, but also by the uncertainty embedded on the future climate projections.

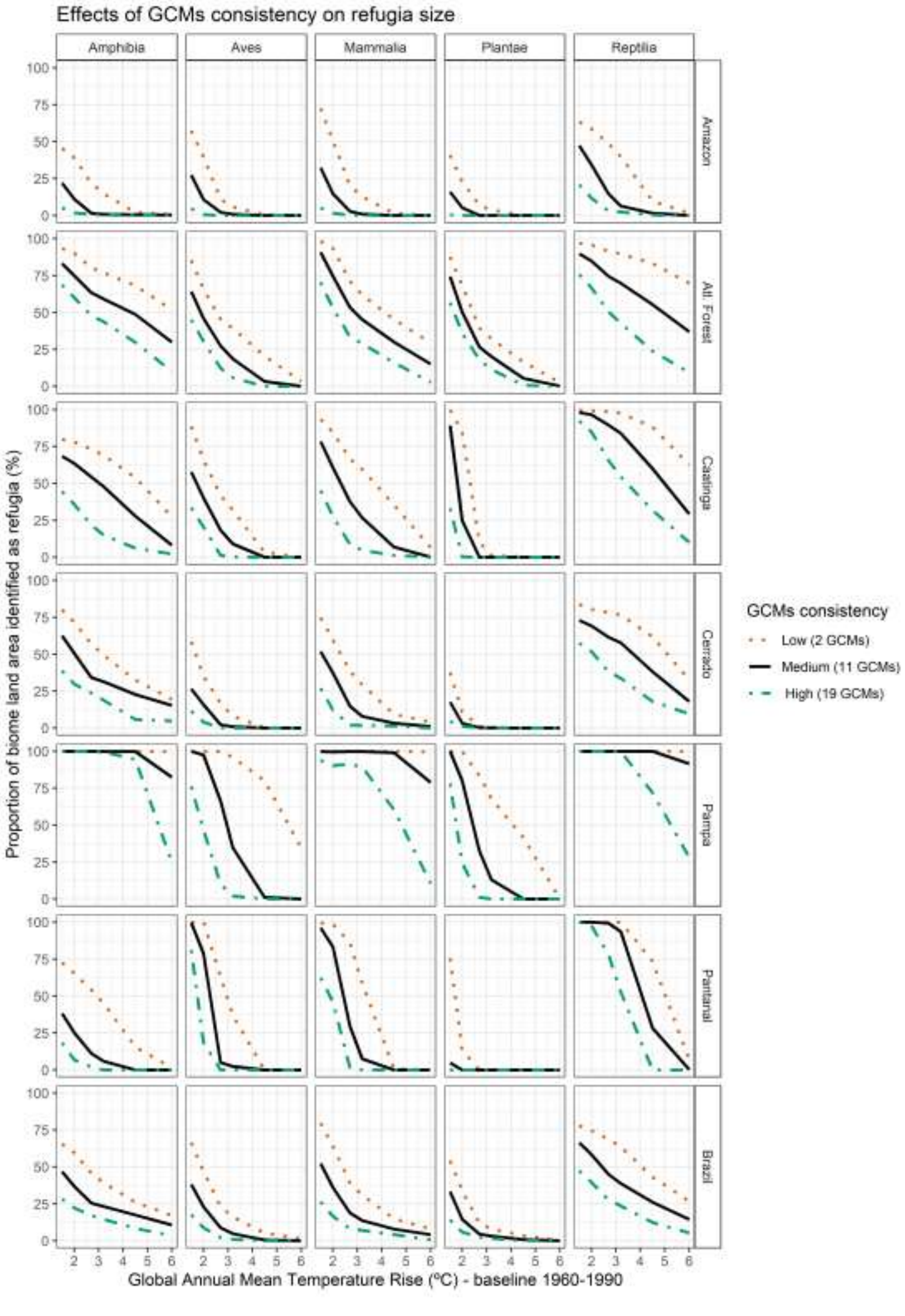


Figure 33: Effects of GCMs agreement on the size of future climatic refugia in Brazil and in each Brazilian biome for terrestrial species of five taxa (Amphibia, Aves, Mammalia, Plantae, and Reptilia) under increased levels of global warming (in relation to pre-industrial times). The three levels of climate models agreement are represented by different linetypes (2 models = low, 11 models = medium, 19 models = high) and the refugia size is measured as a proportion of the country/biome's total land area.

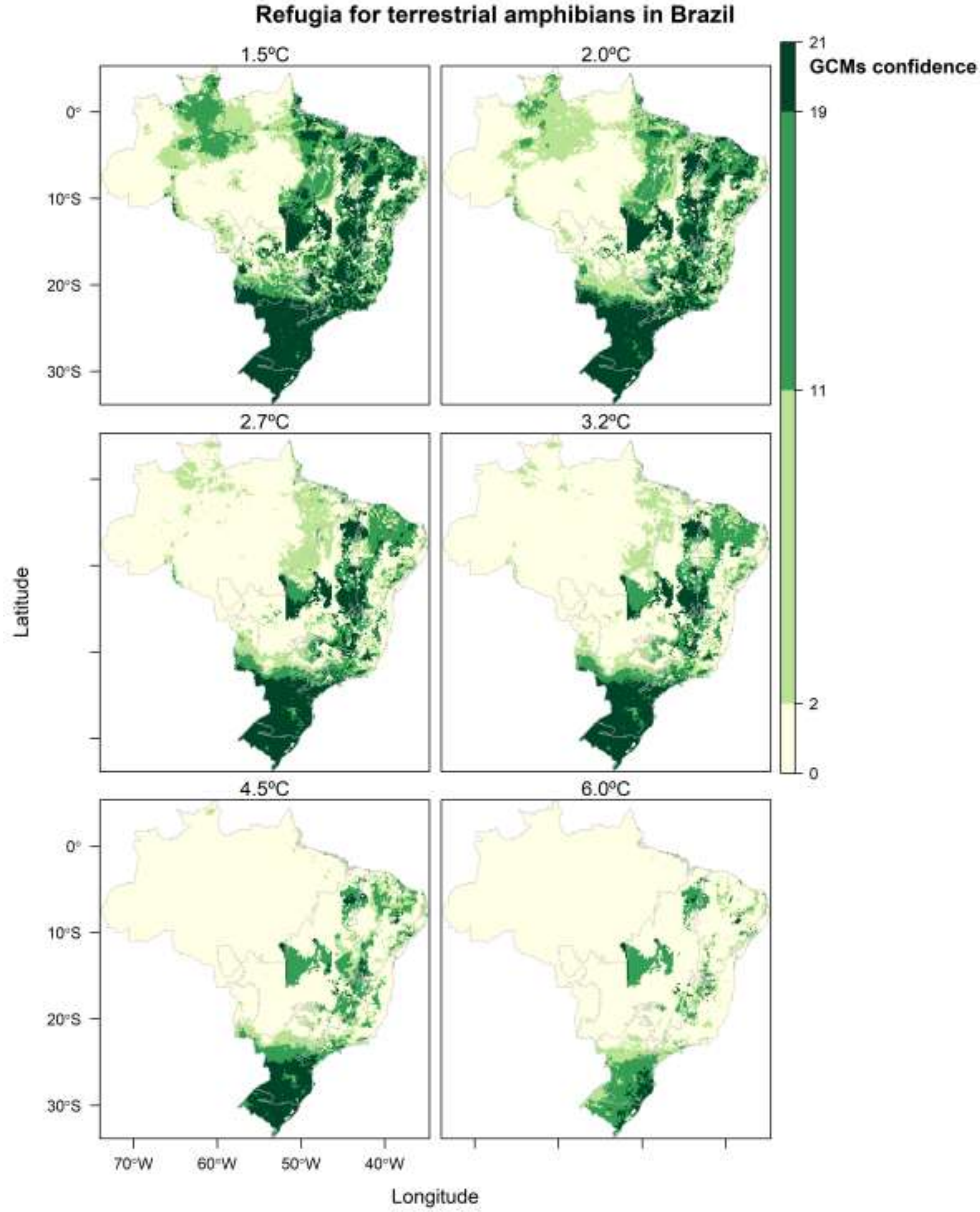


Figure 34: Map of the locations identified as potential refugia for amphibians by at least 2 (light green), 11 (green), or 19 (dark green) GCMs under six different levels of future global warming (in relation to the baseline). Colour scale represent the three different levels of GCMs confidence under analysis.

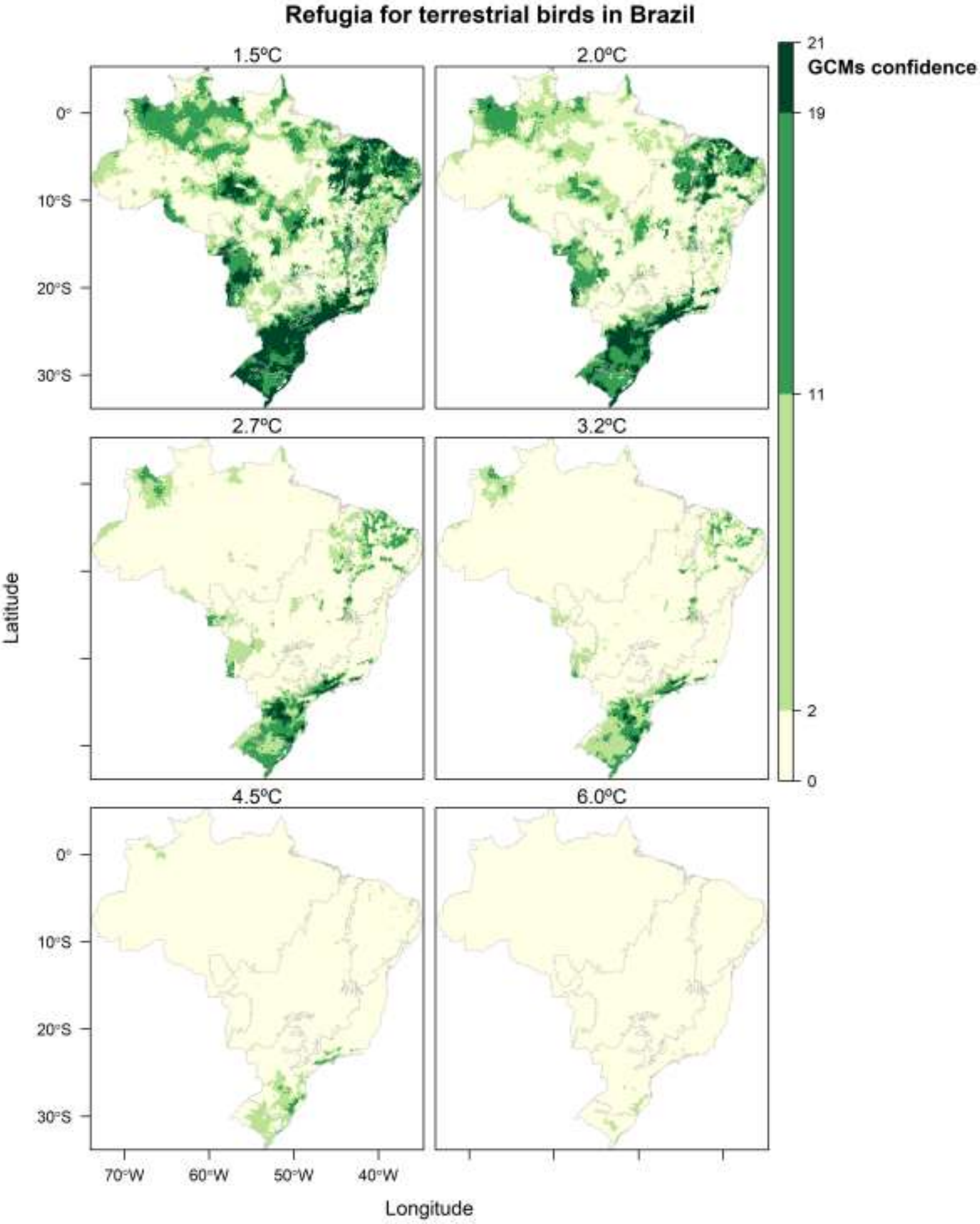


Figure 35: Map of the locations identified as potential refugia for birds by at least 2 (light green), 11 (green), or 19 (dark green) GCMs under six different levels of future global warming (in relation to the baseline). Colour scale represent the three different levels of GCMs confidence under analysis.

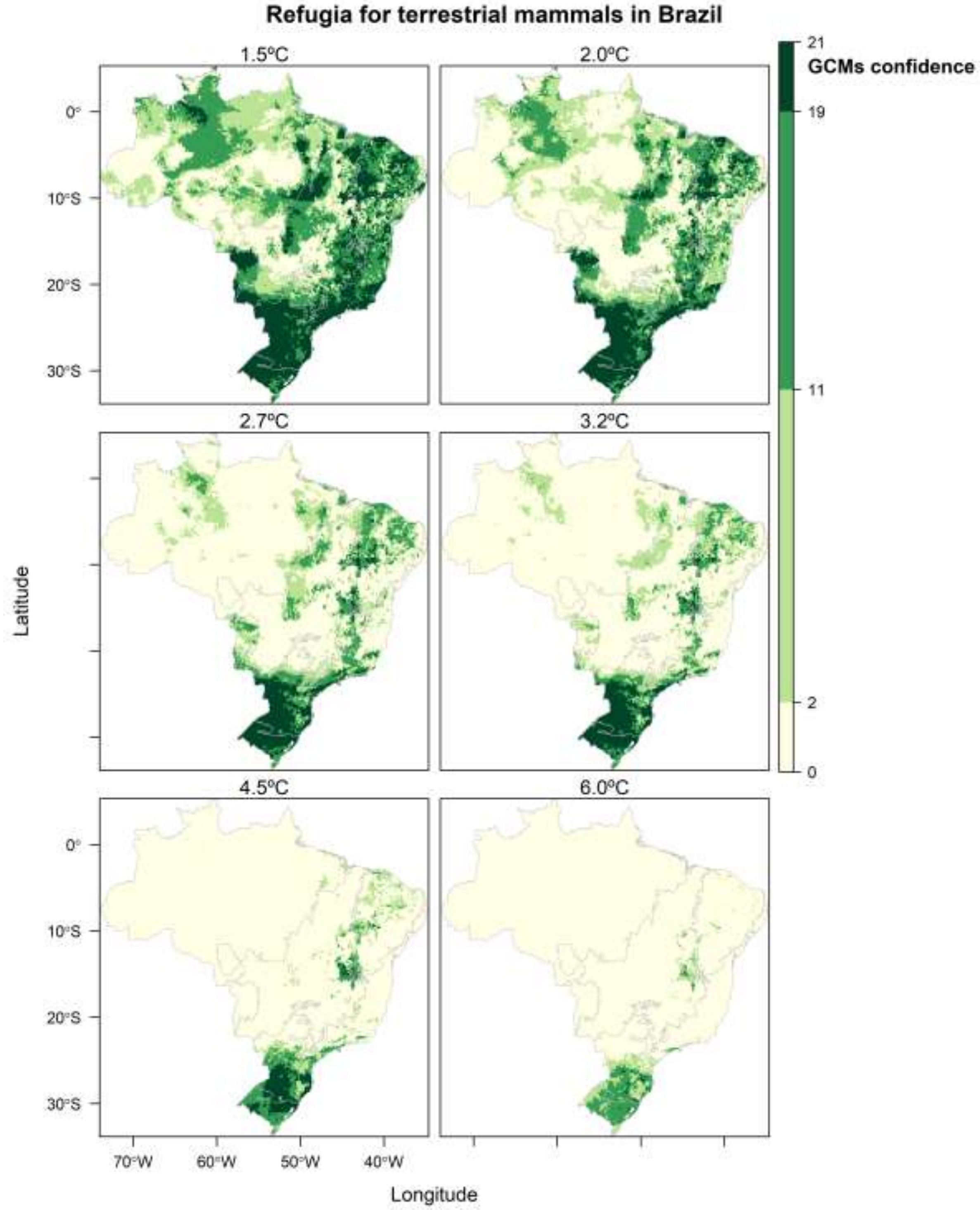


Figure 36: Map of the locations identified as potential refugia for mammals by at least 2 (light green), 11 (green), or 19 (dark green) GCMs under six different levels of future global warming (in relation to the baseline). Colour scale represent the three different levels of GCMs confidence under analysis.

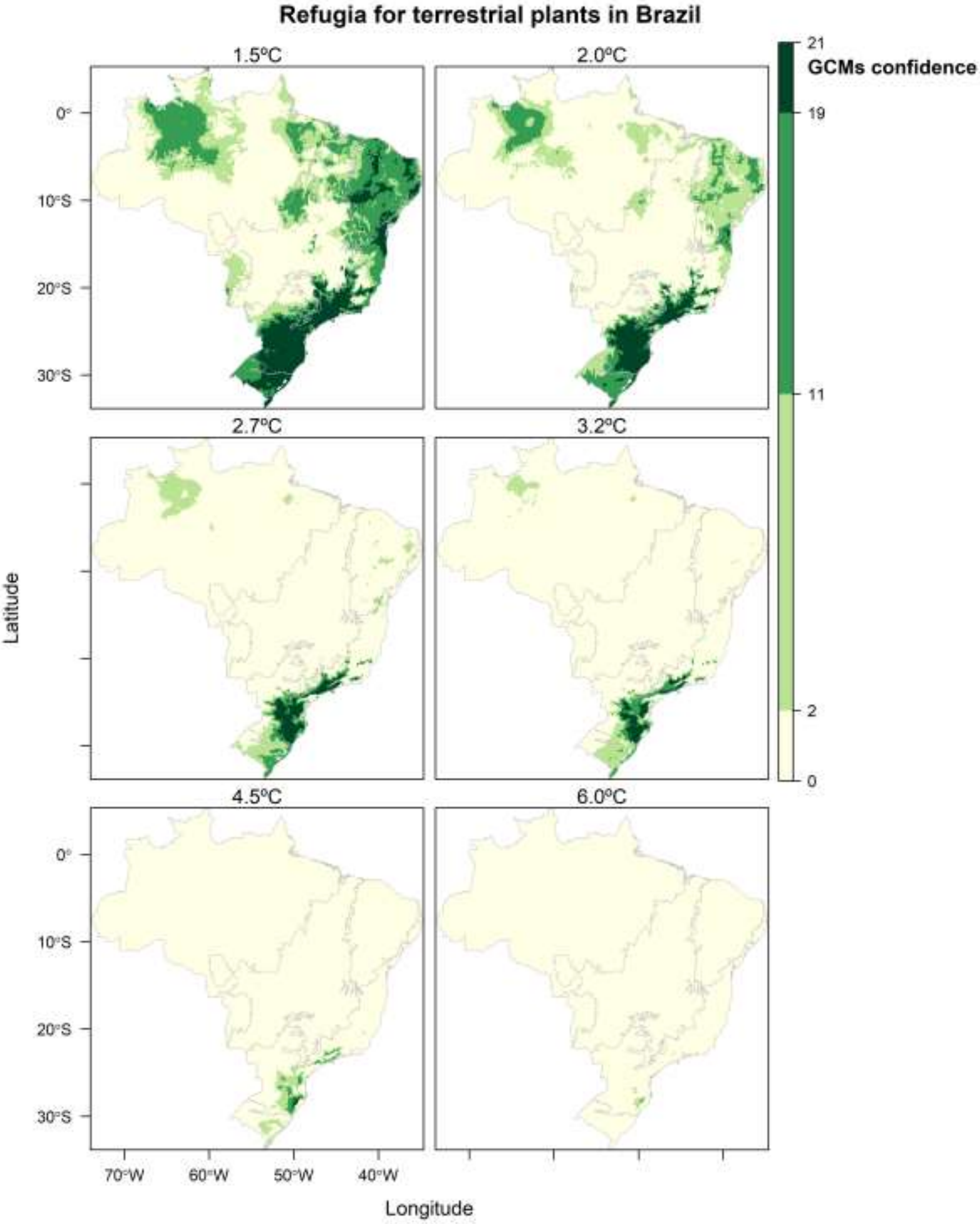


Figure 37: Map of the locations identified as potential refugia for plants by at least 2 (light green), 11 (green), or 19 (dark green) GCMs under six different levels of future global warming (in relation to the baseline). Colour scale represent the three different levels of GCMs confidence under analysis.

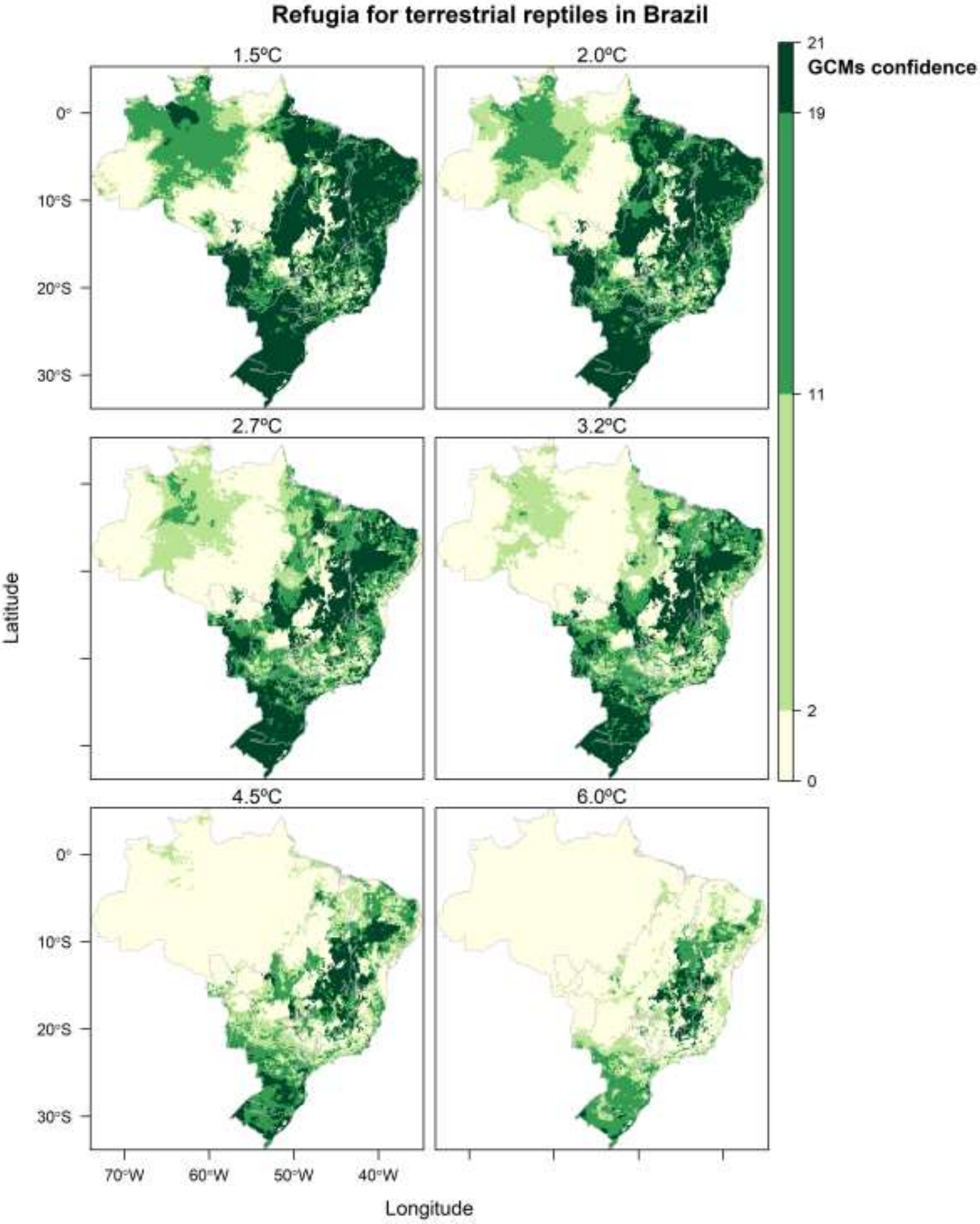


Figure 38: Map of the locations identified as potential refugia for reptiles by at least 2 (light green), 11 (green), or 19 (dark green) GCMs under six different levels of future global warming (in relation to the baseline). Colour scale represent the three different levels of GCMs confidence under analysis.

Based on the findings explained above, the medium GCMs agreement level (at least 11 models in agreement) of the WI ‘future climatic refugia’ dataset was adopted in the following analyses related to future climate change refugia in Brazil presented in this thesis.

b. Analysis related to thresholds on percentage of species remaining

(Warren et al. 2018b) defined climate change refugia as the locations that are projected to remain climatically suitable for at least 75% of the species modelled to currently be there and explained that ‘the threshold chosen [*of 75%*] is a compromise between identifying the highest quality refugia and identifying the most land that might still be available for conservation given land use constraints’. Thresholds lower than 75% would be more likely to imply that ecosystem structure and function would be lost, particularly if keystone species were lost. Thresholds higher than 75% would result in considerably smaller refugia that would constrain conservation options in landscapes were some conversion has already occurred.

However, the study did not investigate how the chosen threshold affects the size and geographical location of the areas identified as refugia. Considering that, this section analyses the effects of several proportion of species remaining under future scenarios of climate change that could be used as thresholds in the identification of refugia. The locations projected to remain climatically suitable for 0-20%, 30%, 40%, 50%, 60%, 70%, 75%, 80%, 90% and 100% of their modelled current number of species are presented considering the adopted threshold of 11 GCMs agreement. Similarly to the analysis related to threshold on GCMs consistency, the proportion of the biome total land area (Figure 39) and the geographical locations (Figure 40 to Figure 44) of the grid cells projected to maintain the abovementioned proportions of species in relation to their current biota were analysed for the five studied taxa, in Brazil and in each biome, under each of the six future climate scenarios included in this research.

Overall, the proportion of Brazilian or the biome’s land area that is projected to remain climatically suitable for their current modelled species decreases with higher levels of global warming, regardless of the threshold on percentage of species remaining used (Figure 39 – with exception of Pampa where the complete extent of the biome is projected to remain climatically suitable for at least 60% of its current amphibians, mammals and reptiles even in a 6.0ºC warmer world – the highest level of future global warming included in this research, but not for at least 75% of the species of these taxa). Moreover, the speed of decline on the amount of land area that is projected to remain climatic suitable under increased levels of global warming is specific to the taxon, and to the combination of taxon and biome (Figure 39) under analysis. However, for all combinations of taxa and biomes, this speed of decline depends on the threshold on percentage of species remaining, with higher thresholds generally leading to steeper declines in land area identified as climatically suitable for the biota modelled to currently be there (Figure 39). Moreover, some combinations of biomes and taxa shows greater resilience to the projected future changes on climate: around 75% of Pampa is projected to remain climatically suitable for at least 90% of its amphibians (resulting in ~64 species), and reptiles (resulting in ~19 species) if global warming is kept under 3.5ºC and 3.2ºC above pre-industrial levels, respectively. Around half of Caatinga land area is projected to remain climatically suitable for all 44 amphibian species modelled to currently be there if the global mean temperature doesn't rise more than 2.5ºC above pre-industrial levels.

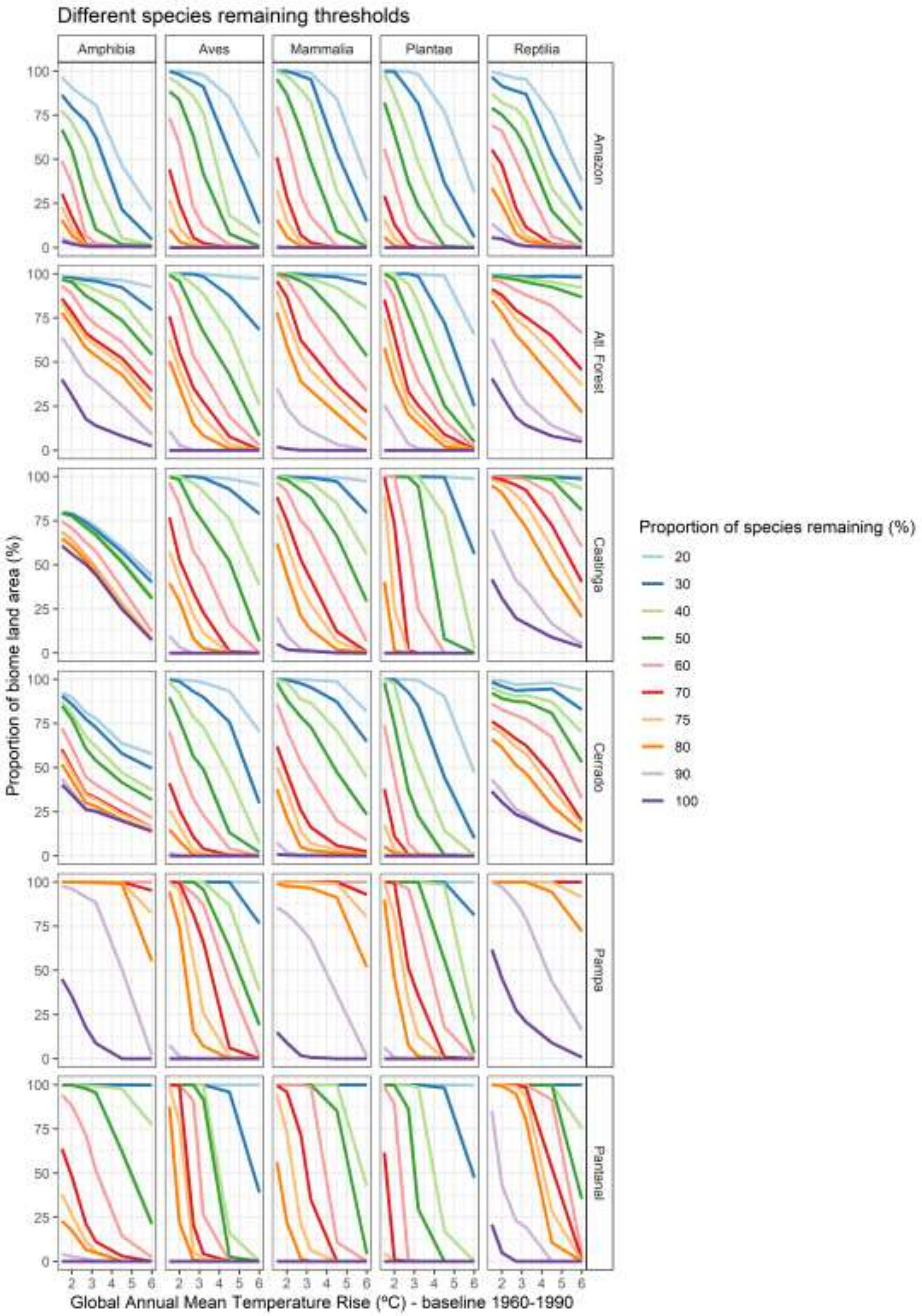


Figure 39: Effects of the species remaining threshold on refugia size in Brazil and in each Brazilian biome under increased levels future global warming (in relation to the baseline). Coloured lines represent the proportion of land area identified to remain climatically suitable for proportion from 20 to 100% of the current species number.

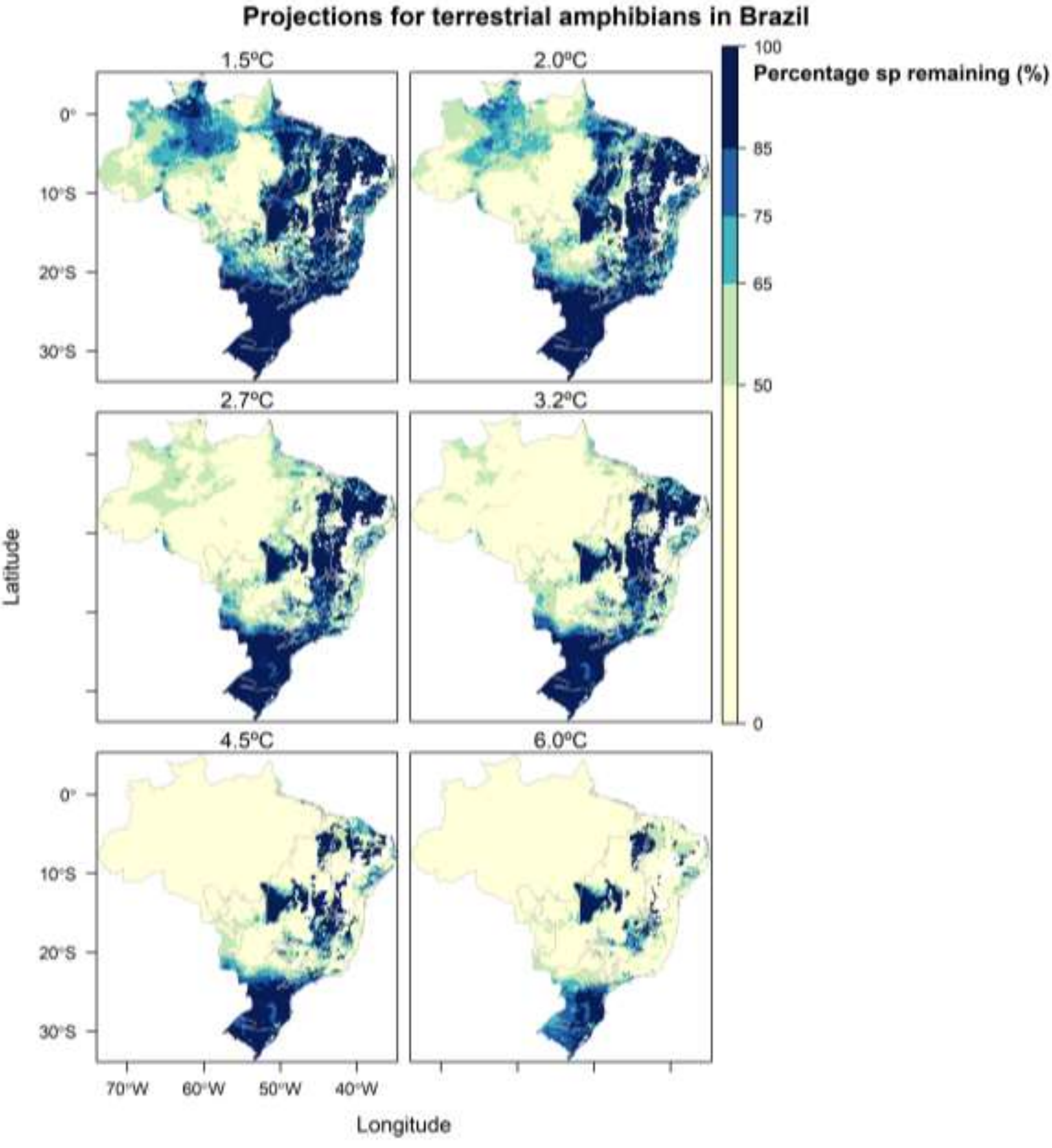


Figure 40: Maps of the locations projected to remain climatically suitable for 50-64% (light green), 65-74% (light blue), 75-84% (blue), and at least 85% (petroleum blue) of the amphibian species currently there by at least 11 GCMs under six different levels of future global warming (in relation to the baseline).

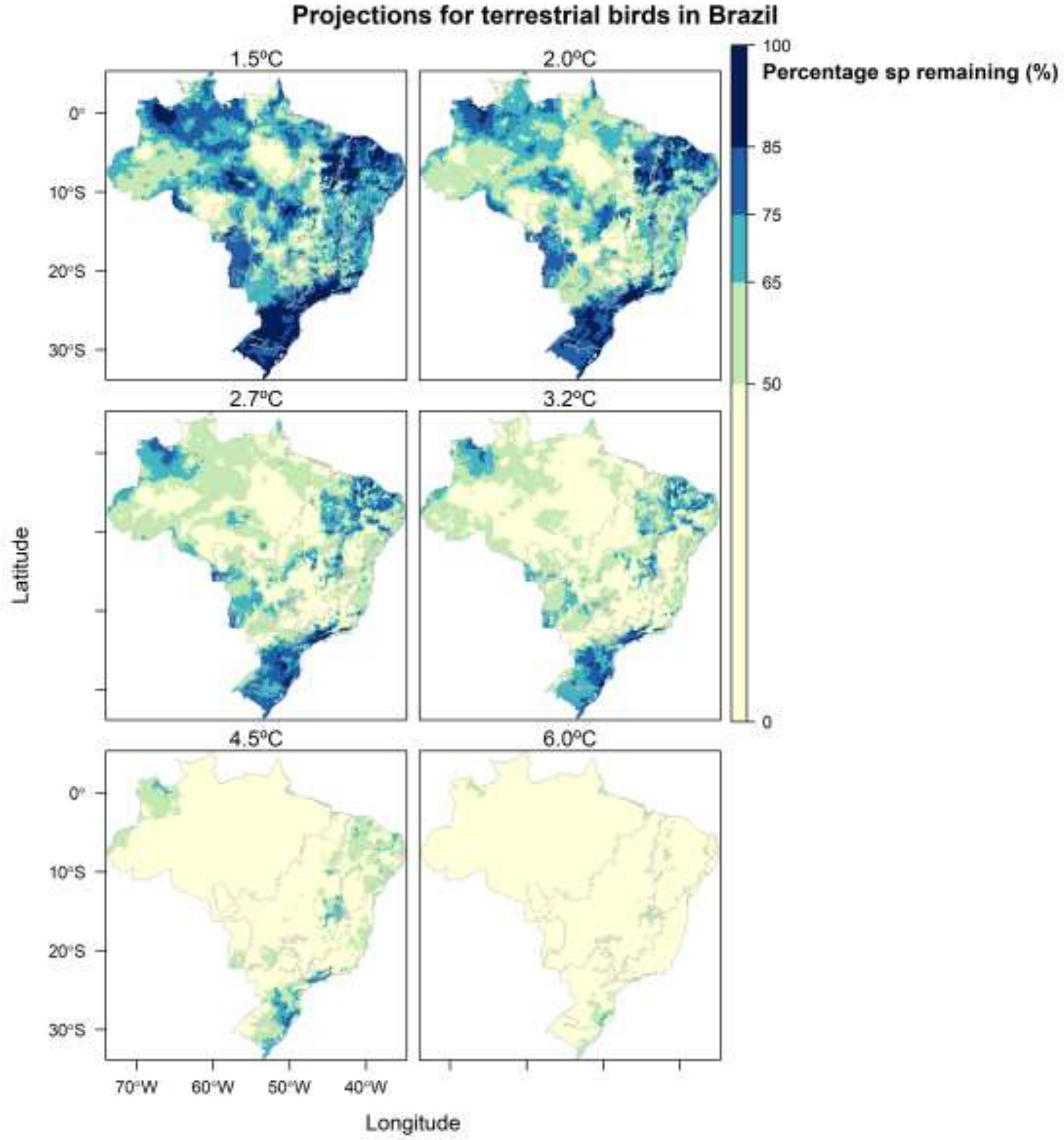


Figure 41: Maps of the locations projected to remain climatically suitable for 50-64% (light green), 65-74% (light blue), 75-84% (blue), and at least 85% (petroleum blue) of the bird species currently there by at least 11 GCMs under six different levels of future global warming (in relation to the baseline).

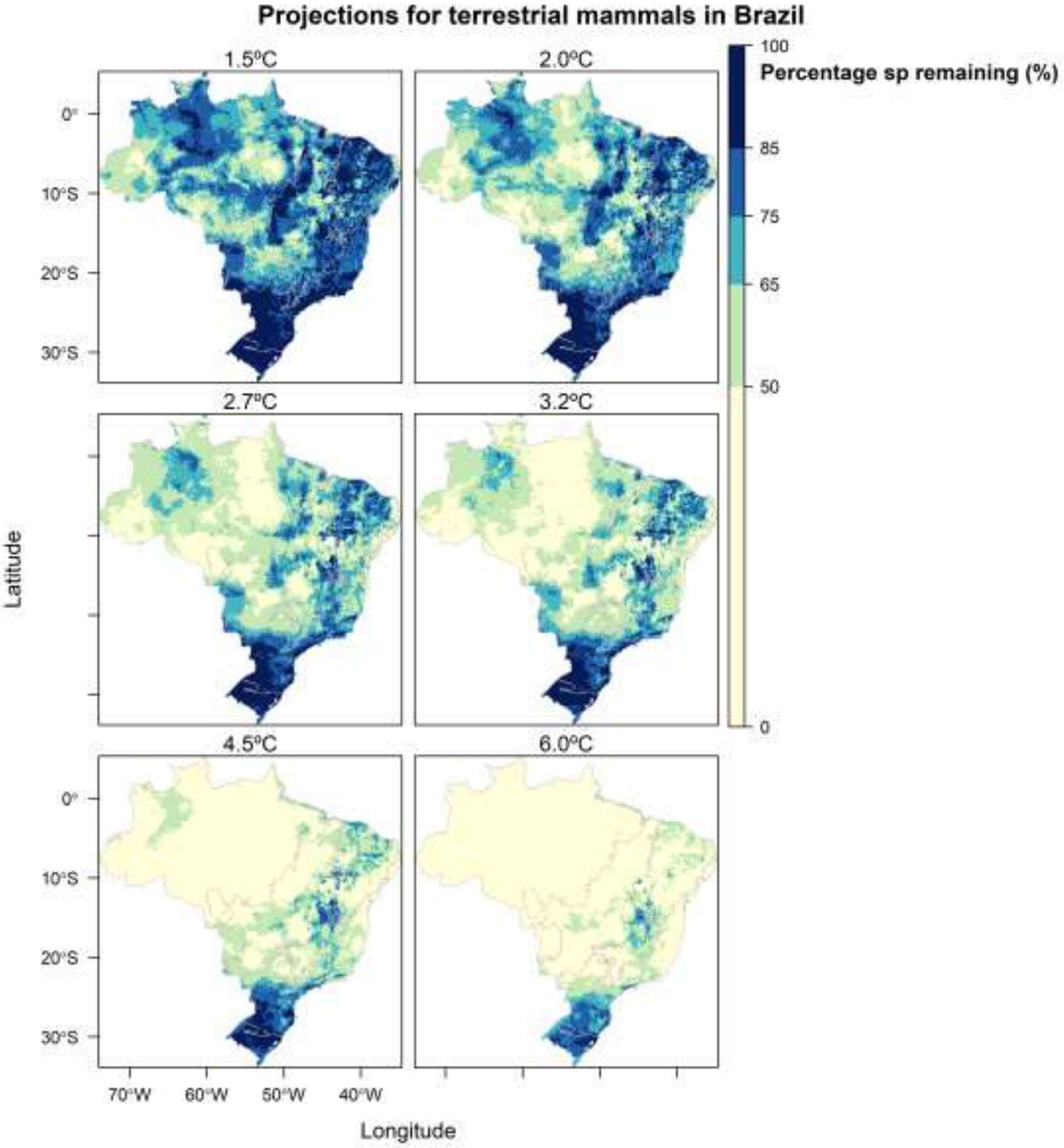


Figure 42: Maps of the locations projected to remain climatically suitable for 50-64% (light green), 65-74% (light blue), 75-84% (blue), and at least 85% (petroleum blue) of the mammal species currently there by at least 11 GCMs under six different levels of future global warming (in relation to the baseline).

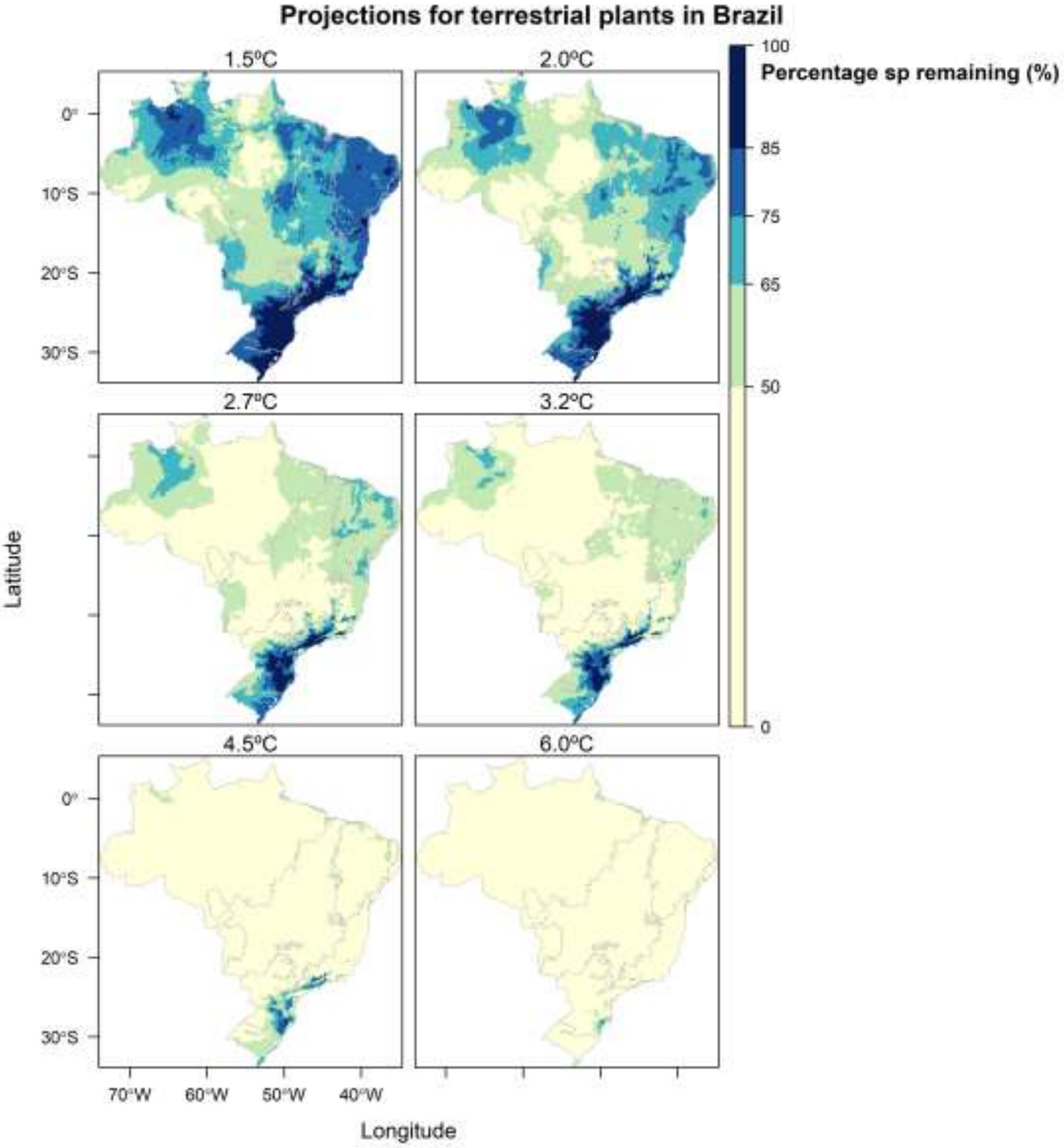


Figure 43: Maps of the locations projected to remain climatically suitable for 50-64% (light green), 65-74% (light blue), 75-84% (blue), and at least 85% (petroleum blue) of the plant species currently there by at least 11 GCMs under six different levels of future global warming (in relation to the baseline).

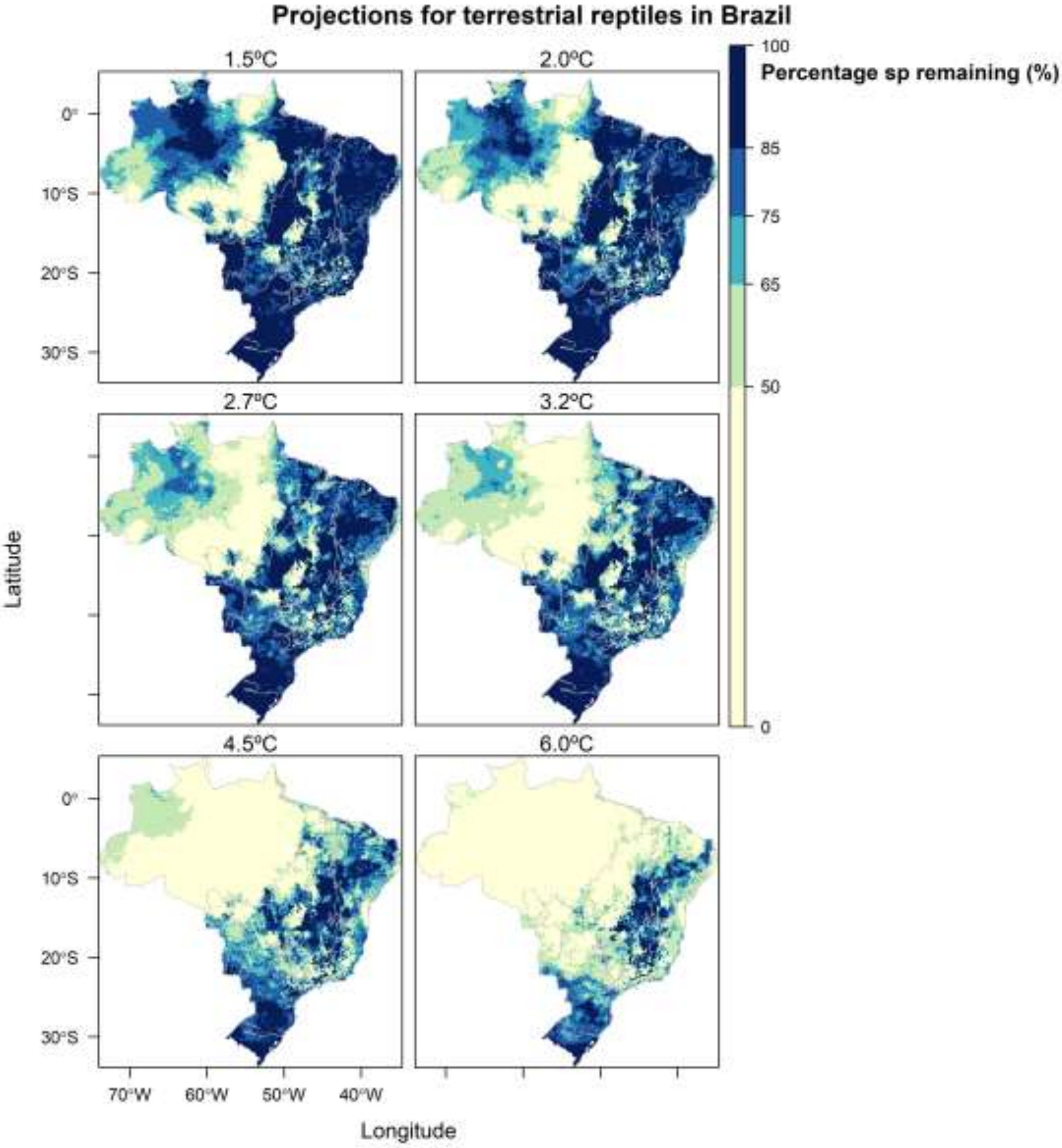


Figure 44: Maps of the locations projected to remain climatically suitable for 50-64% (light green), 65-74% (light blue), 75-84% (blue), and at least 85% (petroleum blue) of the reptilian species currently there by at least 11 GCMs under six different levels of future global warming (in relation to the baseline).

Considering the geographical location of the grid cells projected to remain climatically suitable for two of the presented thresholds, at least 50% and at least 75%, both in relation to the current biota, the areas identified by the lower threshold are generally not only encircling the refugia (i.e., at least 75%) patches, but also if protected would create or improve the connectivity between refugia within the same biome (Figure 40 to Figure 44). This connectivity is created or improved for patches identified as refugia located on:

- the western and eastern parts of the Amazon for all animal taxa and for plants, up to 2.0ºC and up to 1.5ºC warmer world, respectively.
- the northern part of the Amazon for amphibians in a 2.7ºC or 3.2ºC warmer world.
- the western part of the Amazon for birds, mammals, and reptiles up to 3.2ºC warmer world.
- the southern part of the Atlantic Forest for mammals, plants, and its complete extent for reptiles at higher levels of global warming (in a 4.5 or 6.0 ºC warmer for mammals and reptiles, and in a 4.5 ºC warmer for plants).
- Caatinga for amphibians (northern part in a 4.5 ºC warmer world), birds (up to 3.2ºC warmer world), mammals (up to 4.5ºC warmer world), and reptiles at higher levels of warming (in a 4.5 or 6.0 ºC warmer world).
- Cerrado for amphibians (the eastern part at 6.0 ºC warmer world), birds and mammals (up to 3.2ºC warmer world), and reptiles at higher levels of warming (in a 4.5 or 6.0 ºC warmer world).
- Pampa for birds and plants at 3.2ºC warmer world.
- Pantanal for reptiles at higher levels of warming (in a 4.5 or 6.0 ºC warmer world).

Together, the comparisons of size and geographical location of the areas projected to remain climatically suitable for several proportions of their current species suggest that, for designing a large-scale climate-smart biodiversity conservation initiative that promotes long-term connectivity, the patches identified as refugia (75% of species remaining) could act as core reserves or key steppingstones, while the regions identified with the lower species threshold (for example, 50% or 65%) could be useful to delimit larger biological corridors or buffer zones.

Worldwide, long-term *in-situ* biodiversity conservation is fostered by Protected Areas (PAs), classified in seven different categories by IUCN (Dudley, Shadie, and Stolton 2013) along with other area-based conservation measure (OECM), defined by CBD as “a geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the *in-situ* conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socio–economic, and other locally relevant values” (CBD 2018). In Brazil, each category of PA or OECM has a different level of restriction on the activities and uses that could take place within its boundaries (Brazilian PAs are explained in Chapter 5 section 3.b). Therefore, to design these initiatives, locations that are identified to remain climatically suitable for higher proportions of species (e.g., at least 75% as used by Warren et al. 2018b) could be targeted for the creation of new PAs or OECMs that have a higher restriction (for Brazil those could be strictly protected areas or Private natural heritage reserves), and the wider areas projected to remain climatically suitable lower proportions (e.g., for at least 50%) of their current biota could be targeted for the creation of new PAs or OECMs with lower level of restrictions, or for delimiting mosaics of areas with higher and lower levels of activities (for Brazil those could include sustainable use PAs, such as environmental protection area or extractive reserve – see Table 6 for comparison of IUCN PAs categories and Brazilian conservation units sub-categories).

Although it is very likely that the connectivity of future climatic refugia will have a crucial role in allowing species to disperse and to track their suitable climate, it is beyond the scope of this research to analyse species dispersal and potential ways of facilitate that (see discussion in section 7b of this Chapter).

For this reason, the next analysis presented in this chapter focuses in the areas identified to remain climatically suitable for at least 75% of their current biota to achieve the overarching aim of investigating the role that locations identified as future climate change refugia could play in conservation planning in Brazil that takes into consideration future effects of climate change on terrestrial biota.

5. Creation of the future climatic cross-taxon refugia

Future climatic cross-taxon refugia for terrestrial biota in Brazil are built on the results of the two sensitivity studies described in the previous sections of this chapter (sections 4.a and 4.b) regarding the projected future climatic refugia for each individual taxon in Brazil (i.e., the locations that are projected by at least 11 out of the 21 climate models considered by this study to remain climatically suitable for at least 75% of the species of this taxon modelled to currently be there). To address the potential need of keeping a high diversity of plants to maintain the functions of ecosystems undergoing disturbances (Isbell et al. 2011), these refugia include two types of cross-taxon refugia: the first considers as cross-taxon refugia a location that is projected as refugia simultaneously for any combination of two or more taxa (26 combinations possible – hereinafter named cross-taxon refugia). And the second considers as cross-taxon refugia a location that is projected as refugia simultaneously for plants and any animal taxon or any combination of two or more animal taxa (15 combinations possible – hereinafter named cross-taxon refugia conditional to plants). The geographical location of these two types of cross-taxon refugia is identified in Brazil and in its biomes and their sizes are calculated as a proportion of the country's or biome's total land area.

6. Analysis of the future climatic cross-taxon refugia in Brazil

Assuming that cross-taxon refugia are areas that are more likely to retain their current ecosystem structure and function despite the future climatic changes, these refugia could be targeted for conservation efforts that aim to simultaneously mitigate or adapt to future climate change (such as the creation of new PAs or the ecological restoration of degraded areas).

Considering that, the geographical locations of the two types of cross-taxon refugia (conditional on being refugia to plants or not) in Brazil and in its biomes are identified and their extent as a proportion of the country's or biome's total land area is calculated. The locations identified as cross-taxon refugia for all five taxa and cross-taxon refugia to plants and four animal taxa are the same, and for this reason are represented by the same colour on all figures of this section.

In general, the area in Brazil identified as potential cross-taxon refugia decreases as the mean global temperature increases (Figure 45 and Figure 47). If global warming is limited to 1.5ºC above pre-industrial levels, around 63% of the country land area has the potential to act as future climatic refugia for any combination of two or more taxa (Figure 45). However, if countries fail to strengthen their NDCs pledges and future levels of global warming reach 2.7ºC or 3.2ºC above pre-industrial levels, the proportion of the Brazilian land area that is projected to act as refugia for any combination of two or more taxa shrinks to 28% or 23%, respectively (Figure 45). Moreover, at these warming levels only 3% or 2% (respectively) of the country land area is projected to have the potential to simultaneously act as refugia for all five taxa (Figure 45).

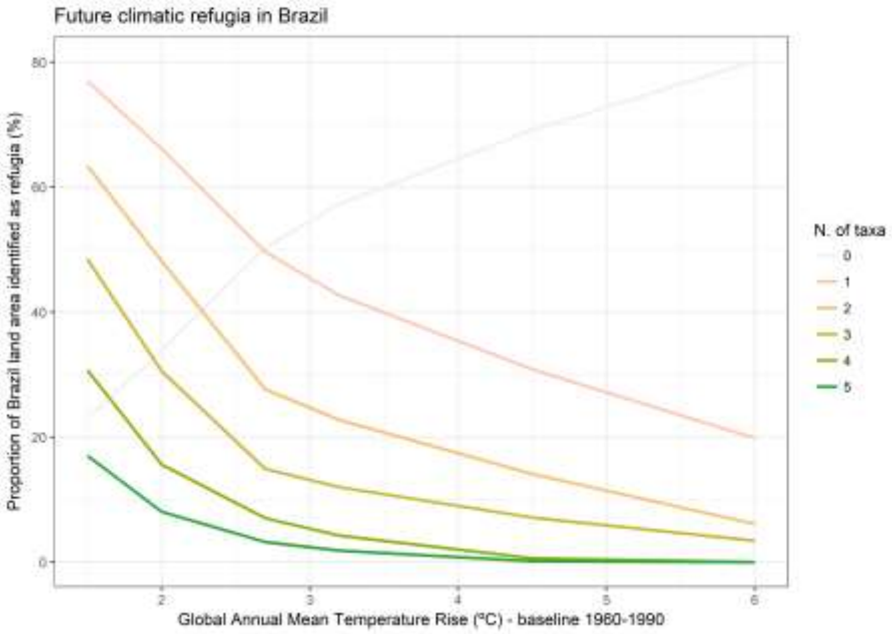


Figure 45: Proportion of land area in Brazil identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that there is a line for the land area not identified as refugia – grey, and one for refugia for one taxon that is not a cross-taxon refugia – light pink). Y-axis goes up to 80%.

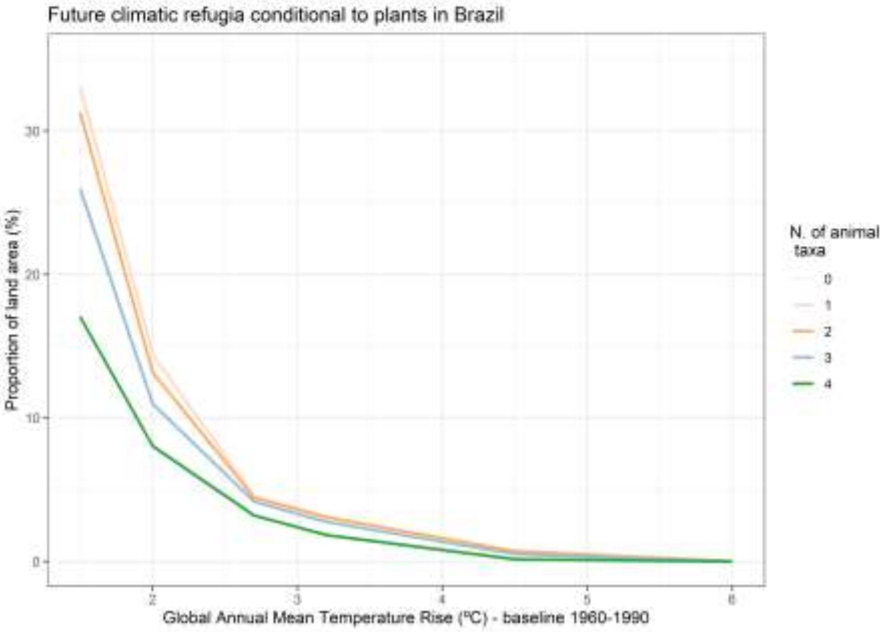


Figure 46: Proportion of land area in Brazil identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of other taxa simultaneously included in the refugia along with plants (note that there is a line for the land area not identified as refugia – grey). Y-axis goes up to 35%.

When the condition that a location needs to be identified as future climatic refugia for plants to be classified as future climatic cross-taxon refugia (i.e., cross-taxon refugia conditional to plants) is included, the size and the geographical spread of these refugia reduce. In a 1.5ºC warmer world, the proportion of the country identified as refugia for at least three taxa decreases from 48% for any three taxa to 31% for plants and any two taxa (any three taxa shown in Figure 45 versus plants and any two animal taxa shown in Figure 46). Moreover, including this condition confines refugia to the southern part of the Atlantic Forest and Pampa in a world 2.7ºC (or more) warmer than pre-industrial times (Figure 48).

Regardless of the type of future climatic cross-taxon refugia (conditional or not on being refugia for plants), the amount of land area identified as cross-taxon refugia in Brazil varies depending on the combination of biome and future warming level under analysis (Figure 47 and Figure 48). Consequently, to better understand the relation between the projected future warming levels and the projected cross-taxon refugia, the analysis of the locations identified as future climatic cross-taxon refugia is presented per Brazilian biome in the following subsections.

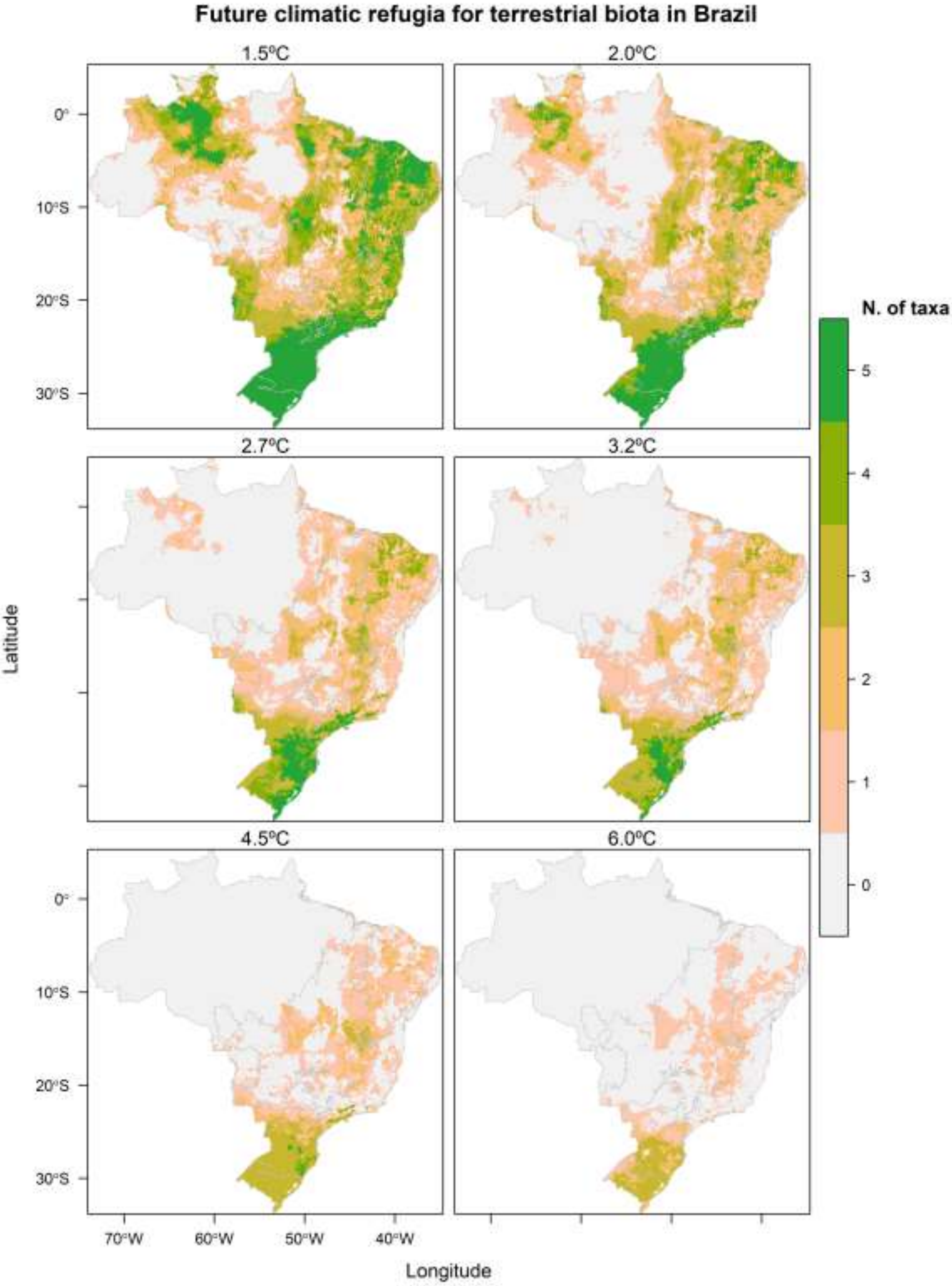


Figure 47: Map of the locations projected as future climatic cross-taxon refugia under six different levels of future global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is grey, and the one identified as refugia for one taxon that is not a cross-taxon refugia is light pink).

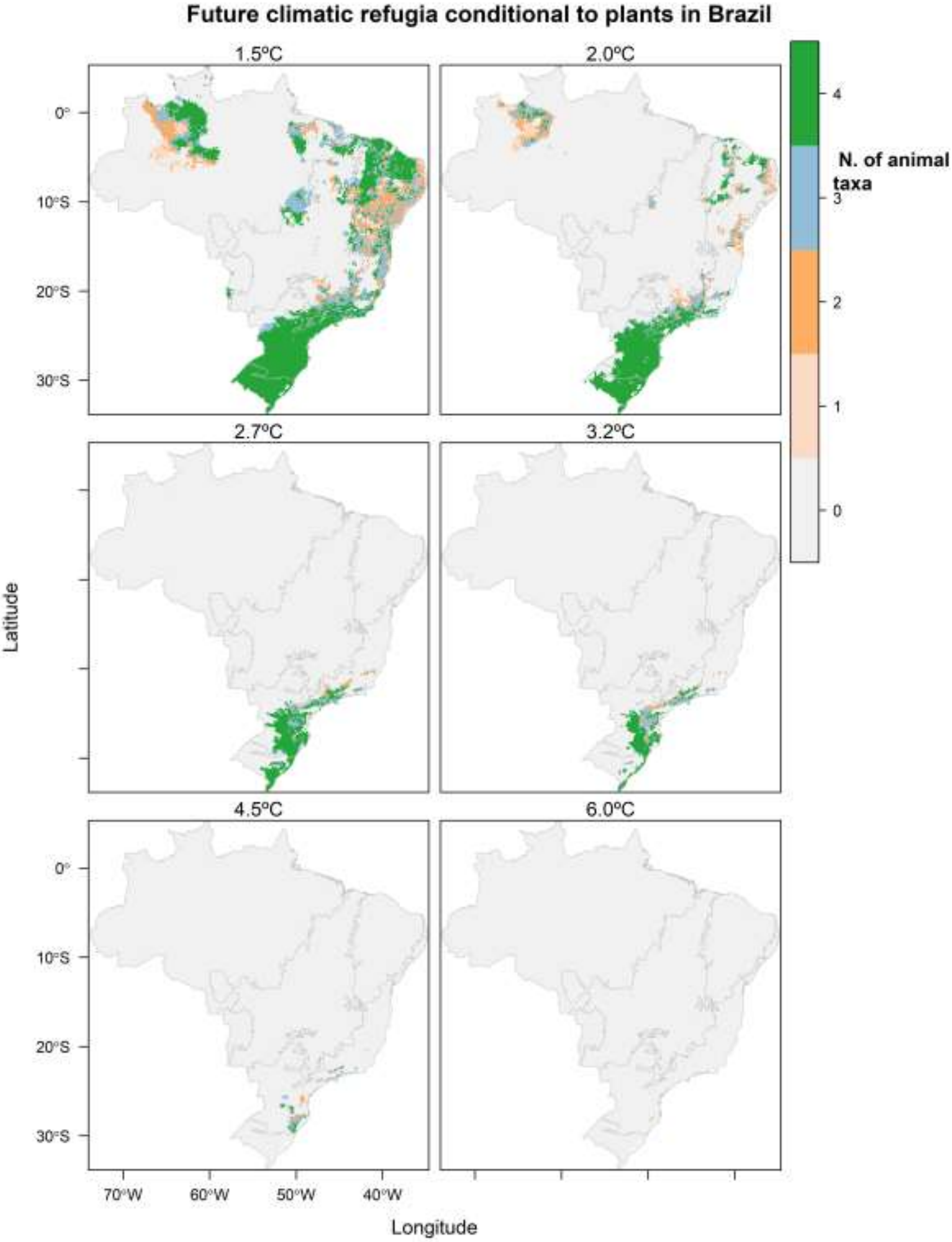


Figure 48: Map of the locations projected as future climatic cross-taxon refugia conditional on being refugia for plants under six different levels of future global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia conditional to plants is grey).

a. Amazon

The land extent that is projected to have the potential to act as future climatic cross-taxon refugia in the Amazon decreases with higher levels of global warming (Figure 49 and Figure 50), exhibiting a similar decreasing trend to the one shown on the national analysis.

However, for the Amazon, even the projections under the lowest warming level analysed (1.5ºC above pre-industrial levels) suggest that this biome's climate suitability for its current biota will substantially diminish. In a 1.5ºC warmer world, only a quarter of the Amazon land area is identified as cross-taxon refugia for any three taxa (Figure 49), and just above 14% of its extent is projected to act as future cross-taxon refugia for plants and any two animal taxa (Figure 18). In a 2.0ºC warmer world, the proportion of Amazon's land area identified as cross-taxon refugia declines to 9% for any three taxa (Figure 49), and 4% for plants and any two animal taxa (Figure 50). In levels of warming above the ones set as "safe" limits by the Paris Agreement, a very small proportion of the biome's land area is identified as future cross-taxon refugia for at least two taxa, regardless if its conditional on being refugia to plants (~0.02% in a 2.7ºC warmer world – Figure 50) or not (3.4-1.2% in a 2.7-3.2ºC warmer world, respectively – Figure 49).

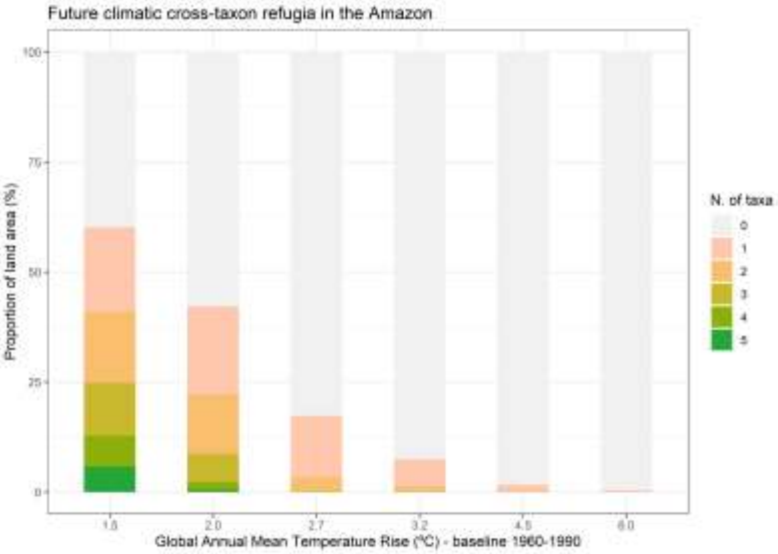


Figure 49: Proportion of land area in the Amazon identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is represented by grey, and refugia for one taxon is represented by light pink).

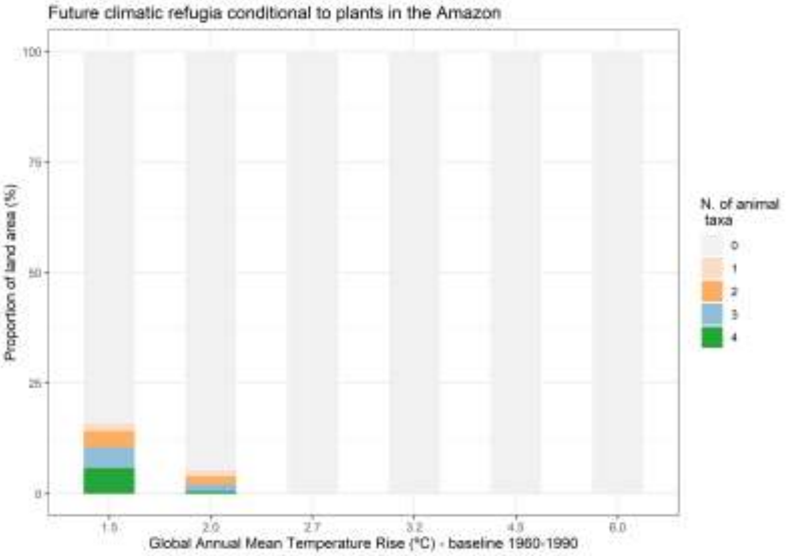


Figure 50: Proportion of land area in the Amazon identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia is represented by grey).

Regarding the geographical location of refugia within the Amazon, cross-taxon refugia for any two taxa (conditional or not on being refugia to plants) is concentrated in the north-east and north-west portions of the biome, and around the middle point of its border with Cerrado in scenarios up to 2ºC warmer than pre-industrial levels (Figure 47 and Figure 48). In scenarios above 2ºC, there is no cross-taxon refugia conditional on being refugia for plants (Figure 48) and only small areas in the border with Cerrado and in the north-western portions of the biome are projected as cross-taxon refugia for any two or three taxa (Figure 47). It should be stated that the bioclimatic projections for these regions identified as future refugia in the Amazon do not present any peculiarity that would distinguish them from the rest of the biome (see chapter 3 section 5.c). Consequently, the refugia potential that these regions are projected to have is due to a combination of the projected future climate and the characteristics of the biota currently there. In addition, it is worth highlighting that the cross-taxon refugia on the north-west portion of the Amazon, which are at the middle course of the Rio Negro (the largest left tributary of the Amazon river), include the Imeri Mountains (at the border of Brazil with Venezuela), one of the Quaternary forest refugia described by Haffer (1969) that triggered the "Amazonian refugia hypothesis", partially supported by the biomes projections in the Last Glacial Maximum (LGM) and in mid-Holocene (Arruda et al. 2018). Finally, the results presented here that this region is not projected as potential refugia if global warming exceeds 2.0ºC above pre-industrial levels corroborate with findings from Brown et al. (2020) that suggest that since the LGM this region have had the climatic conditions to drive a higher species richness but will not be able to act as a refugia under high levels of future climate change.

Although some previous studies that aimed to analyse the interactions between future climate change and biodiversity in the Amazon used different metrics (e.g., vulnerability, exposure), all corroborate that future climate change, if unresolved, will imperil Amazon's biodiversity. Projections for amphibians (Foden et al. 2013; Silva et al. 2018; Warren et al. 2018b), birds (Foden et al. 2013; Warren et al. 2018b; Miranda, Imperatriz-Fonseca, and Giannini 2019; De Moraes et al. 2020), primates (Graham, Matthews, and Turner 2016; Sales et al. 2020), mammals (Ribeiro et al. 2016; Ribeiro, Sales, and Loyola 2018; Pacifici, Visconti, and Rondinini 2018; Warren et al. 2018b; Sales et al. 2020), trees' species (Miles, Grainger, and Phillips 2004; Anadón et al. 2014; Gomes et al. 2019), plants (Warren et al. 2018b), a common snake species (Mesquita, Pinheiro-Mesquita, and Pietczak 2013), lizards (Pontes-da-Silva et al. 2018; Diele-Viegas, Werneck, and Rocha 2019), and reptiles (Warren et al. 2018b), and the ones derived from different vegetation modelling approaches (Salazar, Nobre, and Oyama 2007; Cook and Vizy 2008; Warszawski et al. 2013) showed similar alarming results to the ones presented in this thesis, suggesting that the Amazon rainforest is threatened to undergo an ecosystem change if global warming is not constrained up to 3ºC above pre-industrial levels. In fact, limiting global warming to as close to 1.5ºC as possible, as stated in the Paris Agreement, would be even more beneficial to insects, vertebrates, and plants currently in the Amazon (Warren et al. 2018a). However, empirical studies have shown that the vegetation of this biome is more 'resilient to climatic drying than is currently represented in vegetation-climate models' (Malhi et al. 2008), what could increase the time-lag between when climatic changes happen and when their projected impacts on biota are observed (but note that Seddon et al. 2016, in another empirical study, showed that the sensitivity of Amazon's vegetation to climate variability is mainly driven by temperature and cloudiness).

Therefore, the findings presented here along with previous projections of the impacts of climate change on terrestrial biota in the Amazon suggest that, if there is a climate tipping point for this biome, the current global mean temperature is probably closer to it than previously thought (Lenton et al. (2008) and Salazar and Nobre (2010) suggested global mean temperature of 3-4ºC above pre-industrial levels that has been supported by Nobre et al. (2016) and Lovejoy and Nobre (2018), but more recently Warszawski et al. (2013) suggested a global mean temperature closer to 3ºC), but the effects of exceeding it will probably be observed at a later time.

b. Atlantic Forest

Although the projections of future climate suitability for the Atlantic Forest under future climate change show the same decreasing trend of the projections for Brazil (and for the Amazon), the land area identified as cross-taxon refugia in this biome exhibits lower decline rates than the country as global temperature rises (Figure 51 and Figure 52). Moreover, the Atlantic Forest is one of the two Brazilian biomes that is projected to remain with the potential to act as cross-taxon refugia for all five taxa even if global efforts fail to meet the Paris Agreement targets (Figure 47 and Figure 48). In addition, the Atlantic Forest is projected to be the only biome to host refugia for all five taxa in a 4.5ºC warmer world (Figure 47 and Figure 48).

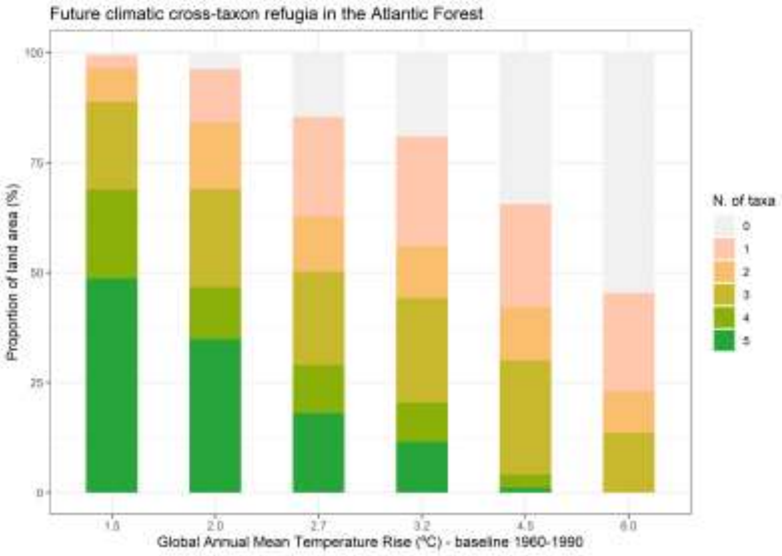


Figure 51: Proportion of land area in the Atlantic Forest identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is represented by grey, and refugia for one taxon is represented by light pink).

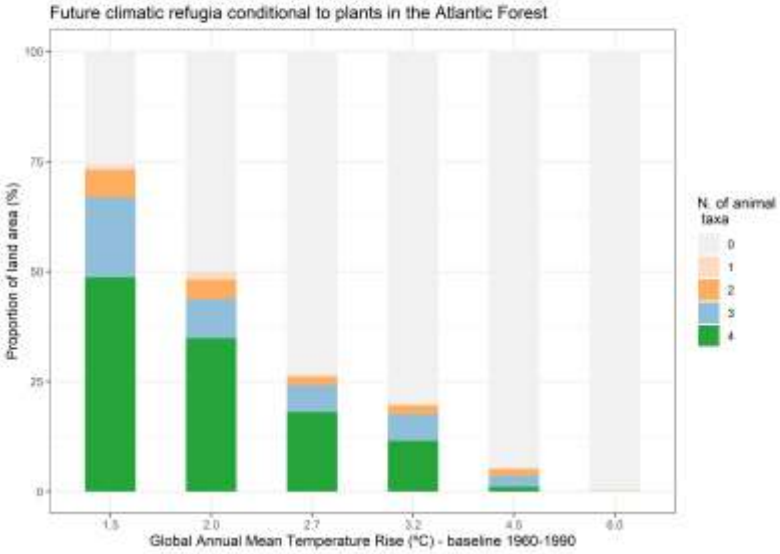


Figure 52: Proportion of land area in the Atlantic Forest identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia is represented by grey).

However, future climatic cross-taxon refugia are not evenly distributed in this biome, as the land area in the Atlantic Forest that is projected as future cross-taxon refugia for at least three taxa (Figure 47) or for plants and any two taxa (Figure 48) is disproportionally bigger on the southern part than on the northern part of the biome. In fact, if global warming is not limited to 2.0ºC above pre-industrial levels, very few and small areas in the northern part of the Atlantic Forest are identified as potential refugia for at least three taxa (Figure 47) or for plants and any two taxa (Figure 48). And in a 3.2ºC warmer world, only the central and southern parts of this biome are projected as potential refugia for plants and at least one animal taxon (Figure 48).

The decrease in climatically suitable locations and predominance of refugia in the central and southern parts of the Atlantic Forest found here corroborate with the projections of future potential distribution under climate change conditions for amphibians (Hof et al. 2011; Lemes and Loyola 2013; Loyola 2014; Vasconcelos and Do Nascimento 2016) – but note that Loyola (2014) also suggested that future climatic changes benefit amphibians basal clades), birds (Marini et al. 2009b; Marini et al. 2009a; Marini et al. 2010; De Souza et al. 2011; Hoffmann, Vasconcelos, and Martins 2015), 38 species of trees (Colombo and Joly 2010), and for a common snake species (Mesquita, Pinheiro-Mesquita, and Pietczak 2013).

It is worth noting that the most resilient future refugia identified by this research are in the central and southern portions of the Atlantic Forest, locations that under future climate change are projected to undergo an increase in the total annual precipitation, as well as in the precipitation of the driest and wettest quarters, differently than the rest of the biome (see chapter 3 section 5.d). Moreover, these future refugia match the regions previously identified as refugia from the Pleistocene for frogs (central part (Carnaval et al. 2009)), and endemic animals (central and southern parts (Porto, Carnaval, and da Rocha 2013) but note that these are not the only putative Quaternary refugia in the Atlantic Forest). These locations that acted as refugia in the past and are projected as refugia under future climatic conditions have potentially the best prospects of safeguarding species while future climate is unfavourable, and then, if conditions are suitable again, allow species to disperse from them (Barrows et al. 2020). Thus, these are ideal locations to be further investigated, validated, and included in landscape planning that aims to simultaneously promote climate change adaptation and biodiversity conservation.

c. Caatinga

The proportion of the land area in Caatinga identified as future climatic cross-taxon refugia for terrestrial biota also declines with increasing levels of global warming (Figure 53 and Figure 54). Different from previous biomes, the rate of decline greatly depends whether cross-taxon refugia is conditional or not on being refugia for plants (Figure 53 and Figure 54).

Regarding the two lower levels of warming adopted by this research, i.e. 1.5 and 2.0ºC above pre-industrial levels, the highest quantity (both in absolute – km^2 and proportionate – % measures) of potential future cross-taxon refugia for all five taxa in the Brazilian regions closer to the Equator falls within Caatinga (Figure 47, Figure 48, Figure 53, and Figure 54). In the 1.5ºC and 2.0ºC warming scenarios, 36% and 9%, respectively, of this biome’s land area is identified as cross-taxon refugia for five taxa (Figure 53 and Figure 54). However, in levels of future warming higher than the ones targeted by the Paris Agreement, there are no refugia for plants in this biome (Figure 39), extending the threat posed by future climate change on endemic plant species (Silva et al. 2019) to all species currently occurring in the biome.

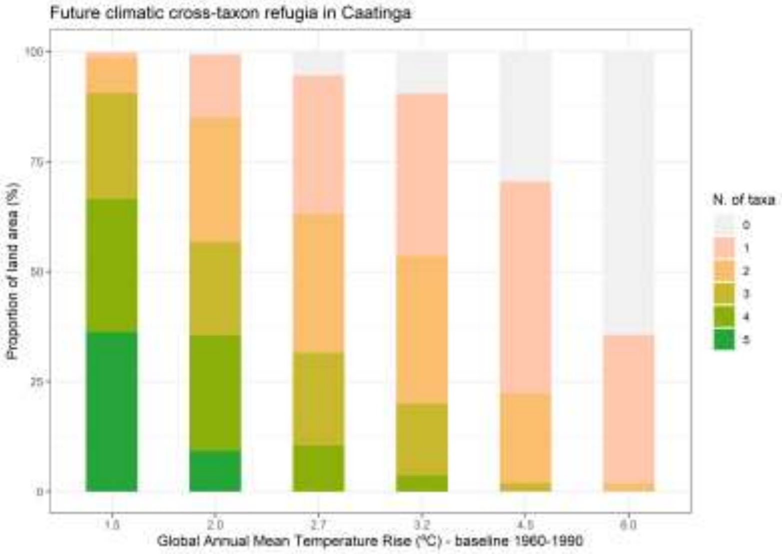


Figure 53: Proportion of land area in Caatinga identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is represented by grey, and refugia for one taxon is represented by light pink).

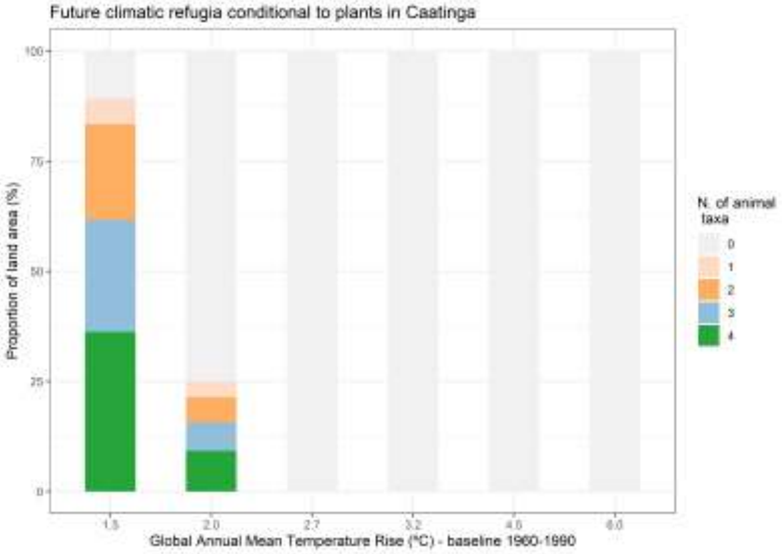


Figure 54: Proportion of land area in Caatinga identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia is represented by grey).

If global warming is limited to 2.0ºC above pre-industrial levels, cross-taxon refugia in Caatinga for the five taxa are mainly in the central-west and northern part of this biome (Figure 47). In the lowest warming scenario considered by this research (1.5ºC warmer), refugia in Caatinga are found in big and well-connected patches. However, allowing further warming of 0.5ºC on global mean temperature (reaching 2.0ºC above pre-industrial levels) drastically reduces these refugia sizes in 75% and is detrimental to their connectivity (Figure 47). Although there are no cross-taxon refugia conditional on being refugia for plants in levels of warming that exceed 2.0ºC, around 10% of Caatinga's land area is projected as cross-taxon refugia for all four animal taxa in a 2.7ºC warmer world, and roughly 4% in a world 3.2ºC warmer than pre-industrial times (Figure 53).

Caatinga's ecosystem has been pinpointed as ecologically sensitive to climate variability mainly due to changes in water availability (Seddon et al. 2016). It is worth recalling that the northern portion of Caatinga is projected to undergo an increase in its total annual precipitation, and in the precipitation of the wettest and driest quarters, with low to high GCMs agreement see chapter 3 section 5.e). However, the precipitation of the wettest quarter is projected to increase almost throughout the biome (regardless of the level of GCMs agreement) and the one of the driest quarter is also projected to increase in a big region that encompasses the central, the south, and the west of this biome (with high GCMs agreement), regions that are not projected as potential refugia. In addition, the lack of agreement among the future projections for temperature and precipitation for Caatinga has been suggested as the reason for the lack of consensus on the projections of changes for the geographical distribution of the Caatinga biome (Salazar, Nobre, and Oyama 2007). Hence, the bioclimatic projections alone cannot fully explain the refugia locations, but rather indicate where most of the terrestrial species currently present in Caatinga might thrive despite the projected changes in precipitation and temperature.

d. Cerrado

The projections of Cerrado's future climate suitability for its current biota presented in this study suggest that the land area in this biome with potential to act as future refugia declines as global mean temperatures rise (Figure 55 and Figure 56), endorsing the findings of (Warren et al. 2018b). In addition, this biome's refugia potential declines at a different rate whether refugia is conditional on being refugia for plants or not (Figure 55 and Figure 56), underscoring that Cerrado is at risk of ecosystem change under future climatic conditions (Warszawski et al. 2013).

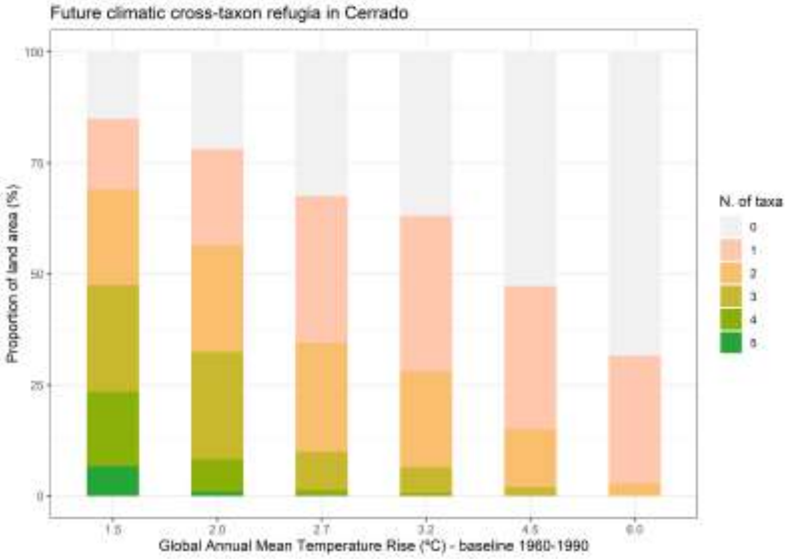


Figure 55: Proportion of land area in Cerrado identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is represented by grey, and refugia for one taxon is represented by light pink).

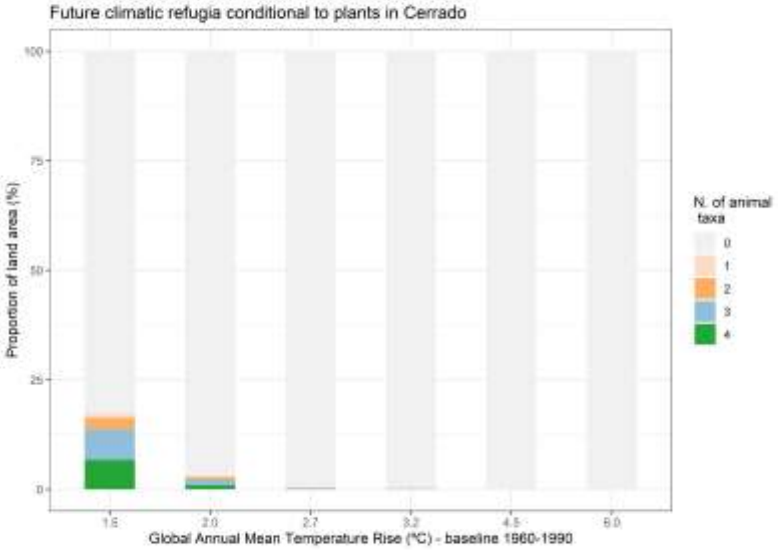


Figure 56: Proportion of land area in Cerrado identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia is represented by grey).

For Cerrado, even when the lowest warming level (1.5ºC above pre-industrial times) is considered, less than half of this biome’s land area has the potential to act as future climatic cross-taxon refugia for any combination of three or more taxa (Figure 55), and just above 16% is projected to act as future cross-taxon refugia for plants and any two or more animal taxa (Figure 56). If the Paris Agreement targets are not met and global warming reaches 2.7ºC above pre-industrial levels, the land area in Cerrado that is projected as potential cross-taxon refugia for any combination of at least three taxa decreases 69-79% when compared to 1.5 and 2.0ºC scenarios respectively, restricting this type of refugia to only 10% of this biome's land area (Figure 55). Moreover, considering cross-taxon refugia conditional on being refugia for plants, the projections are as alarming as the ones for the Amazon, corroborating that Cerrado is also threatened to undergo a severe ecosystem change due to future changes in climate (Warszawski et al. 2013). In a 2.0ºC warmer world, up to 3% of the Cerrado land area is projected as potential refugia simultaneously for plants and one or more animal taxa (Figure 56). And, if warming levels continue to increase reaching 2.7ºC above pre-industrial times, cross-taxon refugia conditional to plants would represent less than 0.5% of Cerrado's land area (Figure 56).

Regarding the geographical location of future cross-taxon refugia within Cerrado, they are mainly located at the edges of the biome, e.g., northern portion of Cerrado, border with the Amazon and Caatinga, central-west portion of Cerrado, border with the Amazon, central-east portion of Cerrado, border with Caatinga, and southern portion of Cerrado, border with Atlantic Forest (Figure 47). Remarkably, a big part of the core of this biome is not identified as refugia for any taxon alone, and this no-refugia area expands in all directions as global temperature rises (Figure 47). However, there is no clear connection between this area of no-refugia in Cerrado and the projections for the eight bioclimatic variables investigated in chapter 3 of this thesis (see Chapter 3section 5.f), contradicting the approach used by (Borges and Loyola 2020) that defined future climate refugia for birds in this biome as areas projected to undergo lower levels of anomaly on precipitation and temperature. On the other hand, the refugia identified in the eastern region of the biome, near the border with the south of Caatinga, are resilient as cross-taxon refugia for any two taxa even under the highest level of global warming included in this research (6.0ºC above pre-industrial times - Figure 47). And these refugia match the locations where there is a high GCMs agreement on the projections that future climate change will lead to an increase in precipitation during the driest quarter (see chapter 3 section 5.f).

Moreover, considering cross-taxon refugia that is conditional on being refugia for plants, there are fewer and smaller patches identified with this potential in a 1.5ºC warmer world (Figure 48), than with the potential to act as refugia for any combination of two or more taxa (Figure 47). In addition, cross-taxon refugia conditional to plants in Cerrado in the scenario of 2.7ºC above pre-industrial levels are very small (less than 0.5% of biome's land area) and situated in Paraná state, where the southern border of this biome with the Atlantic Forest is found (Figure 48).

The results presented here that the central area of Cerrado is not projected as future climatic refugia for any taxon and that the most resilient cross-taxon refugia conditional on being refugia to plants are on the southern border of Cerrado and Atlantic Forest corroborate with the findings from other studies that projected the impacts of future climate change on:

(a) the distribution of vegetation types in Paraná – showed that the savannah vegetation is projected to be constrained to its southern border or to replace forests that are even further south (Trindade, Santos, and Artoni 2020).
(b) plants species relative loss (in relation to the current species richness) within Cerrado - showed that the biome's southern border, along with other few patches, are projected to lose less species (relatively) than the rest of the biome in Brazil (Velazco et al. 2019).
(c) plants species net loss within Cerrado – showed that the biome's central region is projected to lose more species than the rest of the biome in Brazil (Velazco et al. 2019).
(d) presumed late Quaternary climate refugia – showed that the late Quaternary refugia in the central-west part of Cerrado will not have the climate conditions to potentially act as refugia for biodiversity until the end of the 21st century (Brown et al. 2020).
(e) geographical distribution of birds – showed that the centroids of the geographical ranges of the 26 species studied are projected to shift southeast if species are not allowed to disperse beyond their current range (Marini et al. 2009a).
(f) geographical distribution of tree species – showed that the potential geographical distributions of 91-123 (optimistic x pessimistic future climate scenarios) out of the 126 tree species considered are

projected to decrease more than 90%, along with shifts to the south and east parts of the biome (Siqueira and Peterson 2003).

e. Pampa

Pampa is the most southern biome in Brazil and the one with more optimistic projections on the potential to act as future climatic cross-taxon refugia than Brazil as a whole or the other Brazilian biomes (Figure 57 and Figure 58).

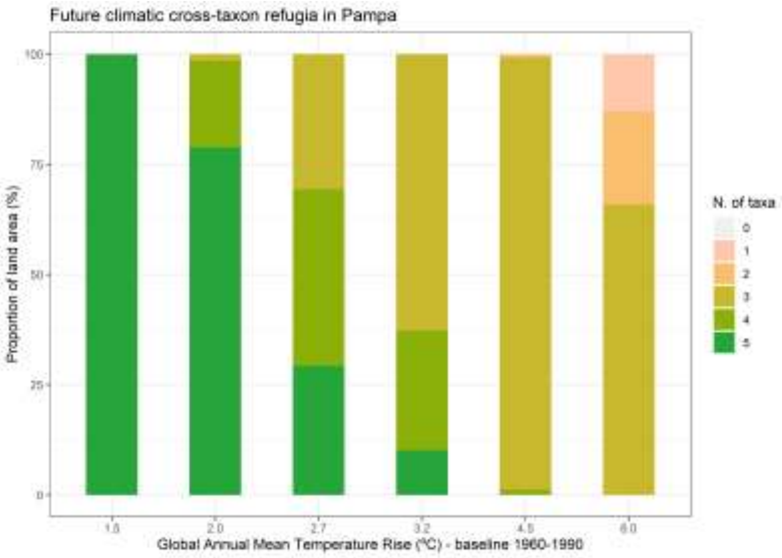


Figure 57: Proportion of land area in Pampa identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is represented by grey, and refugia for one taxon is represented by light pink).

Pampa is the only biome that 100% of its land area is projected to have the potential to act as future climatic refugia simultaneously for all five studied taxa in the lowest warming level considered by this research (1.5ºC above pre-industrial levels), and that almost 80% of its land area is identified as cross-taxon refugia for all taxa in a 2ºC warmer world (Figure 57). It is also the only biome where 99% or more of its land extent is projected to act as cross-taxon refugia for any combination of three taxa in warming levels up to 4.5ºC (Figure 57).

Moreover, Pampa and the Atlantic Forest are the two biomes that have at least 10% of their land areas projected to have the potential to act as cross-taxon refugia for all five taxa if global warming does not exceed 3.2ºC above pre-industrial levels (Figure 57 – Pampa and Figure 51 – Atlantic Forest). In addition, these cross-taxon refugia for all taxa shrink as the global mean temperature rises, contracting to the eastern region of Pampa in levels of warming between 2.7 and 3.2ºC above pre-industrial levels (Figure 48). However, future refugia projections for this biome are not so optimistic when cross-taxon refugia is conditional on being refugia for plants (Figure 58). In this case, the land area identified as cross-taxon refugia for plants and any other three animal taxa decreases 60% between the warming levels of 2.0ºC and 2.7ºC, representing only 13% of the biome's land area in a 3.2ºC warmer world (Figure 58) in a very thin patch along Pampa's eastern coast line (Figure 48).

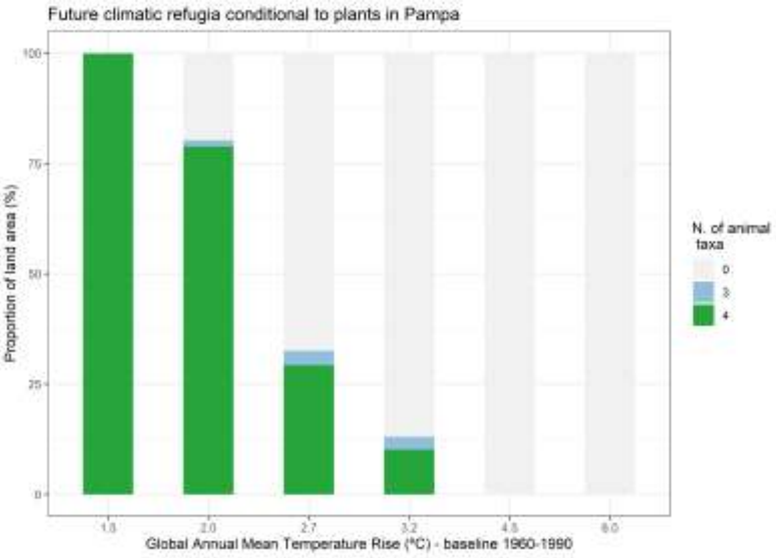


Figure 58: Proportion of land area in Pampa identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia is represented by grey).

It is worth mentioning that this research is the first analysis about the possible impacts of future climate change on Brazilian Pampa's wildlife built on results from SDMs that used species' occurrence data. Previous studies that investigated this topic using different modelling techniques have projected an increase in the forest cover in the Uruguayan or in the Brazilian Pampa at the expense of grassland areas (Salazar, Nobre, and Oyama 2007; Anadón et al. 2014), a transition that has been suggested as a natural process in this biome (Lemos et al. 2014).

The findings presented here show that, if the Paris Agreement targets are met, Pampa will have the potential to act as refugia for plants and vertebrates throughout its land area (Figure 60), meaning that the biome will remain climatically suitable for most of its current biota. Hence, in lower levels of global warming, it is possible to hypothesise an expansion of the forest cover and all the benefits that it could bring for climate change mitigation. However, if global warming reaches 3.2ºC above pre-industrial levels, refugia for the plant species currently present in Pampa will be mainly on the east coast of the biome, an area that is currently dominated by grasslands (Hasenack et al. 2010). Therefore, an expansion of Pampa’s forests seems to be possible only on lower levels of future climate change, but an in-depth analysis of Pampa’s plant species current and future potential geographical ranges is needed to support or contradict this finding.

f. Pantanal

The future projections regarding Pantanal’s potential to act as future climatic cross-taxon refugia for all five taxa are the most pessimistic ones in the country, as it is the only biome that completely loses this potential if global warming reaches 2.0ºC above pre-industrial levels (Figure 59and Figure 60).

Pantanal is the Brazilian biome that has the lowest proportion of its land area (4.7%) with potential to act as future climatic cross-taxon refugia for all five taxa in a 1.5ºC warmer world in relation to pre-industrial levels (Figure 59). These locations identified as potential refugia for all taxa are concentrated in two patches: one is on the central-west portion of the biome, closer to the Brazilian border with Bolivia than to the border between Pantanal and Cerrado, and the other is on the extreme south of Pantanal, close to the border with Paraguay and Cerrado (Figure 47). Moreover, it is the only biome that is projected to completely lose the potential to act as future cross-taxon refugia conditional on being refugia for plants if global warming reaches 2.0ºC above pre-industrial levels (Figure 60 and Figure 48).

On the other hand, considering cross-taxon refugia only for animals (i.e., refugia not limited by plants in levels of warming higher than 1.5ºC above pre-industrial levels), 68% of Pantanal’s land area is identified as cross-taxon refugia for any combination of at least 3 animal taxa in a 2.0ºC warmer world (Figure 59), a much better scenario than the ones projected for the Amazon, Caatinga, and Cerrado, and as good as the one projected for the Atlantic Forest (Figure 48). However, the proportion of land area in this biome that is projected to have the potential to act as cross-taxon refugia for animals decreases 65-90% if global warming exceeds 2.0ºC and reaches 2.7ºC above pre-industrial levels (65% decrease in cross-taxon refugia of any 2 taxa, 90% of any 3 taxa and 80% of any 4 taxa – Figure 58).

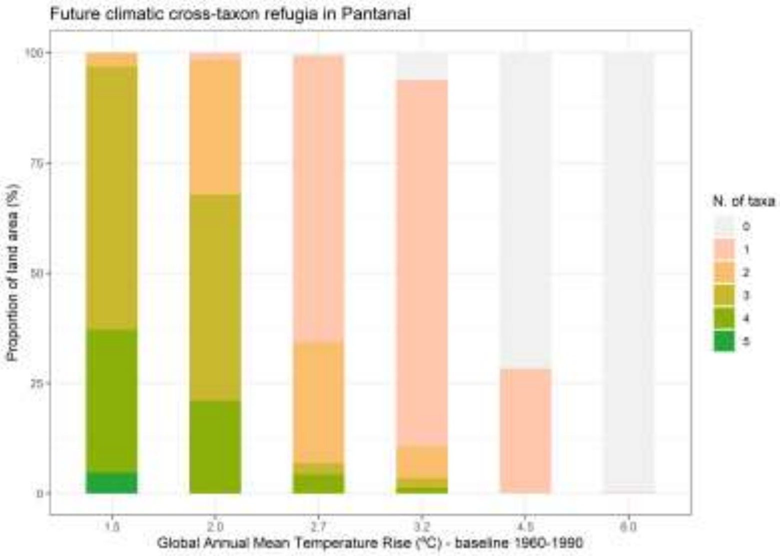


Figure 59: Proportion of land area in Pantanal identified as future climatic cross-taxon refugia under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia (note that the land area not identified as refugia is represented by grey, and refugia for one taxon is represented by light pink).

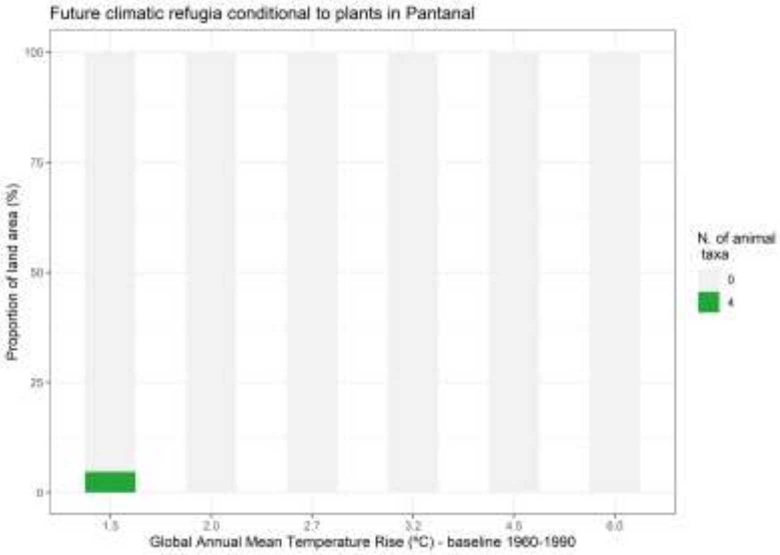


Figure 60: Proportion of land area in Pantanal identified as future climatic cross-taxon refugia conditional on being refugia for plants under increased levels of global warming (in relation to the baseline). Colour scale represents the number of taxa simultaneously included in the refugia along with plants (note that the land area not identified as refugia is represented by grey).

Overall, the results presented here suggest that Pantanal has potential to act as future climatic cross-taxon refugia for any combination of at least two out of the four vertebrate taxa included in this research, in global warming levels up to 2.0ºC (Figure 58). These findings are more optimistic than ones of Vasconcelos and Do Nascimento (2016) that predicted that by 2050 Pantanal will no longer be climatically suitable for the four generalist treefrog species studied. Considering the impacts of future climate change on plant species in Pantanal, the findings presented here corroborate with the ones from Velazco et al. (2019) that pinpointed Pantanal as one of the regions with Cerrado vegetation projected to experience the highest plants species relative loss (in relation to the current species richness) due to future climatic changes. Moreover, combination of the findings on the lack of refugia for plants in levels of warming above 1.5ºC (presented in this chapter) and the projected decrease in precipitation (annual and driest quarter - presented in chapter 3 section 5.f) corroborate that future climatic changes are a severe threat to Pantanal, possibly to the point of turning this biome in a region with optimal precipitation quantity and patterns for the expansion of Caatinga vegetation (Cook and Vizy 2008).

g. Final remarks

Altogether, the analysis of the future climatic cross-taxon refugia for Brazil shows that the climatic suitability of the Brazilian biomes to their current terrestrial biota will be negatively impacted by future climate change, but the severity of the impact will vary according to taxon, biome, and future climate scenario under analysis (Figure 47 and Figure 48), corroborating with the results of the meta-analysis performed by Nunez et al. (2019).

Moreover, the regions identified as future cross-taxon refugia do not always match the regions projected to undergo less climatic changes or the regions projected to experience a presumed positive change (e.g., increase in precipitation – see projections for bioclimatic variables in chapter 3). That means that, for Brazil, locations projected to be exposed to lower levels of future changes in climate (what is considered by some studies as climate refugia - Michalak et al. (2020)), do not match locations where biota is projected to be more resilient to the future changes in climate, what is considered by this thesis and other studies (e.g., Stralberg et al. (2018) and Warren et al. 2018b) as future climate change refugia. Therefore, it is plausible to hypothesise that future climatic refugia for Brazilian terrestrial biota will not be defined solely by the similarity of the current observed climate and the projected future climate, but instead by species' intrinsic characteristics, such as their climatic tolerance. This discrepancy corroborates with the findings from previous comparisons between approaches used to identify future climate refugia Michalak et al. (2020). Michalak et al. (2020) compared locations identified as climate refugia in North America by five different approaches clustered into 3 main refugia classes (climatic exposure, environmental diversity, and climate tracking) and found that only 7% of the North American land area was identified as potential refugia for all three refugia classes. The approaches investigated were: i) based on the physical landscape; ii) based on climatic exposure (as analysis of Chapter 3); iii) based on climate velocity; iv) based on locations that can retain rare climatic conditions; and v) based on current and projected future ranges of resident species (as analysis of Chapter 4). As a conclusion Michalak et al. (2020) suggested that combining approaches may result in more robust results, however no validation of this suggestion was made. Therefore, an important next step to the field would be the validation of whether combining different approaches to identify refugia indeed lead to identifying the most resilient refugia.

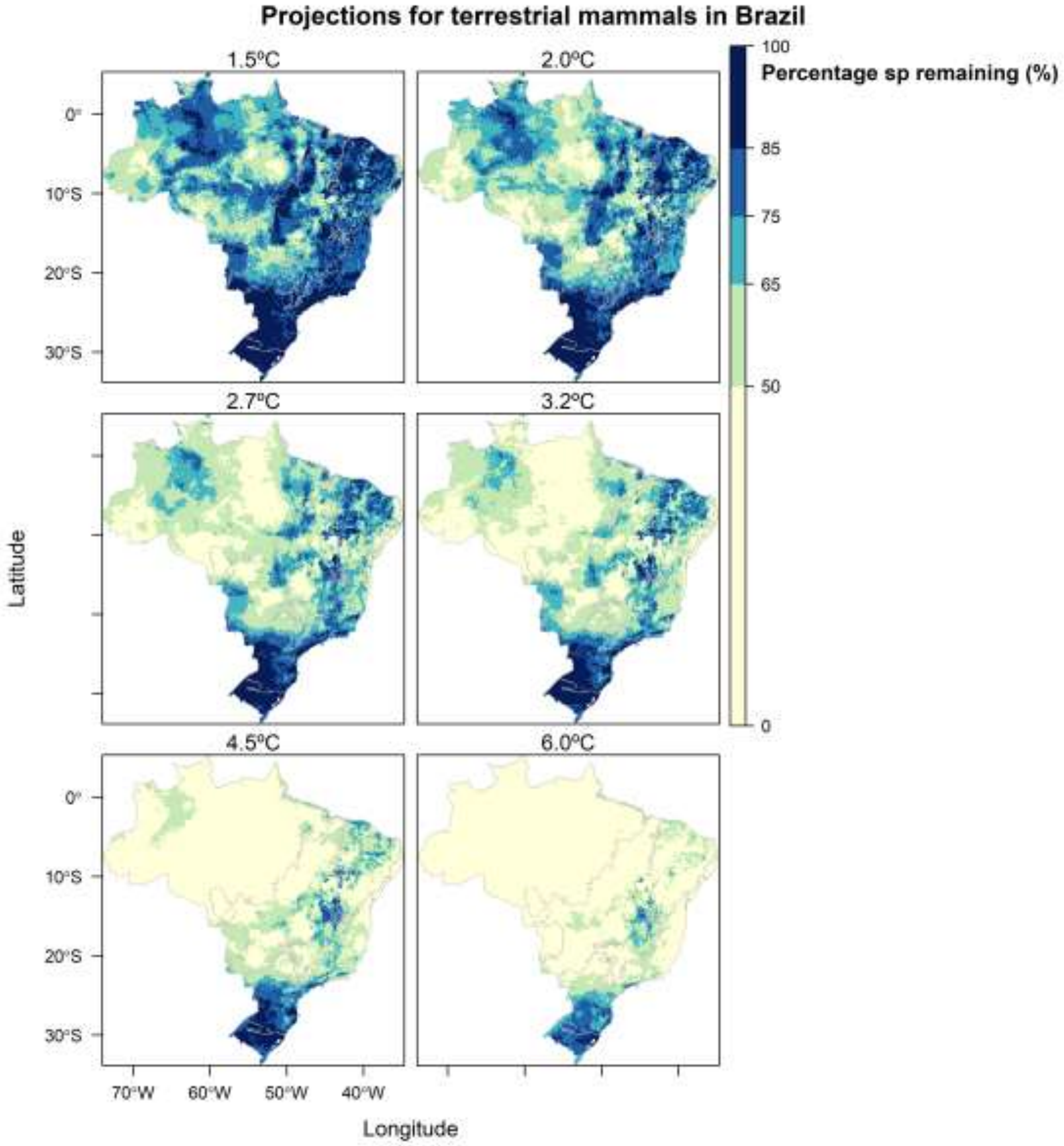
In addition, the results of this chapter show that the terrestrial plant species that are included in the WI database and modelled to currently occur within Brazil are more sensitive to the projected changes in future climate than terrestrial vertebrates, as their refugia size decreases faster than the refugia for animal taxa in Brazil and all biomes (Figure 33). These findings suggest that plant species that occur within Brazil either have narrower climatic niche amplitude, are already experiencing temperatures closer to their upper thermal tolerance or only occur in locations with very similar climatic conditions. This relation between size of refugia and climatic niche characteristics was also found for plant species endemic to Chile (Duarte et al. 2019).

Thus, conditioning refugia on being refugia for plants drastically reduces the size and the number of patches identified as potential future cross-taxon refugia, limiting their existence in tropical biomes / parts of biomes to warming scenarios under 2.7ºC above pre-industrial levels (Figure 48). Finally, the results presented here stress the importance of limiting global warming to as close to 1.5ºC as possible, as stated in the Paris Agreement, and hence a discussion around this topic is presented in the next section of this chapter.

7. Discussion points

a. The importance of achieving the Paris Agreement targets

The Paris Agreement aims at limiting global warming to well below 2ºC above pre-industrial levels and pursuing efforts to be closer to 1.5ºC (UNFCCC 2015). Meeting these targets is important for the conservation of the Brazilian biodiversity, as it increases the size and number of future climate change refugia throughout the country for birds (Figure 41), plants (Figure 43), and in the tropical part of the country for amphibians (Figure 40), mammals (Figure 42), and reptiles (Figure 44). Moreover, limiting global warming up to 1.5ºC, is crucial to have refugia for plants in Pantanal and it increases the prospects of having refugia for plants in the Amazon and Cerrado (Figure 39 and Figure 43). In addition, allowing global warming to reach 2.0ºC decreases the refugia land area in at least 50%



in the Amazon for amphibians, birds, and mammals, and in Caatinga for plants (Figure 39). Finally, if the world completely fails to meet the Paris Agreement targets and global mean temperature increases by 2.7ºC, this decrease of 50% in refugia land area is also projected to occur in the Amazon for reptiles, Caatinga for birds, Cerrado for birds and mammals, Pampa for plants, and Pantanal for amphibians, birds, and mammals (Figure 39).

Considering the cross-taxon refugia, keeping global warming close to 1.5ºC is imperative to have potential cross-taxon refugia for all five taxa in Pantanal (Figure 60) and would allow up to 25% of the land area of the Amazon and Cerrado to potentially act as cross-taxon refugia for at least three taxa and at least four taxa, respectively (Figure 50 and Figure 56). Moreover, if global warming exceeds 1.5ºC and reaches 2ºC above pre-industrial levels, the same potential is constrained to around 8% of the land area of those biomes. In addition, pursuing the 1.5ºC target of the Paris Agreement increases the prospects of a more evenly distributed cross-taxon refugia in Brazil, as at least 13% of each biome is projected to act as refugia for any 4 or more taxa in this scenario (Figure 47).

Therefore, the findings presented here confirm the benefits of achieving 1.5ºC in relation to 2.0ºC for plants and vertebrates found in a global analysis of species ranges made by Warren et al. (2018a). The results here presented also corroborate with previous global studies that supported the importance of strengthening climate change mitigation for biodiversity (Hoegh-Guldberg et al. 2019; Nunez et al. 2019; Manes et al. 2021). In addition, they endorse the IPCC statement that a global mean temperature between 1.5°C and 2.5°C above pre-industrial levels poses a high risk to biodiversity (IPCC 2018). Lastly, they contribute to the ongoing discussion around Paris Agreement, stressing the significance of the 1.5ºC target for safeguarding biodiversity.

b. Caveats of species distribution modelling

All studies based on species distribution modelling (SDMs) have caveats that are intrinsic to the adoption of this research approach (fully explored by Araújo and Peterson (2012)), and others that are related to the choices and assumptions particular of each study. Considering this, this section briefly discusses the main limitations common to all SDM-based studies, then the ones that related to the WI approach, and finishes with the limitations that are specific to this thesis.

SDMs exclude all types of interactions between species. However, in nature species are connected to each other through trophic and space interactions, and these interactions often shape the species' range (Wisz et al. 2013). In addition, interactions between species or between species and the habitat can influence the level of their sensitivity or vulnerability to future changes in climate (Clark et al. 2011). As examples, the competition between tree individuals in the Amazon has been indicated to shape the sensitivity of this forest to future climate change (Levine et al. 2016), while it has been suggested that tropical forest's vulnerability to future droughts vary accordingly to soil type (Vogt et al. 2016).

SDMs also overlook that the projected impacts of future extreme events and fire, and yet they pose a significant threat to biodiversity, especially on the tropics (Beaumont et al. 2011; Brodie, Post, and Laurance 2012). The projected refugia rely on the mean projections of changes in the bioclimatic variables, hence missing the negative impact that changes in extremes pose to biodiversity. Moreover, extreme drought can increase the frequency of natural fire events or the intensity of non-natural fire events. Fire on its own can accelerate shifts that would take decades to occur naturally (Davis et al. 2019). Although fire frequency is not directly included in the SDMs, it is indirectly included as it can be projected using the same bioclimatic variables that SDMs are based on (Krawchuk et al. 2009).

Another limitation on the use of SDMs for projecting future potential geographical occurrence of several different taxa is related to the different lifespans that terrestrial species can have. For the species included in this research, for instance, a small rodent could live up to 10 years, while large trees such as the Brazil nut tree have an individual reported as +400 years old (Schöngart et al. 2015). Different species could not only experience different consequences to the same climatic changes, but the time lag between when these changes start to impact their individuals and when the species start to show signs of these impacts could vary greatly (Esquivel-Muelbert et al. 2019). As a conclusion, the impacts of the same climatic changes on two or more species will be observed at different times and this lagging could exacerbate the impacts by causing a mismatch on species that interact (two species that interact are projected to retreat to the same area but one responds a decade before the other).

Furthermore, SDMs often base on the assumption that all land grid cells that have a suitable climate for biota also have a suitable habitat. This limits the accuracy of the modelled geographical distribution, as the models do not consider barriers that are natural (e.g., rivers) or anthropogenic (e.g., cities) to the species' ranges, especially if those barriers are in a different spatial scale than the one used on SDMs (Araújo and Peterson (2012) – but note that the next chapter of this thesis addresses this point by analysing the current land use of future refugia – see chapter 5 section 5).

One of the main assumptions while using the Maxent algorithm to predict a species environmental suitability is that the chosen environmental variables determine this species' geographic range (Elith et al. 2011; Renner et al. 2015). WI internally tested the complete set of bioclimatic variables to find the minimum number of variables (using more variables risk overfitting the models) that would provide the best modelling results for a set of species from the WI database (Warren et al. 2013a). One of the assumptions of this thesis is that the same set of variables directly limits the distribution of the species modelled to currently be present in Brazil.

In addition, the WI excluded in the models endemic small ranged species that remained with less than ten observation records after the check for outliers (see Chapter 2 section 3.a for details). Therefore, although the majority of widespread and common species are included in the analysis, as well as some endemic and threatened species with large ranges (please see Table 2), small ranged species could not be included in the WI, and hence the refugia analysis may not capture their needs. Recent findings show that endemic species have around three times higher risk of extinction due to future climate change than native species (Manes et al. 2021). Therefore, the refugia results shown here could be refined by refugia for endemic or small-ranged species, or in the lack of data for this, by areas of high irreplaceability (e.g., high number of endemics or high number of small-ranged as the ones from Jenkins, Pimm, and Joppa (2013)) to identify locations where urgent conservation action would be most needed.

Moreover, some subgroups of the five taxa studied here have more species included in the WI database than others (e.g., the plant class Magnoliopsida that has around 70% of the species modelled to occur in Brazil), and it has not yet been assessed if that reflects the documented disparity between the subgroups. Therefore, the identified refugia could completely miss large subgroups that are under-represented in the WI database (implications for this thesis are discussed at the end of this section).

Finally, the WI projected climate and biodiversity at a coarse resolution of 20x20km, possibly underestimating refugia potential by overlooking microrefugia (Dobrowski 2011). This is particular important for species of mountain ecosystems, that, for instance, might not be able to track their suitable climate from one mountain top to another, and even more important if they are also small ranged. Recent analysis suggested that 84% of mountain species are at high extinction risk due to future changes in climate (Manes et al. 2021). For this reason, considering the spatial scale of the WI datasets (global) and the results of this chapter (Brazil, 5th largest country in land area), the results here presented should be seen as a starting point of a more detailed investigation of future climate change refugia, that would include other important features for biota's resilience and long-term persistence (e.g., habitat quality – as assessed in Chapter 5).

Regarding the limitations particular to this thesis, four out of the six Brazilian biomes have a very large land area, and the refugia projections are presented in the graphs as an overall average per biome. To overcome this limitation, the maps presented in this chapter show how these refugia projections vary throughout the extent of each biome, and areas inside each biome that are identified as refugia are highlighted in the text. Therefore, the graphs and maps presented in this chapter should be interpreted together in order to analyse the potential of each biome to act as future refugia.

In addition, although the modelling exercise performed by the WI included a scenario in which species were able to track their shifting climate envelope (i.e., 'realistic' dispersal explained in chapter 2 section 3.c and Warren et al. (2018a)), this research only looked at future species distribution that did not allow species to follow their current climate envelope (i.e., no dispersal scenario). It has been reported that some species are already shifting their occurrence to higher latitudes and altitudes to follow the climate conditions that they are used to (Settele et al. 2014; IPCC 2018; IPBES 2019). However, there is not enough information to assume that all species of one taxon or all taxa included in this research would find adequate resources (habitat, food, interactions, etc) to be able to equally do so (Lawler et al. 2013). Moreover, the dispersal ability reported in the literature for some taxa (amphibians, reptiles, and plants) is not enough to keep pace with the speed of future climatic changes (Zhu et al. 2011; Warren et al. 2018a). Therefore, at the spatial resolution that this research's analyses were performed, it would have been possible to include dispersal scenarios only for mammals and birds, probably leading to a miss-match between species of different groups that naturally interact. Finally, the dispersal scenarios for birds and mammals considered by Warren et al. (2018a) assume that the species of these taxa are capable of moving through any landscape, without taking notice of barriers that different habitats or land covers/use (e.g., a river, grassland, farm or city) might pose to their dispersal (Lawler et al. 2013).

Finally, not all taxonomic groups analysed in this research are equally represented in the WI-III database but they were treated equally in this analysis. While Aves has more than 100% of the number of species recorded in to occur in Brazil according to the Taxonomic Catalogue of Brazilian Fauna, Amphibia has 27% and Reptilia has only 8% (Table 3 – Mammalia and Plantae have ~50%). Not surprisingly, the two taxonomic groups for which the WI has less absolute and proportional number of species for Brazil (in relation to the nationally accepted figures), amphibians and reptilians, are the ones that present the most optimistic results regarding the amount of land area per biome identified as refugia under future climate change (Figure 33, Figure 34, Figure 38, Figure 39, Figure 40, and Figure 44). Moreover, results for reptiles (n=63 representing 8% of nationally known) often present a much slower decrease on the land area identified as refugia as global mean temperature rises than other taxa for the same biome (Figure 33 and Figure 39). Therefore, results of single-taxon refugia for these two groups underrepresented in the WI-III database and results of cross-taxon refugia for any two taxa should be interpreted with caution, as they could be considering just the most generic species of these two taxonomic groups.

8. Key messages

Overall, Brazilian biomes' climatic suitability to their modelled current biota, and hence their potential to act as future climatic refugia, declines as the global mean temperature increases. In addition, the severity of the impact is strongly dependent on the warming level, taxon, and biome under analysis.

The Amazon is the biome that has the lowest extent projected to act as future climatic cross-taxon refugia for any combination of two taxa regardless of the warming level, while Pampa has almost 100% of its land surface identified as cross-taxon refugia for any combination of two taxa for all scenarios up to 4.5ºC warmer than pre-industrial levels. Moreover, in a 4.5ºC warmer world, the Atlantic Forest is the only biome projected to host refugia for all five taxa. This uneven geographical distribution of potential cross-taxon refugia in Brazil emphasizes the need for sub-national level biodiversity conservation targets and planning.

Meeting the Paris Agreement target of keeping global warming up closer to 1.5ºC above pre-industrial levels will enhance the prospects of having future climatic cross-taxon refugia for all five studied taxa in all Brazilian biomes (Figure 48). Moreover, if global warming is not limited to 1.5ºC above pre-industrial levels, future climatic refugia for plants are likely to become non-existent in Pantanal and almost non-existent in the Amazon and Cerrado (Figure 39).

Furthermore, achieving the Paris Agreement 2 degrees target is also important when considering future climatic refugia for each individual taxon, as in any level of warming above that, refugia are likely to become non-existent in the Amazon for amphibians, birds, and plants; in Caatinga for plants; in Cerrado for birds and plants; and in Pantanal for birds and plants (Figure 39).

Concluding, to fully meet the ultimate goal of the UNFCCC that includes allowing ecosystems to adapt naturally to the unavoidable climatic changes, countries need to make stronger efforts to keep global warming to closer to 1.5ºC above pre-industrial levels, as any warming above that threatens the existence of evenly distributed cross-taxon refugia throughout Brazil and, very importantly, of climatic refugia for terrestrial plants species, the base of every terrestrial ecosystem.

Chapter 5: Planning in a changing climate: how can future climatic refugia help inform biodiversity conservation planning in the context of future climate change?

This chapter demonstrates the role that future climatic cross-taxon refugia can play in biodiversity conservation planning under future climate change. It accomplishes this by showing for Brazil and each Brazilian biome: (a) the extent to which Brazilian protected areas (PAs) will remain climatically suitable for most species currently there by acting as potential future climatic cross-taxon refugia; and (b) the potential of these locations identified as refugia to be employed in conservation measures such as the expansion of the current PA network or the restoration of converted ecosystems.

1. Introduction

Biodiversity loss is happening at unprecedented rates, directly or indirectly due to human activities. A traditional way to promote *in situ* biodiversity conservation and avoid species extinction is through the designation of Protected Areas (PAs) (Kramer and Mercer 1997; Chape et al. 2005; Saout et al. 2013), highlighted by some as the most important conservation tool (Rodrigues, Akçakaya, et al. 2004).

Since the 80s, organizations of different governmental levels have included the creation and expansion of representative PAs in their policies' goals (Sarkar et al. 2006). A decade ago, as part of a global effort to halt the ongoing biodiversity crisis, countries were called by the United Nations (UN) Convention on Biological Diversity (CBD) to increase their PAs and/or other effective area-based conservation measures (OECMs) to at least 17% of their land area (Aichi target 11), and to enhance ecosystem resistance and resilience through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems (Aichi target 15) by 2020. More recently, the UN Framework Convention on Climate Change (UNFCCC) Paris Agreement also called its parties to 'conserve and enhance' forests and other carbon sinks and reservoirs, recognising the role of healthy ecosystems in climate change mitigation and adaptation.

Parties of these conventions must show their efforts and plans to meet the global goals for biodiversity, through national reports and National Biodiversity Strategies and

Action Plan (NBSAP), and for climate, through national greenhouse gas (GHG) inventories and the recently created Nationally Determined Contribution (NDC).

Under the CBD, Brazil has committed to increase its PA network to cover 30% of the Amazon land area and 17% of other biomes (national target 11), and to restore at least 15% of the degraded ecosystems in the country (national target 15), both by 2020 (Brazil 2013; CONABIO 2013). While under the UNFCCC, Brazil's original contribution to the global climate action included reducing its GHG emissions by 37 and 43% below 2005 levels in 2025 and 2030, respectively, restoring 15 million hectares (~1.76% of the country's land area) of degraded pasturelands, and restoring and reforesting 12 million hectares (~1.41% of the country's land area) of forests for multiple uses by 2030 (Brazil 2016a). It is worth noting that those intentions related to reforestation and restoration were omitted in the recently updated version of Brazil's NDC (Brazil 2020a).

Along with Brazil, many other countries have included reforestation and ecosystem restoration pledges as part of their NDCs (Strassburg et al. 2020) and other international commitments (e.g., CBD Aichi target 15, UNFCCC REDD+ goal, United Nations Convention to Combat Desertification). The Bonn Challenge (IUCN 2011) gathered all these efforts and created a global target of restoring 150 million hectares of deforested and degraded land by 2020 and 350 million hectares by 2030.

This recent interest in increasing the land area under protection and recovering degraded ecosystems, reflects the growing acknowledgement that promoting biodiversity conservation simultaneously assists bending the curve of biodiversity loss and counteracting climate change. Synergetic solutions like these have been defined by the International Union for the Conservation of Nature (IUCN) (IUCN 2016) as Nature-based Solutions (NbS) and they also address other societal goals such as human wellbeing, including poverty alleviation and economic development.

However, NbS long-term effectiveness could be jeopardized by the same climatic changes they intend to mitigate or promote adaptation to (Anderegg et al. 2020). A location targeted to be reforested could be projected to experience droughts that would prevent trees from thriving (Locatelli et al. 2015). Or a current or proposed new PA could be projected to become climatically unsuitable for most of its current plant species and not stock as much carbon as expected (Bastin et al. 2019). Moreover, future climate change is projected to impact every level of biodiversity, but the severity of these impacts depends on the taxonomic group(s) and location(s) targeted, and on the level of future climate change analysed (Settele et al. 2014; IPCC 2018; Nunez et al. 2019). For this reason, planning robust NbS to meet the current international commitments under the Rio Conventions needs to consider different possible future climatic scenarios and how these projected changes in climate would affect the biota on the location(s) under analysis.

In light of the interactions between climate change and biodiversity conservation, this chapter first presents an analysis of the current land use and protection status of locations where biota is projected to be resilient to future changes in climate, i.e., the future climatic cross-taxon refugia identified in the previous chapter. Then it shows an investigation of the degree to which the projected changes in future climate could imperil the potential of the current Brazilian PAs in promoting biodiversity conservation. Based on the current land use of these refugia, an evaluation of their potential to be employed as NbS, such as the creation of new PAs and OECMs, or at actions aimed at restoring degraded or converted ecosystems is made. Following that, this chapter presents two discussion points: the first is around the pledges made by the Brazilian government under the CBD related to area-based conservation and the effects of including areas protected by the Forest Code as OECMs, and the second is around the limitations and caveats of this part of the research. Finally, the role that future climatic cross-taxon refugia could play in informing sustainable and resilient conservation planning is highlighted on the key messages section.

2. Objectives

This chapter’s objectives are:

1. to identify, for each biome within Brazil, the extent to which the PA network is projected to have the potential to act as future climatic cross-taxon refugia for terrestrial biota under different levels of future global warming.
2. to identify future climatic cross-taxon refugia in Brazil outside of the current PA network where conservation efforts could be focused to (a) avoid deforestation or degradation (e.g., through new PAs or OECMs) or (b) restore degraded or converted ecosystems.

3. Data

All analyses presented in this chapter use the future climatic cross-taxon refugia results (chapter 4) that are built on the Wallace Initiative III climate envelope modelling for terrestrial biodiversity under six future climate change scenarios (1.5, 2.0, 2.7, 3.2, 4.5 and 6.0ºC above pre-industrial times). Data on the Brazilian protected areas network and on its current land use are also considered in this chapter.

a. Biodiversity data

Future climatic cross-taxon refugia

This chapter uses biodiversity results from chapter 4 that show the location of the future climatic cross-taxon refugia for any combination of two or more taxa (up to the five taxa considered: Amphibia, Aves, Mammalia, Reptilia, and Plantae) in Brazil under six different exploratory scenarios of future climate (1.5, 2.0, 2.7, 3.2, 4.5 and 6.0ºC of global warming above pre-industrial levels). The creation of these results is explained in the previous chapter of this thesis.

Future climatic cross-taxon refugia are the locations that are projected by at least 50% of the climate models included in the WI (i.e., 11 out of 21) to remain climatically suitable for at least 75% of the species of a taxon included in the WI database and modelled to currently be there, simultaneously for any combination of two or more taxa. The future climatic cross-taxon refugia conditional on being refugia for plants are not considered in this chapter because the impacts of losing substantial number of species within an animal taxon to ecosystem structure and function is still largely unknown, and even more if there are simultaneous losses from multiple animal taxa (Dirzo et al. 2014). For instance, a recent experiment has shown that the presence of large herbivores can decelerate changes within the plant community and loss of plant diversity of forests (Villar and Medici 2021), highlighting the importance of other trophic levels to secure ecosystems structure and function. Moreover, refugia conditional to plants fall mainly on the Atlantic Forest in levels of global warming of 2.7ºC or higher in relation to pre-industrial times. Therefore, by not restricting refugia to the condition on being refugia for plants, the analysis presented in this chapter have findings that are relevant to all Brazilian biomes, even when higher levels of future global warming (such as 4.5ºC above the baseline) are considered. However, it is worth mentioning that cross-taxon refugia that are not refugia for plants might be less resilient to future climate change because plants are the base of each ecosystem, and a high diversity of plants potentially helps maintaining functions of ecosystems undergoing disturbances (Isbell et al. 2011).

b. Brazilian Protected Areas

In its latest NBSAP (for the period of 2016-2020), Brazil has recognized four groups of areas protected by different legislations for different purposes (page 45 of (Brazil 2017)):

- Conservation Units (regulated by the Law 9985 of 18/07/2000),
- Indigenous lands (regulated by the Federal Constitution of Brazil of 1988, Law 6001 of 19/12/1973, and legislative Decree 1775 of 08/01/1996),
- Quilombola territories (regulated by the Federal Constitution of Brazil of 1988, and Decrees 4886 and 4887 of 2003), and
- areas protected under the Brazilian Forest Code, legal reserves and permanent protection areas (regulated by the Law 12651 of 25/05/2012).

There are two main subclasses of Conservation Units (UCs in Portuguese) in Brazil: integral protection or strictly protected areas (that includes parks and other four categories) and sustainable use (that includes six categories). All UCs are created with the purpose of safeguarding biodiversity, and hence they are considered by the Brazilian government as the official PAs, and are the only PAs used as indicators towards the achievement of targets set under the CBD (MMA 2019). UCs are registered under the National System of Conservation Units (SNUC in Portuguese) controlled by the Brazilian Ministry of the Environment (MMA in Portuguese). There are currently 2429 terrestrial UCs registered in SNUC, covering around 18.15% of the country’s land area (or 1,545,425 km^2) (MMA 2020), an area bigger than the combined land area of Germany, France, Spain, and Portugal. The proportion of land area that is currently protected as UCs varies widely among the Brazilian terrestrial biomes: while Amazon has around 28% of its land area as UC, Pampa has only 3% (see Table 9 for proportion of land area protected as UC per biome and the proportion of land area considered as protected by this study (UCs and TIs) per biome).

Although IUCN has developed categories to classify PAs worldwide, the responsibility of voluntarily assigning these categories to the national PA systems lays with national governments. To date, Brazil has not an official position of which UC categories matches the IUCN ones. However, most studies (Rylands and Brandon 2005; Silva 2005; Crouzeilles et al. 2013; Pack et al. 2016; Resende et al. 2021) consider that UCs of integral protection match IUCN categories I-III, and that the sustainable use UCs match IUCN categories IV-VI, as represented in Table 6 (but note that Carranza et al. (2014) and Ferreira et al. (2020) have considered Brazilian strictly protected areas to match IUCN category IV).

Table 6: Crosswalk table between IUCN protected areas categories and Brazilian conservation units (UCs) categories and sub-categories. For the Brazilian UCs the name of the categories and sub-categories in Portuguese is presented between brackets.

IUCN protected area category	Brazilian conservation unit category	Brazilian conservation unit sub-category
Ia Strict Nature Reserve	Strictly protected areas | integral protection (Unidades de Proteção Integral)	Ecological Station (Estação Ecológica)
Ib Wilderness Area		Biological reserve (Reserva Biológica)
II National Park		National Park (Parque Nacional)
III Natural Monument or Feature		Natural Monument (Monumento Natural); Wildlife refugee (Refúgio de Vida Silvestre)
IV Habitat/Species Management Area	Sustainable use protected areas (Unidades de Uso Sustentável)	Area of relevant ecological interest (Área de Relevante Interesse Ecológico); Private natural heritage reserves (RPPN - Reserva Particular do Patrimônio Natural)
V Protected Landscape/ Seascape		Environmental protection area (Área de Proteção Ambiental)
VI Protected area with sustainable use of natural resources		Fauna reserve (Reserva de Fauna); National forest (Floresta Nacional); Sustainable development reserve (Reserva de Desenvolvimento Sustentável); Extractive Reserve (Resex – Reserva Extrativista)

The Indigenous lands (TIs in Portuguese) and the Quilombola territories (QT) are created with the objective of protecting the right of these people and communities to maintain their culture, language, and habits. TIs are registered by the National Indian Foundation (FUNAI in Portuguese), while QT are mainly registered by National Institute for Colonization and Agrarian Reform (INCRA in Portuguese). Currently, there are 619 TIs in Brazil recognized or undergoing the process to be recognized by

FUNAI, corresponding to approximately 14% of the country's land area (or 1,179,679 km^2 - FUNAI 2020). INCRA spatial data for the Quilombola territories includes 435 sites that add up an area equivalent to 0.33% of the national land surface (or 28,526 km^2 - (INCRA 2020)).

The areas protected under the Brazilian Forest Code (FC) include the permanent protection areas (APP in Portuguese) and the legal reserves (RL in Portuguese). Under the previous FC legislations, private rural landholdings were obliged to keep native vegetation in all areas considered as APP and RL or to restore any ecological degradation in them. Since 2012, among other modifications, the new FC changed that obligation, excluding small landowners from the obligation to spare land for the legal reserve, giving amnesty to the landowners who had deforested these protected areas before 2008, and allowing the ones that have deforested more land than the quota allowed by the FC after 2008 to compensate this clearing excess in another property in the same biome with more native vegetation than the minimum required by the FC (Stickler et al. 2013). The 2012 Forest Code also created an online platform that gathers all spatial information about the rural properties, the SICAR, where landowners must upload on a self-declaratory status, geographical information about their properties including the geographical location of the areas protected by the FC. So far, more than 6 million properties have been registered in the SICAR, delimiting 216,880 km^2 of APP (2,5% of Brazil's land area) and 1,351,941 km^2 of RL (16% of Brazil's land area - (SFB 2020)). A breakdown of these numbers per biome is presented in Table 7.

Table 7: Land area registreted in the SICAR as protected by the Forest Code (both APP and RL) as a proportion (percentage) of each biome's total land area (in kilometers square). FC-PAs1 represent the total land area registred regardless of the current land cover, and FC-PAs2 represent the land area that the land owner has registred and declared to currently have native vegetation.

Biome	Total area (km^2)	FC-PAs1 (%)	FC-PAs2 (%)
Amazon	419694300	19.4	16.6
Atl. Forest	110612500	15.1	9.1
Caatinga	84445300	12.0	4.8
Cerrado	203644800	20.9	15.8
Pampa	17649600	12.3	7.8
Pantanal	15035500	27.3	25.3

Considering the information about the four types of PAs in Brazil, this study considers as part of the Brazilian PA network all the UCs included on the National System of Conservation Units (SNUC) and all indigenous lands registered by FUNAI. UCs are included for being the official PAs, having biodiversity conservation as the principal aim, and for being the core of the indicators for the Brazilian NBSAP target 11 (MMA 2019). Indigenous lands are included due to their vast land extent, overall importance for the conservation of the Amazon (Peres 1994), and more specifically due to their similar effectiveness in avoiding deforestation (Soares-Filho et al. 2010; Nolte et al. 2013) and similar vertebrate biodiversity (Schuster et al. 2019) when compared to PAs. The areas protected under the Forest Code are excluded from the spatial analysis because the majority of the registrations in the SICAR happened between 2016 and 2020 (same time as this analysis was performed – comparison of data available in the Brazilian NBSAP Brazil (2017) and SICAR (SFB 2020)), the data on them are built on self-declarations made by landowners that still need to be verified by state governmental agencies (SFB 2020), and properties in one state (Espírito Santo) are not included in the federal system. Yet, the implications of considering them as OECMs and as part of the national effort to deliver the commitments made under the CBD are discussed in this chapter.

The spatial data on PAs and Indigenous lands used to create the ‘current Brazilian PA network’ datum considered by this research were obtained from the Brazilian Ministry of the Environment’s website (MMA 2018a) and is presented in **Error! Reference source not found.** below.

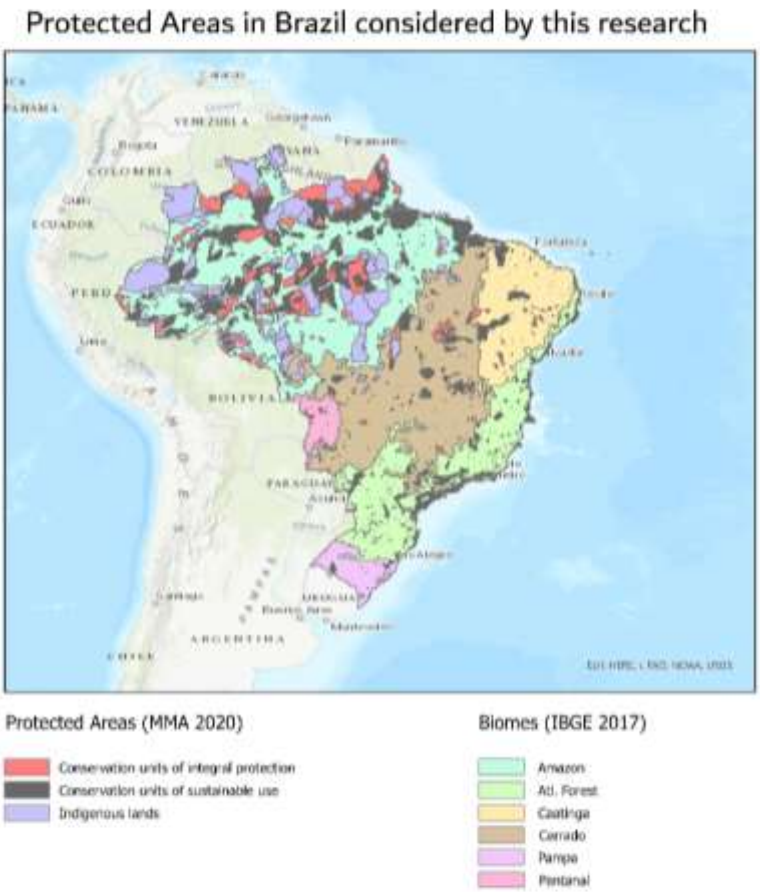


Figure 61: Map of Brazilian PAs considered by this research: Conservation Units (UCs) and Indigenous lands (TIs).

c. Land use in Brazil

The spatial datum on the Brazilian land use considered by this research is built on the ‘IBGE land cover and use map’ version of 2014 (IBGE 2018). The IBGE map derived from remote sensing (mainly MODIS and LANDSAT 8 satellite images but RapidEye images were also used in some regions), expert knowledge and field visits made by IBGE’s team. The IBGE’s map distinguished 14 land use and land cover classes briefly described below.

1. Artificial area: areas with at least 75% occupied by anthropic infrastructure such as cities, industries, or roads
2. Cropland: sites that have at least 75% occupied by permanent crops

3. Mosaic with predominance of cropland but that has forest remnants: mosaic of 50-75% of cropland and pasture, plus forest remnants
4. Mosaic with predominance of cropland but that has grassland remnants: mosaic of 50-75% of cropland and pasture, plus grassland remnants
5. Native forest: areas with at least 75% of forest
6. Mosaic with predominance forest remnants but that has cropland: mosaic of 50-75% of forest plus cropland and pasture
7. Natural grassland: sites with at least 75% of natural grassland, shrubland or herbaceous vegetation under no anthropic interference
8. Wetland: areas that are permanent or seasonally flooded
9. Natural pasture: natural grassland with low intensity of anthropic interference
10. Managed pasture: pastureland with high intensity of anthropic interference
11. Planted forests: areas with more than 75% occupied by cropland of non-native forest species
12. Barren land: areas that are covered by rocks, or soil without vegetation
13. Inland water bodies: rivers, lakes, and artificial water reservoirs
14. Coastal water bodies: Brazilian coastal area

4. Post-processing

a. Manipulation of Brazilian PAs and land use data

Data on the Brazilian PAs are available as vector, so they were converted to raster using ArcGIS's 10.5 tool 'Polygon to Raster' with optional settings selected to match the coordinate system, extent, and cell size of the WI-III data. PAs that are smaller than half of the grid cell used by this research (smaller than ~200km^2) were excluded from the spatial data and the land use of the cell is based on IBGE's map.

The 14 classes distinguished in IBGE's land use and cover map were combined into four land use categories (Table 8) considered relevant to this thesis's aim and defined as:

1. Anthropic: areas that are mainly occupied by anthropic infrastructure or cropland and therefore were not considered by this study as a target for conservation planning.
2. Restore: non-pristine areas that were considered by this study to currently present a good potential to be restored due to the presence of natural vegetation (forest or grassland) remnants. These patches have a good restoration potential because they act as nuclei from where natural vegetation expands into suitable habitat (Corbin and Holl 2012) preserving the ecosystem composition and diversity at lower costs (Bechara et al. 2016).
3. Biofriendly: areas that are mainly natural and hence were considered by this research as currently appropriate for biodiversity conservation planning measures.
4. Other: areas with other land uses that most times were not possible to represent at the scale of this study (e.g., small inland water bodies as lakes and rivers, small patches of bare land), or land uses that were considered controversial in relation to their suitability for biodiversity conservation measures (e.g., managed pastures (Correa et al. 2020) and planted forest (Bremer and Farley 2010; Paquette and Messier 2010))

The modification of the IBGE's map was carried out by first splitting it into five new vector files (i.e., one for each adapted land use category in Table 8) using ArcGIS's 10.5. As this research only considers terrestrial biota, the 'coastal water bodies' file was not used on the next steps. Following that, the remaining four new vector files were converted into raster files using ArcGIS's 10.5 tool 'Polygon to Raster' with optional settings selected to match the coordinate system, extent, and cell size of the WI-III data.

Table 8: Original (IBGE's datum) and corresponding (this research) land use categories.

IBGE land cover/use class	Postprocessed land use category
Artificial area	Anthropic
Cropland	
Mosaic: predominance of cropland but has forest remnants	Restore

Mosaic: predominance of cropland but has grassland remnants	
Native forest Mosaic: predominance forest remnants but has cropland Natural grassland Wetland Natural pasture (rangeland)	Biofriendly
Managed pasture Planted forest Bare land Inland water bodies	Other
Coastal water bodies	Not relevant

The next step was to include the current Brazilian PA network datum as a land use category, excluding the previous land use categories on areas within the PAs boundaries (i.e., the land cover and use inside PAs were excluded from all analyses performed by this research). This process was performed using ArcGIS 10.5 ‘Raster Calculator’ tool, R package ‘raster’ and QGIS Serval Plugin. Finally, the resulting five raster files (one for each land use: anthropic, restore, biofriendly, other and PAs) were combined (using ‘raster’ package of R) to create the datum on ‘current land use in Brazil’ presented in Figure 62 and Table 9. It is worth mentioning that the proportion of each biome’s land area identified as PAs (which includes Conservation Units and Indigenous Lands) by this research does not match the amount recognized by the Brazilian federal government as protected by Conservation Units (MMA 2018a) (values represented on Table 9 as ‘UCs-MMA*’) The observed discrepancy for some biomes is due to the small size of the PAs within these biomes (small PAs are not considered in this study), and for the Amazon and Cerrado is due to the Indigenous Lands present in these biomes that are not included on the PAs-MMA data. For the purpose of discussing the current and future national area-based conservation commitments made under the CBD, this research considers the highest value between PAs and PAs-MMA, compensating for the exclusion of some PAs caused by coarse resolution used for the spatial analyses performed in this study.

Table 9: Proportion of the land area in Brazil or in a Brazilian biome that falls within each land use category adopted by this study (anthropic, biofriendly, other, PAs,

restore), and proportion of the land area in Brazil or in a Brazilian biome that falls within Conservation Units recognized by the Brazilian Ministry of the Environment (UCs-MMA*). Values are shown in percentage (%).

	Anthropic	**Biofriendly**	**Other**	**PAs**	**Restore**	**UCs-MMA***
Brazil	7	37	19	27	10	18
Amazon	1	37	13	48	0	28
Atl. Forest	19	13	22	7	40	10
Caatinga	2	59	8	7	24	9
Cerrado	13	38	33	10	6	8
Pampa	25	44	22	3	7	3
Pantanal	0	68	19	4	8	5

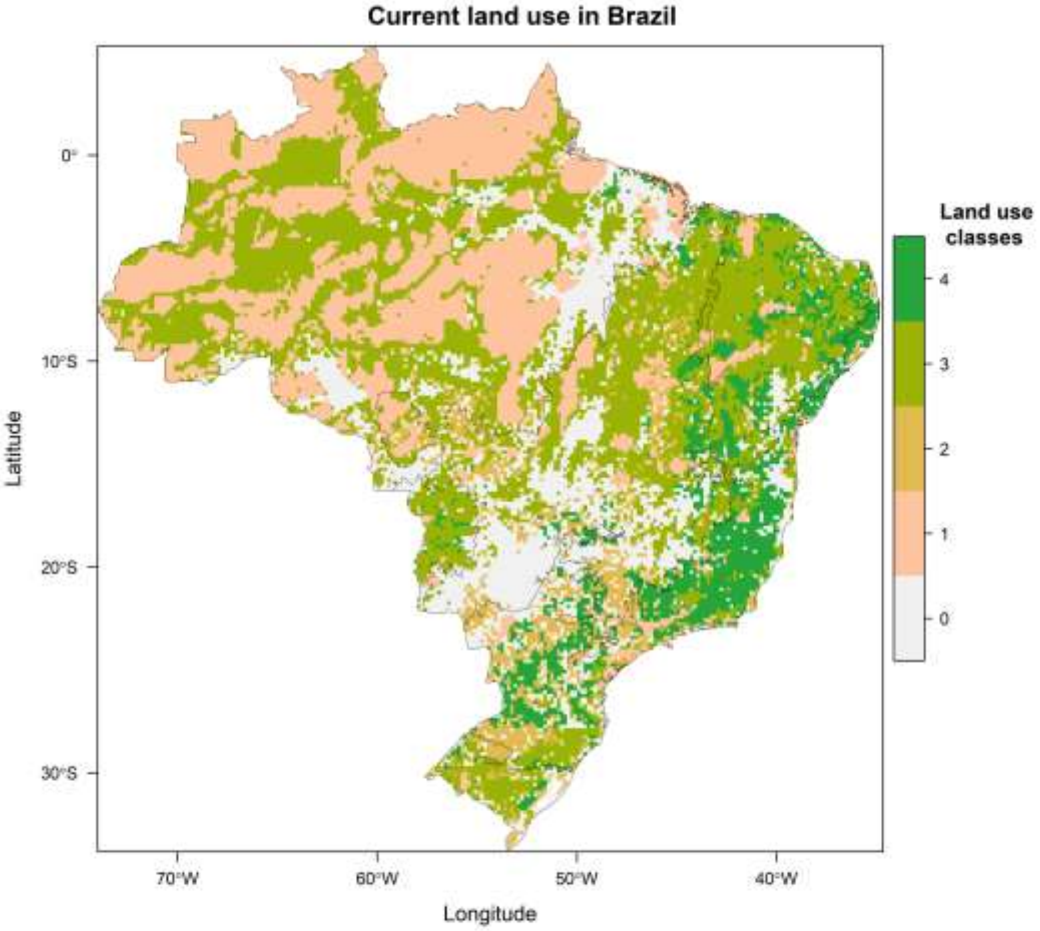


Figure 62: Postprocessed current land use in Brazil that was used by this research. The five categories considered are represented as: 0 – Other, 1 – PAs, 2 – Anthropic, 3 – Biofriendly, and 4 – Restore. Biomes boundaries are represented by a dark grey line.

b. Calculation of Brazilian PAs identified as refugia

The geographical location of the current PAs projected as potential future climatic cross-taxon refugia is identified for any combination of two, three, four, and for all five taxa, under each of the six levels of future global warming studied (totalling 24 combinations of refugia and future climate). The proportion of the PA network that is projected as potential future refugia is calculated as the percentage that the land area identified as refugia represents in relation to the total land area of the Brazilian PA network or of the PA network in each biome within Brazil in each of the 24 combinations of refugia and future climate. The proportion of the PA network that is projected as potential future refugia was also calculated for each taxon under each future climate scenario and these results are presented in the section 1.b of this thesis' Appendix.

c. Calculation of current land use of future refugia

The current land use of the future climatic cross-taxon refugia is calculated as the percentage that the refugia land area that falls within each land use category (anthropic, biofriendly, protected area, restore, and other) represents in relation to the total land area of Brazil or of each biome within Brazil in each of the 24 combinations of refugia and future climate described in the previous subsection.

In addition, the geographical location of the future refugia that currently fall within the two land use categories considered by this research most suited for future conservation efforts (biofriendly and restore – defined in section 3.c "Land use in Brazil") is spatially identified for the 24 combinations of refugia and future climate.

d. Note about plots and maps

All plots and maps presented in this chapter were created using packages 'raster', 'RColorBrewer', and either 'ggplot2' (for plots) or 'rasterVis' (for maps) of the software R.

5. Analyses of climate-smart biodiversity conservation efforts for Brazil and its biomes

This section presents four analyses that aim to demonstrate how future climatic cross-taxon refugia could be used to inform sustainable and resilient conservation planning for Brazil and its biomes that promotes biodiversity conservation despite future climate change. These analyses are:

- current land use of the locations projected as future climatic cross-taxon refugia.
- current PA network's potential to act as future climatic cross-taxon refugia.
- climate-smart expansion of the PA network.
- climate-smart restoration.

The first analysis shows the proportion of the locations in Brazil projected as future climatic cross-taxon refugia (for at least two out of the five taxa simultaneously) that fall within each of the five land use categories (anthropic, biofriendly, other, protected area, restore), under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). The second presents an assessment of the current Brazilian PA network's potential to act as future climatic cross-taxon refugia for terrestrial biota under abovementioned levels of future climate warming. This investigation shows the proportion of the PA network land area and the geographical location of the PAs identified as future climatic cross-taxon refugia.

The last two analyses evaluate the potential of the refugia that are not protected but that fall within land use categories with good prospective to simultaneously promote biodiversity conservation and climate change mitigation / adaptation, and hence suitable candidates for NbS measures such as the creation of new PAs or OECMs and ecosystem restoration. These land use categories are the ones that either (a) currently have native vegetation (hereinafter biofriendly areas – see section 4.a for definition) and where new PAs would avoid deforestation and ecosystem degradation, or (b) have been anthropized but still have native vegetation remnants (hereinafter areas to restore – see section 4.a for definition) and where reforestation and ecosystem restoration could take place at lower costs (Bechara et al. 2016).

All analyses are first presented individually considering the national scale (next four subsections), and later are presented collectively for each Brazilian biome (subsections 5.a to 5.f).

a. Current land use of future refugia

The analysis of the current land use of the future refugia considers the amount of refugia land area that falls within each land use category adopted by this research (anthropic, biofriendly, other, protected area, restore – see section 4.a for definitions) in relation to the total land area of the country. The future climatic cross-taxon refugia considered here are locations simultaneously identified as refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae), under six different levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels).

Around 60% of Brazil’s land area has been projected to have the potential to act as future climatic cross-taxon refugia for at least two taxa simultaneously if the 1.5ºC Paris Agreement goal is delivered (Figure 63 – note that the Y-axis goes up to 65). However, not the entire land area identified as refugia for any two taxa in a world up to 1.5ºC warmer (in relation to pre-industrial levels) is currently under a land use that is compatible with biodiversity conservation. Out of these refugia, only 18% is covered by PAs, while 53% is not currently protected in spite of having native vegetation (39% falls in the biofriendly category – mainly covered by native vegetation, and 15% falls in the restore category – with native vegetation remnants). Considering that 37% of the country land area is still mainly covered by native vegetation, i.e., biofriendly areas (Table 9), it is not a surprise that most of the land area identified as future refugia falls within this land use category (Figure 63).

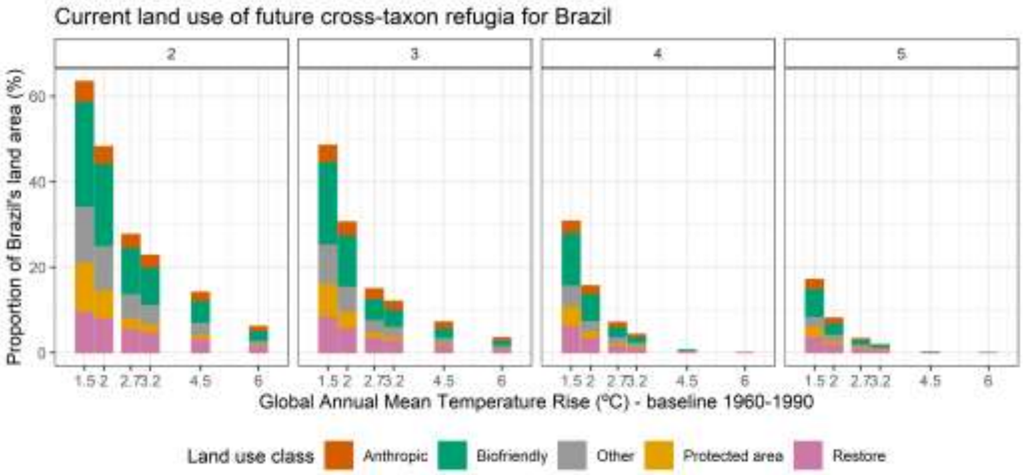


Figure 63: Current land use and size (expressed as a percentage of the country total land area) of the locations in Brazil projected to have the potential to act as future climatic cross-taxon

refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae), under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels).

However, it is interesting to note that the representativeness of the cross-taxon refugia within each land use category varies according to the warming level under analysis. As an example, the proportion of refugia for at least two taxa within PAs decreases with higher levels of future warming, reaching 9% and 7% of the land area identified as refugia in scenarios of 2.7 and 4.5ºC warmer, respectively. On the other hand, the representativeness of these refugia within areas with potential to be restored increases as the global mean temperature rises, reaching 19% and 20% of the refugia's total land area in the same two future scenarios. This increasing trend is also observed for the proportion of these refugia that fall in anthropized areas, but do not show substantial changes for these refugia that falls within locations classified as 'biofriendly' or 'other'.

Table 10: Current land use and relative size (as percentage) of land area identified as future climatic cross-taxon refugia for at least anty two taxa in relation to Brazil's total land area and to the total land area identified as this type of refugia in the country, under three levels of future warming.

Warming level (ºC)	Land use class	Brazil land area (%)	Refugia land area (%)
1.5	Anthropic	5	8
1.5	Biofriendly	25	39
1.5	Other	13	21
1.5	PA	11	18
1.5	Restore	9	15
2.7	Anthropic	3	12
2.7	Biofriendly	11	39
2.7	Other	6	21
2.7	PA	3	9
2.7	Restore	5	19
4.5	Anthropic	2	16
4.5	Biofriendly	5	36
4.5	Other	3	21
4.5	PA	1	7
4.5	Restore	3	32

These variations occur because refugia are shrinking faster in the portions of the country that currently have more PAs (e.g., Amazon), concentrating in the portions that have already been completely or partially converted (e.g., Atlantic Forest).

Therefore, if the ongoing biodiversity crisis is to be halted, not only the global efforts to pursue the Paris Agreement temperature targets need to be stronger, but Brazil needs to adopt a large portfolio of conservation measures that would address the different challenges that biota in each biome will face under future climatic conditions.

b. Current PAs' potential as future refugia

The analysis presented here aims to investigate the extent to which the projected changes in future climate could imperil the potential of the current Brazilian PAs (Conservation Units and Indigenous Lands – as explained in section 3.b) in promoting biodiversity conservation. This analysis is performed by assessing the proportion of the Brazilian PAs' land area and identifying the geographical location of the PAs that are projected to have the potential to act as future climatic cross-taxon refugia for terrestrial biota under six different levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5 and 6.0ºC above pre-industrial levels).

Overall, the proportion of the Brazilian PAs' land area that is projected as future climatic refugia for any combination of at least two taxa (total of 26 possible combinations) decreases as the global mean temperature rises, and the rate of the decrease varies depending on the biome under analysis and the number of taxa included in the refugia (Figure 64 Figure 65), corroborating with the findings from chapter 4 and references therein (see chapter 4 section 6.g). Moreover, even if the Paris Agreement 1.5ºC goal is delivered, less than half of the current Brazilian PAs' land area is projected to act as future climatic cross-taxon refugia for any combination of two or more taxa (Figure 64 – note that the Y-axis goes up to 43), and only 8% is identified as refugia for all five taxa simultaneously (Figure 64). In addition, only if future warming is kept below 1.5ºC above pre-industrial levels, will there be PAs in all biomes with the potential to act as refugia for all five taxa (Figure 65).

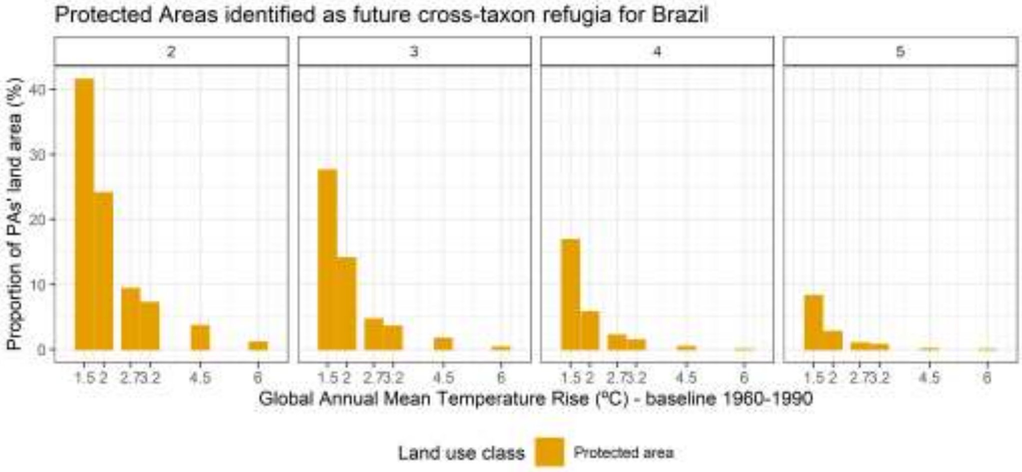


Figure 64: Proportion of the current Brazilian protected area network that is projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae), under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels).

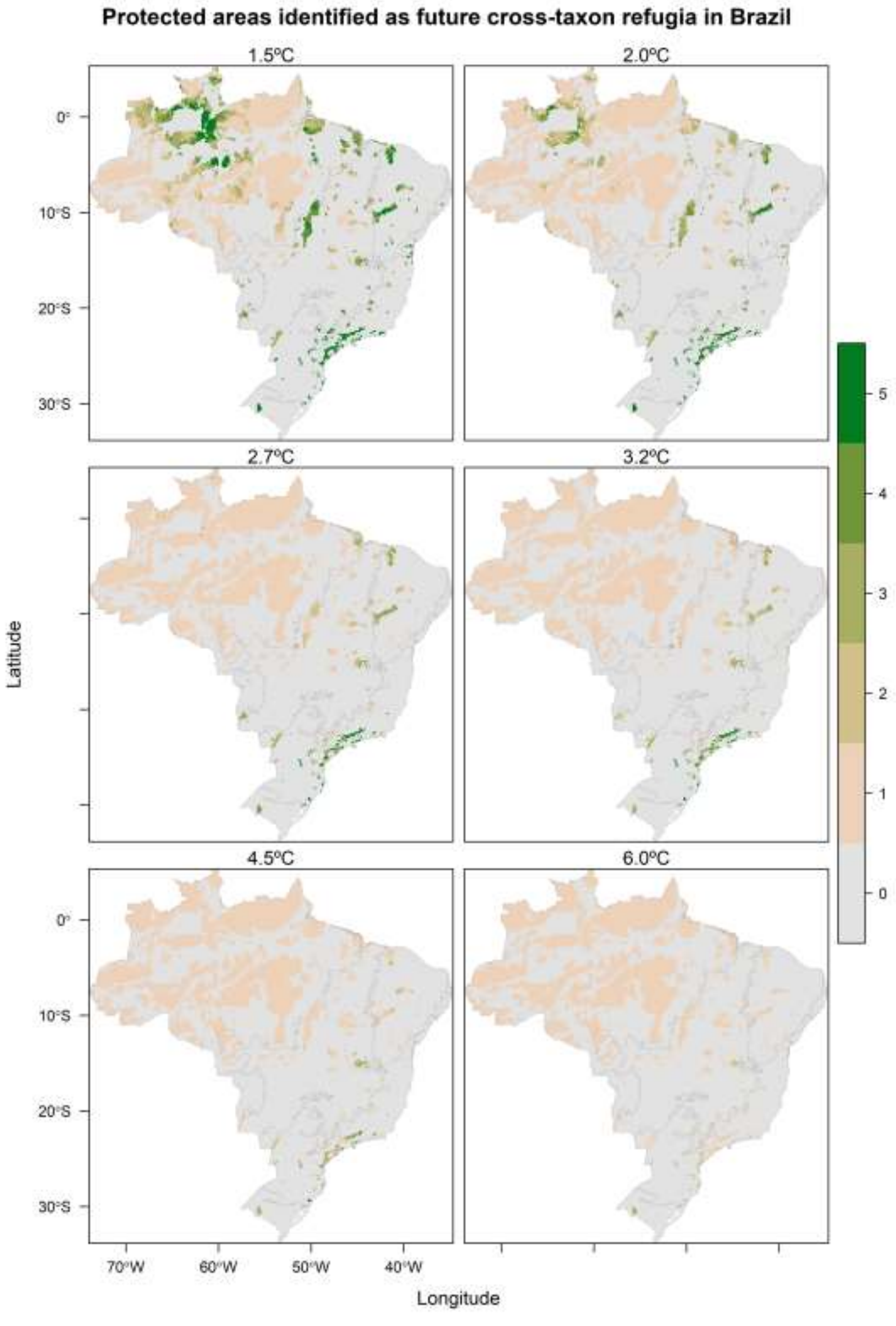


Figure 65: Brazilian protected areas projected to have the potential to act as future climatic cross-taxon refugia under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Colourkey code: 0 = land area not currently protected; 1= PAs not identified as refugia; 2 = PAs identified as refugia for any two taxa; 3 = PAs identified as refugia for any three taxa; 4 = PAs identified as refugia for any four taxa; and 5 = PAs identified as refugia for all five taxa.

The PA network considered by this research represents 27% of Brazil's land area (approx. 2,297,780 km^2, an area bigger than Greenland), and if OECMs defined by the 2012 Forest Code are also included, an additional 18% of the country's land area (SFB 2020) can be considered protected (page 45 of (Brazil 2017)). However, these PAs are unevenly distributed among Brazilian biomes (see Table 9 and comments from (Pacheco, Neves, and Fernandes 2018), and, for this reason, the current commitment assumed by the Brazilian government under the CBD has different goals per biome: 30% of the Amazon land area and 17% of other biomes (see national target 11 (Brazil 2013)).

The results presented here indicate that while Brazil has reached the overall CBD target of 17% of land protection by 2020 (Aichi Biodiversity Target 11 (CBD 2010)), future climate change will still greatly threat the ability of current PAs to foster biodiversity. If countries follow their NDCs pledges and global warming is limited to between 2.7ºC and 3.2ºC above pre-industrial levels, only 9-7% (respectively) of the current PA network in Brazil is identified as refugia for at least two taxa, and just 1% has the potential to act as refugia for all five taxa simultaneously (Figure 64). Under these scenarios, all PAs identified as refugia for five taxa are in the southern part of the country, in a region that encompasses the central and southern Atlantic Forest, southern Cerrado and north-eastern Pampa, and that the most southern ones are poorly connected to the others (Figure 65).

Moreover, the results shown here suggest that PAs in all biomes have potential to act as future climatic cross-taxon refugia in the lower levels of warming analysed (Figure 65). However, under medium and high levels of warming, mainly PAs outside of the Amazon will remain with this potential (Figure 65), despite the high relative and absolute amount of PAs in this biome.

In addition, it is important to highlight that the current Brazilian PA network has been reported to included less than half of the 3,286 vertebrate, 10,611 arthropod and 11,818 angiosperm species within its boundaries (Oliveira et al. 2017), yet two thirds of threatened plants have occurrence records within PAs (Ribeiro, Sales, and Loyola 2018). Hence, a well-planned expansion of the Brazilian PA network has been still repeatedly asked in the literature (Fonseca and Venticinque 2018; Vieira, Pressey, and Loyola 2019), and is assessed in the next subsection of this thesis.

c. Climate-smart expansion of the PA network

A conservation measure that has been adopted by Brazil and many other countries as a NbS with potential co-benefits for biodiversity conservation and for addressing climate change is the expansion of the PA network. The creation of a new PA or OECM can have a variety of objectives: to protect an endangered species, rare and threatened habitats, iconic landscapes, cultural practices, ecosystem services among others (Joppa, Loarie, and Pimm 2008; Watson et al. 2014). Since 2011, the creation of PAs and OECMs has been globally pushed forward by the CBD through Aichi target 11, that asks CBD's Parties to protect at least 17% of their land area by 2020 (CBD 2010). Currently the CDB is preparing the "Post-2020 global biodiversity framework" that will set a new area-based protection target to be met by 2030 (zero draft (CBD 2020b) and proposed changes (CBD 2020a)), for which two proposals are having great attention: protect 30% of the planet by 2030 (Dinerstein et al. 2019) and 50% by 2050 (Half Earth - (Wilson 2016) and Nature Needs Half - (Locke 2015)).

The current Brazilian PA network covers 27-45% of the country land area, depending if the areas protected by the Forest Code are considered or not as part of the national effort (but note that Brazil's updated NDC (Brazil 2020a) states that Brazil already has 50% of its land area protected). Therefore, Brazil is on an easy track to reach 30-50% of its land area protected and meet even the most ambitious target related to protection proposed for CBD's post-2020 agenda. However, if Brazil genuinely endeavours a more sustainable future, where the biodiversity and climate change crises are tackled synergistically, protection targets set for the next decade not only need to be higher than the proportion of land protected currently, but also need to focus on strategical locations.

This section uses the locations identified as future refugia in Brazil to investigate reasonable pathways for a climate-smart expansion of the current PA-network. In this analysis, future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) that fall within areas mainly covered by native vegetation (i.e., biofriendly land use class) are considered under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5 and 6ºC above pre-industrial levels).

In general, the relative amount (as a proportion to Brazil's total land area) of 'biofriendly' land area identified as refugia in Brazil decreases with higher levels of global warming (Figure 66), showing a similar trend as the one observed for total land area identified as refugia in the country (Figure 63).

If global warming is kept below 1.5ºC above pre-industrial levels, up to 7% of Brazil's land area is identified as future refugia for all five taxa (simultaneously) that are currently not protected but have native vegetation (Figure 66 – note that Y-axis goes up to 25). Under this scenario, these cross-taxon refugia occur in patches in all Brazilian biomes (Figure 67). Under the same future climatic condition, locations with the potential to act as refugia for at least two taxa represent around a quarter of the country's land area (Figure 66), difference that is mainly justified by bigger refugia patches in Caatinga, Cerrado, and Pantanal (Figure 67).

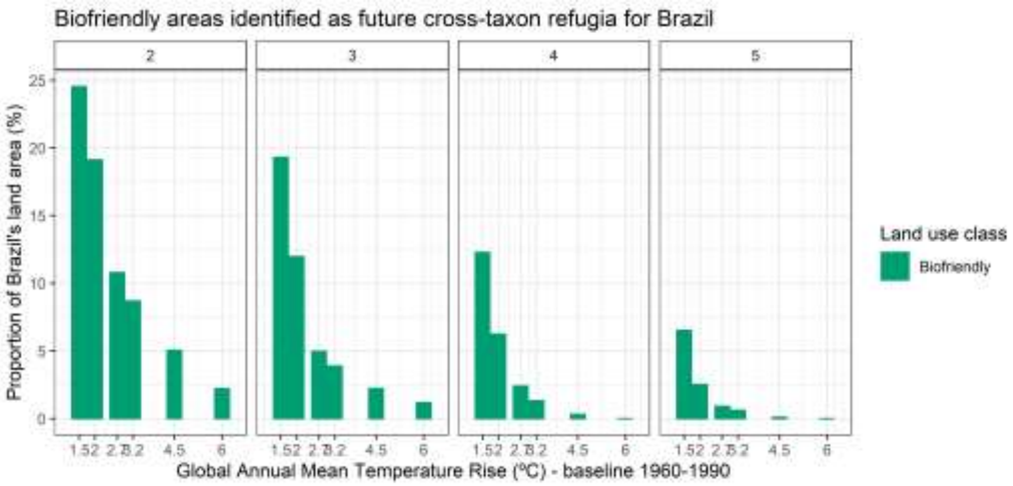


Figure 66: Land area (expressed as a percentage of the country total land area) in Brazil currently with with native vegetation (i.e., biofriendly land use class) that is projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae), under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels).

It is worth mentioning that this research does not spatially analyse the areas protected by the Forest Code, and hence some of the areas pinpointed in this subsection could be already protected by this legislation. Nevertheless, the results shown here indicate that **there are refugia in all Brazilian biomes outside PAs that if protected could help the country promote long-term climate-smart biodiversity conservation and avoid carbon emissions from deforestation and ecosystem degradation**.

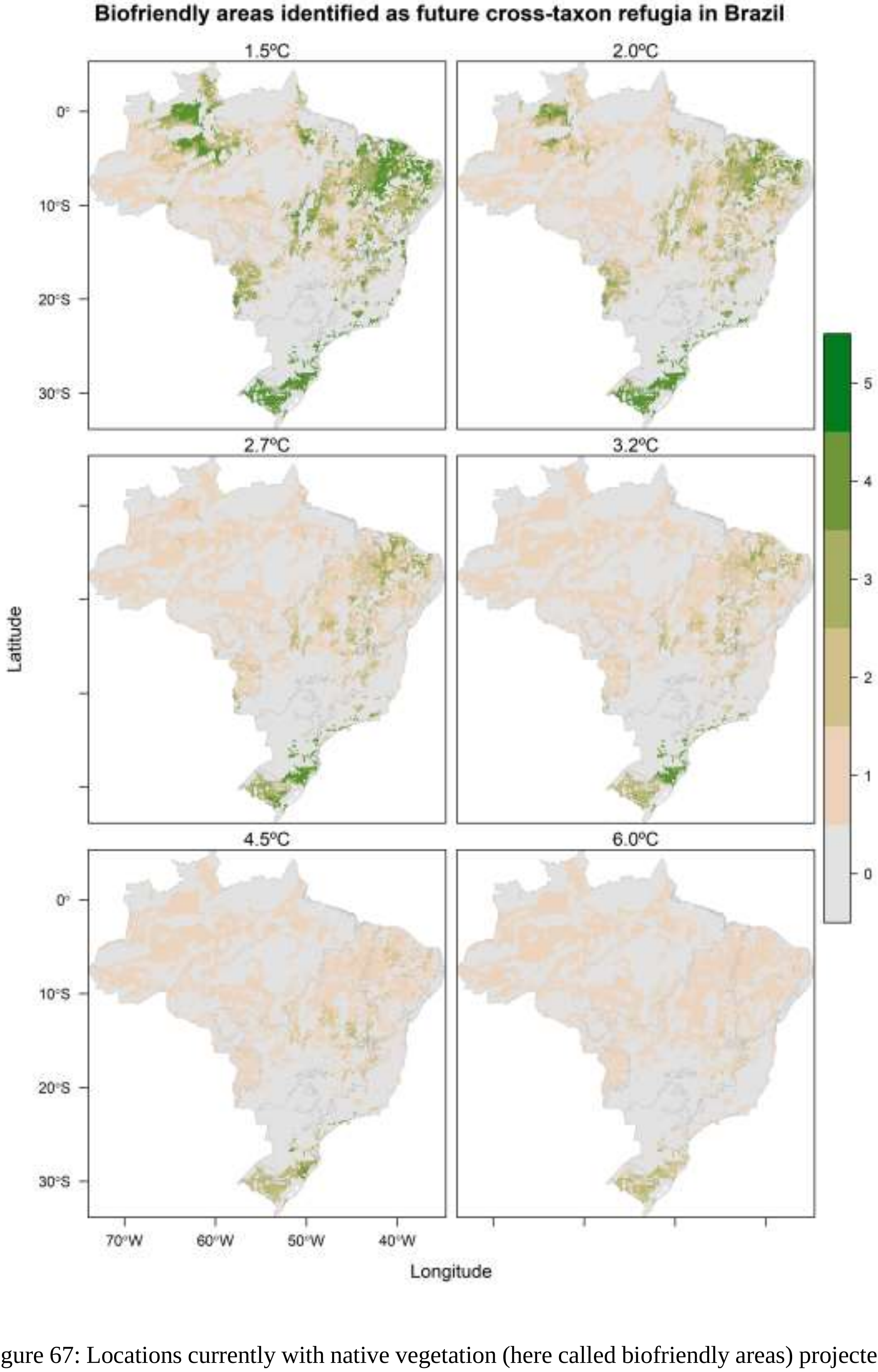


Figure 67: Locations currently with native vegetation (here called biofriendly areas) projected to have the potential to act as future climatic cross-taxon refugia under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Colourkey code: 0 = land area currently protected or without native vegetation; 1= biofriendly areas but not identified as refugia; 2 = biofriendly areas identified as refugia for any two taxa; 3 = biofriendly areas identified as refugia for any three taxa; 4 = biofriendly areas identified as refugia for any four taxa; and 5 = biofriendly areas identified as refugia for all five taxa.

Moreover, some refugia under the 1.5ºC warmer scenario that fall within the ‘biofriendly’ land use class overlap locations that were considered of extremely high biological importance on the latest national assessment (MMA 2018b), such as the refugia on the northern and north-west portions of the Amazon, the northern refugia on Caatinga, refugia in the border of Cerrado and the Amazon and Cerrado and Atlantic Forest, the most northern refugia in the Atlantic Forest, the ones in the central and southern coast of this biome, and refugia on the eastern coast of Pampa (Figure 67), just to mention a few. This coincidence reinforces the value of the locations identified by this research as future refugia for long-term biodiversity conservation and the urgent need to assess their protection status (especially regarding the different types of protected areas under the Forest Code).

The previous subsections show that the PAs in all biomes have the best chance of acting as future climatic cross-taxon refugia if the Paris Agreement temperature targets are delivered. Yet, even under these scenarios (1.5ºC and 2.0ºC above pre-industrial levels), the current PAs are protecting less than 20% of the land area identified as refugia for at least two taxa (Table 10) and less than 15% of refugia for all five taxa, sometimes in PAs very poorly connected (Figure 65). In addition, the analysis of the current land use of the locations identified as future refugia shows that at the national scale, the highest proportion of land area with refugia potential falls within the ‘biofriendly’ land use class, reinforcing the suitability of these locations for further expansion of the Brazilian PA network. Finally, refugia with native vegetation are not only abundant throughout the country (meaning that there are patches in all biomes) in the lower levels of warming investigated, but also well located to create and/or improve the connectivity between the PAs with refugia potential (compare Figure 65 Figure 67). Certainly, the contribution that these refugia with native vegetation yet not protected could give to long-term conservation planning vary depending on the biome under analysis (Figure 67), as the proportion of the land area still not converted varies greatly among biomes (Table 9). Bearing these differences in mind, the expansion of the current Brazilian PA network could consider creating a mosaic of areas with higher and lower levels of anthropic interference (similarly to the spatial planning explained in chapter 4 section 4.b), where the level of restriction would reflect the number of taxa for which that location is projected to act as refugia, how resilient these refugia are, and the suitability of the current land use for biodiversity conservation.

Concluding, the results here presented strengthen the requests for a well-planned expansion of the Brazilian PA network (Fonseca and Venticinque 2018; Vieira, Pressey, and Loyola 2019), and shine light on the feasibility of prioritizing the locations where biota is projected to be most resilient to future changes in climate (i.e., locations identified as refugia). In addition, the results demonstrate that an expansion of the current PA network could address the lack of connectivity between the parts of refugia currently within PAs, perhaps through a mosaic of areas with higher and lower levels of restrictions.

d. Climate-smart restoration

In addition to expand its current PA network, Brazil has adopted the reforestation and the restoration of degraded or converted ecosystems as synergetic solutions to the climate and biodiversity crises. Since 2010, the federal government has publicly declared its intention to promote restoration and reforestation throughout the country in at least three international initiatives (note that unlike the CBD protection target, these goals have not been translated sub-nationally):

1. under the CBD, Brazil has committed to restore at least 15% of degraded ecosystems by 2020 (national target 15 (Brazil 2013)).
2. under the UNFCCC, Brazil, on the first version of its NDC, has expressed its intention to restore 15 million hectares (~1.76% of the country's total land area) of degraded pasturelands and to restore and reforest 12 million hectares (~1.41% of the country's total land area) of forests for multiple uses by 2030 (Brazil 2016a).
3. and under the Bonn Challenge, the same reforestation target of 12Mha was assumed (Brazil 2016c).

The pledge made under the CBD does not have a direct measurable indicator and hence has been measured indirectly through the CO_2 emissions from land use change, the amount of land area deforested and rate of occurrence of wildfires (MMA 2019). Although the pledge made under the UNFCCC was not confirmed in the recently updated NDC (Brazil 2020a), its reforestation part seems be secured due to an overlap with the pledge made under the Bonn Challenge. In addition, as reforestation using a single species and afforestation have very questionable values as NbS (Seddon et al. 2016) or even just as climate change mitigation measures (Lewis et al. 2019), this section considers restoration as a measure that aims to recover of the ecosystem function and structure, whether this ecosystem is forested or not. Therefore, this subsection explores the interaction between future climatic cross-taxon refugia and the restoration of 12Mha at the national scale.

Currently around 10% of the Brazilian land area (approximately 85Mha) is a mosaic with predominance of cropland but with native vegetation remnants, thus classified by this research within the ‘restore’ land use category (Table 9 – see section 3.c for detailed definition). Overall, in the same manner as observed for total refugia, the amount of land area identified as future climatic cross-taxon refugia that falls within the ‘restore’ class decreases with higher levels of global warming and with higher number of taxa simultaneously considered in the cross-taxon refugia (Figure 68 - note that the Y-axis goes up to 9.5).

Out of the total amount of land area classified as ‘restore’, 30% is projected as cross-taxon refugia for all five taxa simultaneously if global warming reaches 1.5ºC above pre-industrial levels (i.e., 3% of Brazil’s land area), and 20% if the global mean temperature rises to 2.0ºC above the baseline (Figure 68 - note that the Y-axis goes up to 9.5). Both amounts are higher than the current pledge of restoring 12Mha (~ 1,4% of the country’s land area), indicating that, if the Paris Agreement 2.0ºC target is met, Brazil has the potential to choose the locations with the best cost-benefit among the ones identified as future climatic cross-taxon refugia for five taxa.

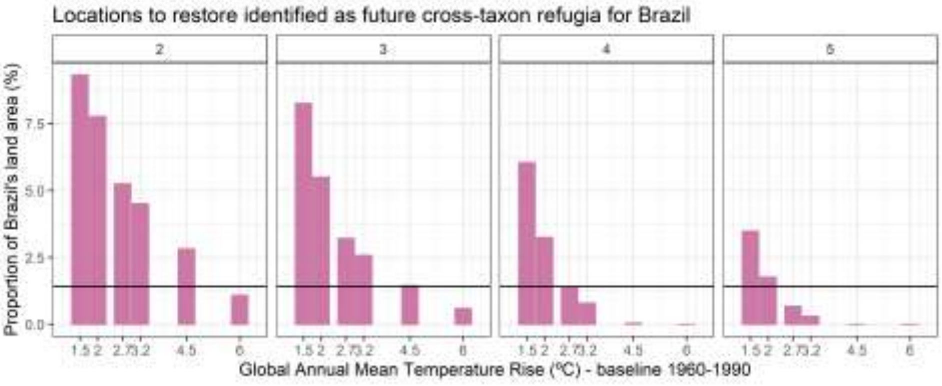


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Figure 68: Land area (expressed as a percentage of the country total land area) in Brazil currently with potential to be restored (due to the presence of native vegetation remnants) that is projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae), under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). The black line intersecting the Y axis represents the current reforestation pledge made by the Brazilian government on the first version of Brazil’s NDC and under the Bonn Challenge (12 Mha ~ 1.41% of the country land area).

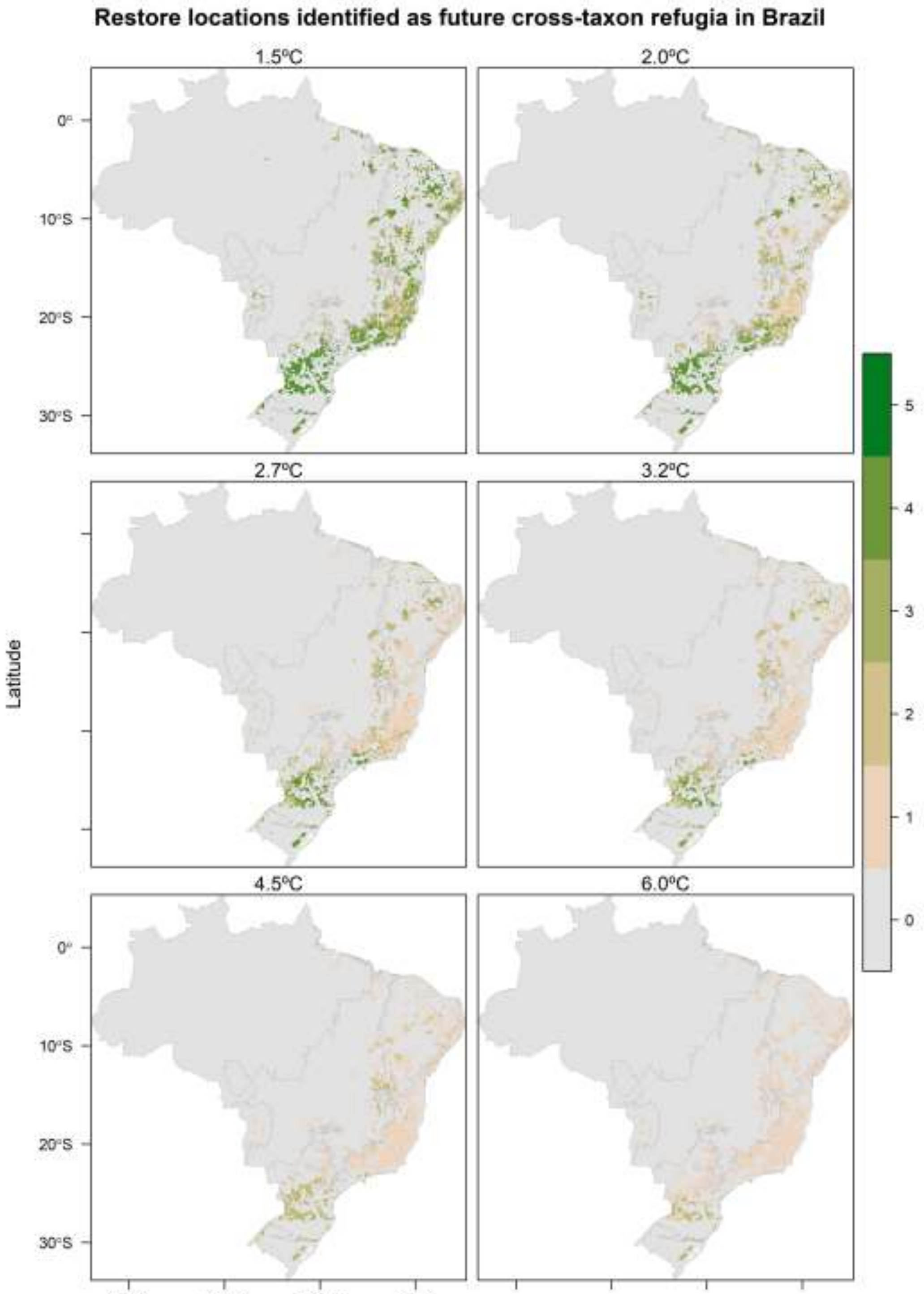

Figure 69: Locations currently with potential to be restored (here called restore areas) projected as future climatic cross-taxon refugia under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Colourkey code: 0 = land area currently protected or without potential to be restored; 1= restore areas not identified as refugia; 2 = restore areas identified as refugia for any two taxa; 3 = restore areas identified as refugia for any three taxa; 4 = restore areas identified as refugia for any four taxa; and 5 = restore areas identified as refugia for all five taxa.

Regarding the geographical location of these cross-taxon refugia for five taxa with potential to be restored if global warming is kept under 1.5ºC (Figure 69), most are in the Atlantic Forest (65% of the land area of these refugia, representing 16% of this biome's land area), but there is a considerable amount in Caatinga (22% refugia, 8% biome), and a smaller proportion in Cerrado (7% refugia, 1% biome) and in Pampa (5% refugia, 7% biome). It is worth highlighting that these refugia include parts of Caatinga's north-east refugia and parts of Pampa's eastern refugia that are completely not protected (see sections 5.c and 5.e), and a good portion of the southern Atlantic Forest refugia that currently also lacks protection (see section 5.b).

The results presented here also suggest that if Paris Agreement temperature targets are not met, restoration actions that are put in place at locations that are projected to lose their potential to act as refugia under levels of warming above 2.0ºC (even if partially by losing the potential to act as refugia for one or more taxa) might have their long-term contribution to biodiversity conservation and/or to tackling climate change jeopardized. This concerns cross-taxon refugia in Pantanal that falls within 'restore' category, that not only shrink in land area as warming levels increase, but also decreases the number of taxa included in its refugia (under the two lower levels of warming part of these refugia includes any four taxa, but in a 2.7ºC warmer world these refugia are only for any two taxa – Figure 69). Similar findings are observed for refugia with potential to be restored in Caatinga, Cerrado, the central and northern portions of the Atlantic Forest, and the western part of Pampa (Figure 69). Finally, it is particularly worth mentioning that failing to meet the Paris Agreement temperature targets eliminates the possibility of having refugia for plants in most parts of the Brazilian biomes (see chapter 4 section 6), increasing the uncertainty about the long-term success of any restoration project. As an example, some of the areas in Cerrado for which restoration has been proposed as part of the solution towards a more sustainable future for the biome (the south-western and central patches identified by (Strassburg et al. 2017)) are projected to remain climatically suitable only for up to 50% of its current plant species if global mean temperature reaches 2.7ºC above pre-industrial levels - see Appendix section 1.c). Therefore, if the national restoration commitments are to be delivered at the locations projected to have the best prospects of fostering the greatest variety of wildlife taxa whilst promoting climate change mitigation and adaptation, the Paris Agreement temperature goal needs to be achieved.

Finally, the result presented in this and in the three previous subsections show that how future climatic cross-taxon refugia could be used to inform conservation planning varies among the Brazilian biomes. Therefore, the next subsections show these analyses in more detail for each of the six Brazilian biomes.

e. Amazon

The Amazon has almost 50% of its land area (~2,014,532 km^2) currently set aside as PAs, an amount that is disproportionally higher than the one for other biomes (Table 9) and that greatly exceeds the national target of having 30% of Amazon's land area protected, set under the CBD (national target 11 (Brazil 2013)). However, less than 3% of the biome's land area is currently a PA and projected as future climatic cross-taxon refugia simultaneously for all five taxa in scenarios of global warming reaching 1.5ºC above pre-industrial times (Figure 70 - note that the Y-axis goes up to 42). Under this future warming scenario, around half of the land area identified as future refugia for all five taxa simultaneously currently has native vegetation despite falling outside of PAs (Figure 70 – 'biofriendly' land use class).

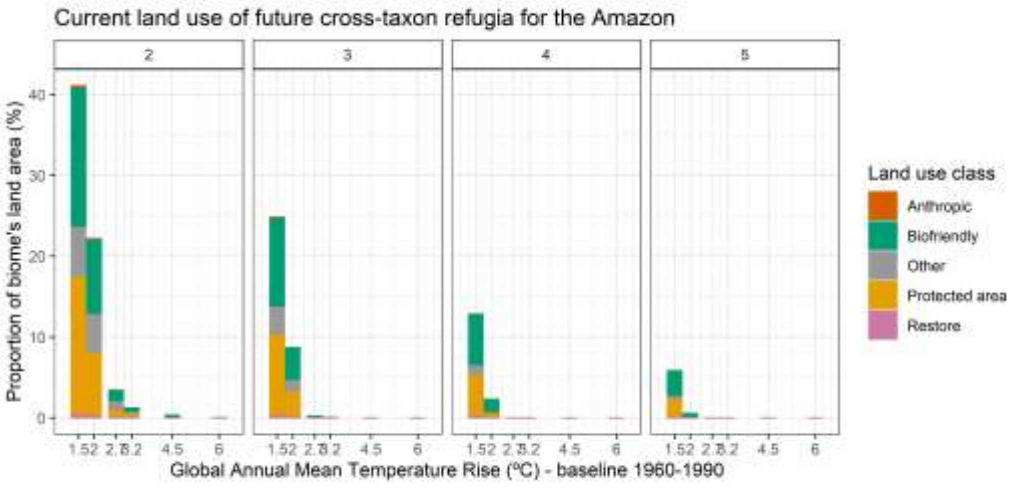

Figure 70: Current land use and size (expressed as a percentage of the biome's total land area) of the locations in the Amazon projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) simultanously, under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Considered land use classes: anthropic (orange), biofriendly (green), other (grey), protected area (yellow) and restore (pink), described in details on section 4.a of this chapter.

Still analysing a world up to 1.5ºC warmer than the baseline, 41% of the land area identified as refugia for at least two taxa currently falls in the biofriendly land use class, and area that corresponds to 17 % of the Amazon’s land area (Figure 70). Therefore, there are locations in this biome that currently have good conditions to foster biota and that if not deforested (and, more importantly, if incorporated into the PA network) could support Amazon’s biodiversity while it strives to be resilient to future climate change.

The protected status of locations in the Amazon is undoubtedly linked to lower deforestation and hence lower carbon emission rates (Nepstad et al. 2006; Soares-Filho et al. 2006; Nolte et al. 2013; Barber et al. 2014; Walker et al. 2020). Moreover, it has been suggested that the current PA network could shield the biome against potential tipping points if no deforestation takes place within PAs (Walker et al. 2009). Yet, being protected does not immediately award a better prospect of safeguarding biodiversity under future climate change, as the projected impacts of these changes on the biota are alarming throughout this biome (see chapter 4 section 6.a and references therein).

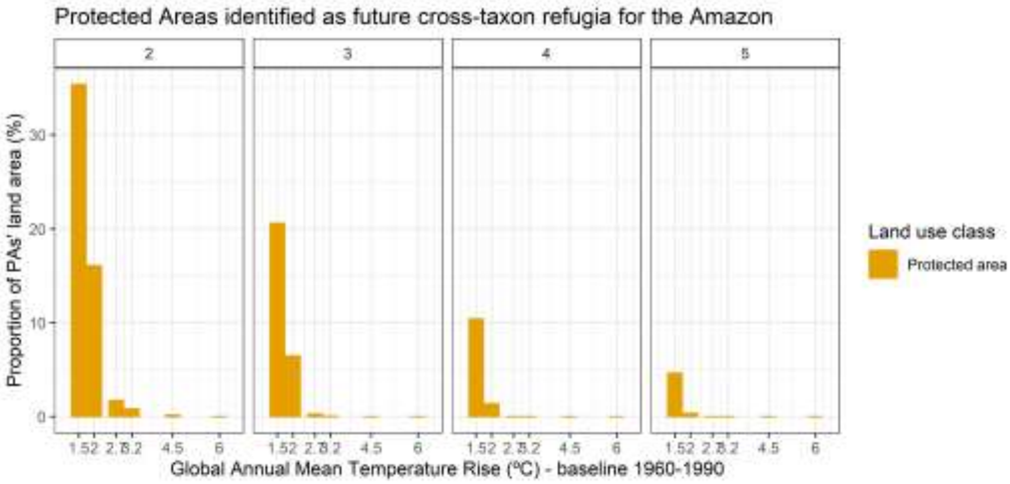

Figure 71: Proportion of the protected areas’ land area within the Amazon biome identified as future climatic cross-taxon refugia for any combination of two or more taxa under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Number of taxa that are simultaneously been included in the refugia analysis is shown on the top of each box.

Even if global warming is limited to 1.5ºC warmer than pre-industrial times, less than 5% of the Amazonian PAs’ land area is projected as future refugia for all five taxa simultaneously (Figure 71 – note that the Y-axis goes up to 37). Under the best future climatic circumstances analysed by this research and the least restrictive cross-taxon refugia type considered by this research (i.e., lowest global warming level considered, and lowest number of taxa used as threshold for refugia), only 35% of the Amazonian PAs' land area is identified as refugia for any combination of two or more taxa (Figure 71).

Moreover, Amazon PAs' potential to act as cross-taxon refugia decreases sharply in scenarios with higher global mean temperatures. In a 2.0ºC warmer world, only 1.4% of the Amazonian PAs' land area has potential to act as refugia for five taxa, and less than 17% has potential to act as refugia simultaneously for at least two taxa, respectively representing decreases of 87% and 55% in relation to the 1.5ºC scenario (Figure 71). Finally, if global warming reaches (or exceeds) 2.7ºC above pre-industrial levels, the PAs in the Amazon completely lose the potential to act as cross-taxon refugia for three or more taxa, and just up to 2% of the PAs' land area within this biome is identified as refugia for any two taxa (Figure 71).

Regarding the geographical location, the Amazonian PAs have the potential to safeguard only small (and mostly poorly connected) parts of the big cross-taxon refugia patches identified in the north-west and north-east regions of this biome under a 1.5ºC warmer world in relation to baseline (Figure 65, chapter 4 Figure 17 and chapter 4 section 6.a). Moreover, as the global mean temperature rises, the size and connectivity of the cross-taxon refugia that fall within the Amazonian PAs boundaries (Figure 65) decreases more sharply than the size and connectivity of the total land area identified as refugia in this biome (chapter 4 Figures 17 and 19). In addition, the parts of these refugia that fall outside PAs and currently have native vegetation (Figure 67) have also been pinpointed as areas of very high biological importance by the latest national assessment (MMA 2018b).

Habitat loss is the leading cause of species extinction globally. In the Amazon, deforestation and forest degradation menace biodiversity, local and traditional communities, and even the global climate. In this biome, PAs have proven to successfully safeguard these (Nepstad et al. 2006; Soares-Filho et al. 2006; Nolte et al. 2013; Barber et al. 2014), even under the recent increase of deforestation (Walker et al. 2020).

Future climatic refugia are the locations where biota is most resilient despite projected changes in climate. In the Amazon, less than a quarter of the biome is identified as refugia for at least two taxa in a 2.0ºC warmer world (Figure 70), and of these refugia, less than 35% currently falls within PAs (Figure 70). Part of the remaining refugia (the ones outside PAs) currently have native vegetation (41% – Figure 70) and overlap with areas defined of very high biological importance by other study (MMA 2018b). Therefore, the results here presented provide evidence that the inclusion of all refugia not protected in a long-term biodiversity conservation planning that contains the expansion of the current PA network could increase the connectivity between the PAs identified as refugia and enhance the resilience of this biome in face of future climatic changes. This would be especially true for the largest refugia for all five taxa in a world up to 1.5ºC warmer in the Amazon (chapter 4 Figure 47), located on the north-west portion of the biome, and that are currently deficiently protected (Figure 65).

f. Atlantic Forest

Although almost the complete land extent of the Atlantic Forest is projected as future climatic cross-taxon refugia for at least two taxa under the lowest level of warming (1.5ºC), roughly 7% of these refugia are currently protected, and ~ 13% of them fall outside PAs but have native vegetation (Figure 72).

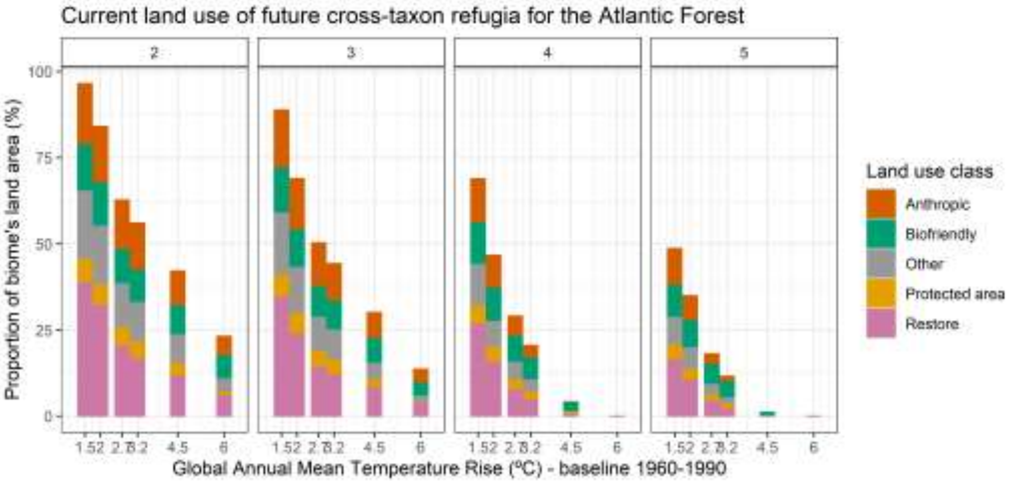

Figure 72: Current land use and size (expressed as a percentage of the biome's total land area) of the locations in the Atlantic Forest projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) simultanously, under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Considered land use classes: anthropic (orange), biofriendly (green), other (grey), protected area (yellow) and restore (pink), described in details on section 4.a of this chapter.

On the other hand, under the two lower levels of future warming the locations identified as cross-taxon refugia (regardless of the number of taxa included) mainly fall within the land category ‘restore’ (areas with native vegetation remnants), and the same is true under the two intermediate levels of future warming for refugia for any two or any three taxa (Figure 72), highlighting the current fragmented state of this biome (Ribeiro et al. 2009) and the importance of restoration measures to enhance the resilience of this biome (Zwiener et al. 2017).

The Atlantic Forest currently has around 7% of its land area (roughly 77,428 km^2) currently considered as PAs (Table 9). The projections for this biome’s PAs potential to act as future climatic cross-taxon refugia for all five taxa if global efforts fail to deliver the Paris Agreement goals are the most optimistic of all Brazilian biomes (Figure 65). If the global mean temperature reaches 2.7ºC above pre-industrial times, a little more than a quarter of the PA network land area within this biome is projected to act as future cross-taxon refugia for all five taxa (Figure 73). Moreover, the Atlantic Forest is the only biome where at least a small portion (3%) of the PAs’ land area remains as potential refugia for all five taxa even if global warming reaches 4.5ºC above pre-industrial levels (Figure 65 Figure 73).

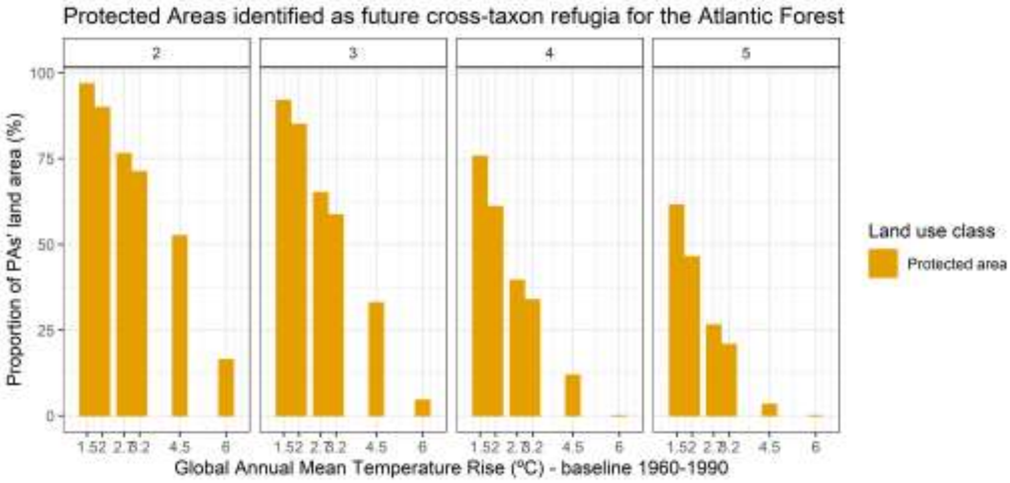

Figure 73: Proportion of the protected areas’ land area within the Atlantic Forest biome identified as future climatic cross-taxon refugia for any combination of two or more taxa under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Number of taxa that are simultaneously been included in the refugia analysis is shown on the top of each box.

In the lowest warming scenario included in this research, the PAs identified as potential future climatic cross-taxon refugia in the Atlantic Forest are evenly distributed through this biome (Figure 65). However, in the moderate and high levels of warming (2.7ºC or more above baseline), the PAs in this biome with potential to act as refugia are mainly concentrated on the eastern and south-eastern coast of the biome (Figure 65), covering only small and disconnected patches of the total land area in the Atlantic Forest projected as refugia (chapter 4 Figure 17).

Although the current PA network (Conservation Units - UCs and Indigenous Lands - TIs) covers only 7% of the Atlantic Forest land area (Table 9), if the areas protected under the Forest Code (FC-PAs1 Table 7) are considered as OECMs and included as part of the national effort related to the CBD Aichi target 11, Brazil has exceeded the aim of having 17% of the Atlantic Forest protected by 2020. Even if only the areas protected by the FC that have native vegetation (FC-PAs2 Table 7) are considered as OECMs, around 18.9% of the biome is protected by either a PA or an area protected under the FC (but note that data on the FC are self-declaratory have not yet been verified). However, it is worth noting that the current PAs within the Atlantic Forest only protect a small portion of the land area identified as future refugia in this biome.

Considering that only the protected areas under the Forest Code declared with native vegetation are included along with the PAs as part of the national effort for the CBD's post-2020 area-based target, and that this target will be 30%, an expansion of the PA network representing around 11% of the Atlantic Forest's land area would need to be planned to fulfil the goal. If the Paris Agreement 1.5ºC target is met, this expansion could protect almost all future climatic cross-taxon refugia for at least four taxa that currently have native vegetation (i.e., 'biofriendly' land use class, representing in this scenario 11.5% of the biome's land area) located throughout the central and on the south-eastern parts of the biome (Figure 65). This would increase the protection of important sites for biodiversity, such as some of the putative Quaternary refugia (Carnaval et al. 2009; Porto, Carnaval, and da Rocha 2013) and of some priority areas for conservation along the central and southern coast of this biome identified by previous study (Zwiener et al. 2017) or listed on the latest national assessment (MMA 2018b).

On the other hand, if only locations identified as refugia that currently have native vegetation are considered in future conservation efforts in the Atlantic Forest, these measures would fail to cover a considerable extent of the total land area identified as refugia on the northern and south-western parts of the biome, that currently have native vegetation remnants (i.e., classified by this study as "restore" - Figure 69). These regions are currently insufficiently represented on this biome's PA network (Figure 65) despite also having several patches identified as high or very high biological importance (MMA 2018b). Therefore, the results presented here corroborate with the findings from Zwiener et al. (2017) that restoration measures need to be included on future conservation planning for the Atlantic Forest.

Due to the high level of fragmentation of the Atlantic Forest, this biome has highest proportion of land area in the 'restore' land use class (40% of the total biome land area) among all Brazilian biomes (Caatinga is the second with 24% – Table 10). Not surprisingly, this biome also has the highest relative amount of land area identified as refugia for at least two taxa with native vegetation remnants among all biomes (Figure 69 Figure 72).

Considering all, if future conservation planning aims to enhance the resilience of the Atlantic Forest hotspot, it would need to simultaneously adopt conservation measures aimed at expanding the PA network and at promoting ecosystem restoration (that would include reforestation of suitable sites).

g. Caatinga

If the Paris Agreement targets are met, between 85 and 99% of Caatinga's land area is identified as future climatic cross-taxon refugia for at least two taxa (99% in a 1.5C and 85% in a 2.0C warmer word – Figure 74). Of these refugia within Caatinga under a 1.5ºC warmer world, only 7% are currently within the PA network, while 82% are not protected but are either mainly covered by native vegetation or partially covered by native vegetation remnants (Figure 74). However, under this same future climatic scenario, the amount of land area identified as refugia for all five taxa represents 36% of Caatinga's land area (Figure 74), a decrease of 64% in relation to the size of refugia for any two taxa, emphasising that different taxa that co-occur in Caatinga are projected to be impacted differently by the same future changes in climate. Moreover, out of these refugia for five taxa in a world up to 1.5ºC warmer than baseline, 23% falls currently within areas classified as 'biofriendly', and 8% falls within areas classified as suitable for restoration. In addition, if countries fail to deliver the Paris Agreement targets, the projections of future climatic cross-taxon refugia for Caatinga are affected by the lack of refugia for plants in this biome under warming levels above

2.0ºC (chapter 4 Figure 13 and chapter 4 section 6.c). Therefore, if the ongoing climate crisis is not tackled, future climate change could imperil Caatinga's biota and all restoration measures made in this biome.

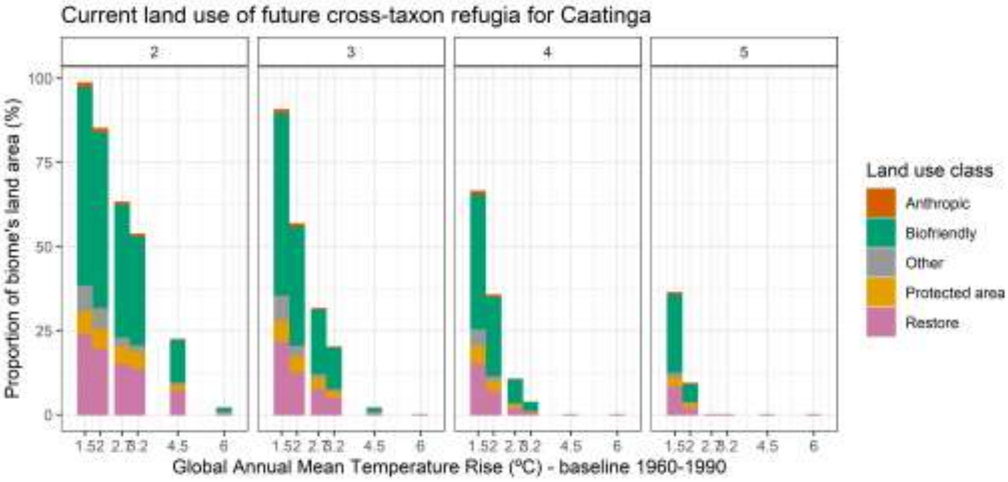

Figure 74: Current land use and size (expressed as a percentage of the biome's total land area) of the locations in Caatinga projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) simultanously, under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Considered land use classes: anthropic (orange), biofriendly (green), other (grey), protected area (yellow) and restore (pink), described in details on section 4.a of this chapter.

Currently, the PA network covers around 7% of Caatinga's land area (~ 59,112 km^2 - Table 9). Considering that the Paris Agreement targets are achieved, between 85 and 98% of the PA network land area within this biome is projected to have the potential to act as future climatic cross-taxon refugia for any combination of two or more taxa, and between 20 and 39% is projected as potential refugia for all five taxa (Figure 75). However, as previously explained, Caatinga's PAs potential to act as refugia for all taxa is limited to future climate scenarios that do not exceed 2.0ºC above the baseline due to the lack of refugia for plants above this threshold. Finally, in warming levels of 4.5ºC above pre-industrial times, up to a quarter of PAs' land area within Caatinga is projected as future refugia for any combination of two taxa (Figure 75).

The current PAs in Caatinga are mainly on the west portion of the biome and do not form a well-connected network (Figure 65). Therefore, they can only safeguard patches of the future refugia identified in this part of the Caatinga biome, failing to protect (even if only partially) the north-east portion of the biome that is projected as refugia simultaneously for all five taxa if global warming is limited to 3.2ºC above pre-industrial levels (chapter 4 Figure 17).

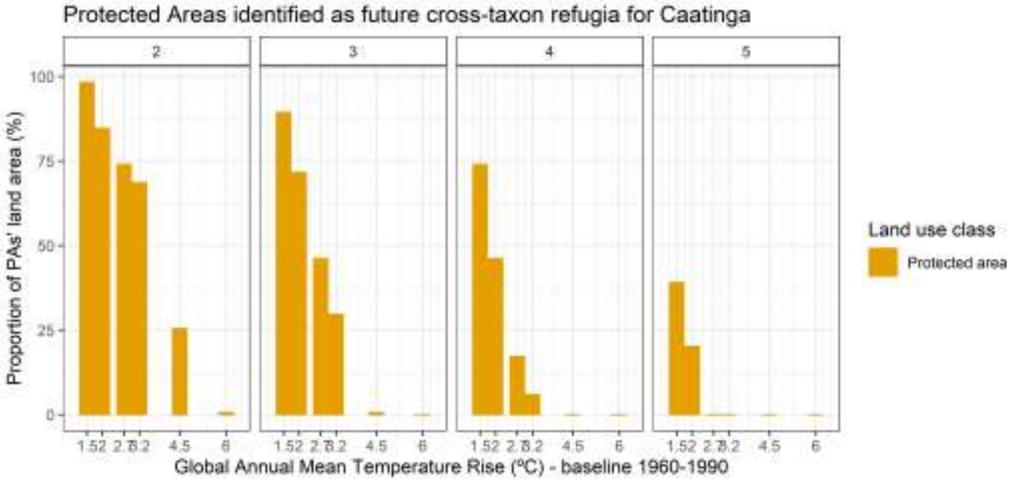

Figure 75: Proportion of the protected areas' land area within the Caatinga biome identified as future climatic cross-taxon refugia for any combination of two or more taxa under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Number of taxa that are simultaneously been included in the refugia analysis is shown on the top of each box.

A planned expansion of the current PA network to incorporate part of the locations identified as refugia for all taxa under the 1.5ºC scenario that currently have native vegetation (Figure 67) could address the lack of connectivity and the unevenness of protection in Caatinga. In addition, these refugia currently not protected overlap with areas identified as of very high biological importance on the latest national assessment (MMA 2018b), an analysis that included the need to promote landscape connectivity as one of the conservation targets (Fonseca et al. 2017). However, it is worth mentioning that if the areas protected under the Forest Code (FC-PAs Table 7) are included as part of the national target related to the CBD Aichi target 11, the aim of having 17% of Caatinga protected by 2020 has been fulfilled. Yet, this is not true if only the areas protected by the FC that were declared to have native vegetation are considered, different from the situation presented for the Atlantic Forest. If this last scenario is considered, Brazil would have failed to deliver its commitment of having 17% of Caatinga protected, as the sum of PAs and the areas protected under the Forest Code with native vegetation total around 13.8% of the biome's land area. These findings emphasise the importance of the validation of the information regarding the areas protected by the Forest Code and the need for an assessment of their suitability for biodiversity conservation purposes, if they are to be included as part of the national strategy to safeguard ecosystems, species, and genetic diversity.

Therefore, for Caatinga, in addition to considering the refugia that are currently not protected as priority in the planning process of long-term conservation measures, it is vital that the recovery of the areas protected under the Forest Code is enforced, and that current efforts to halt future climate change are strengthened, in order to decrease the threat of losing refugia for plants in the biome that could consequently preclude the success of restoration actions.

h. Cerrado

Under the lowest level of future warming included in this research, almost 70% of Cerrado's land area is projected as future climatic cross-taxon refugia for at least two taxa (Figure 76 - note that the Y-axis goes up to 72). Out of these refugia for two taxa, 9% is currently within PAs, 40% is not protected but has native vegetation (i.e., 'biofriendly' land use class), and 7% falls within areas classified with potential to be restored (Figure 76).

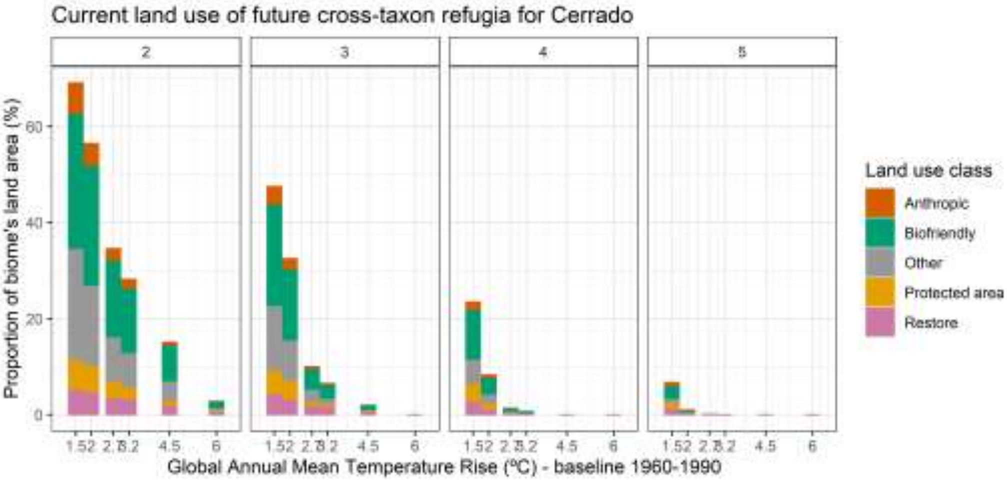

Figure 76: Current land use and size (expressed as a percentage of the biome's total land area) of the locations in the Cerrado projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) simultanously, under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0°C above pre-industrial levels). Considered land use classes: anthropic (orange), biofriendly (green), other (grey), protected area (yellow) and restore (pink), described in details on section 4.a of this chapter.

Interestingly, 34% of these refugia for two taxa in a 1.5ºC warmer world fall within areas classified as 'other' (Figure 76), a category that includes managed pastures and forests (see section 4.a for definition). Still analysing refugia projections under the lowest warming scenario, less than 7% of the biome is identified as refugia for all taxa, and for these refugia, the areas classified as other are over represented in comparison to the other classes (36% of refugia for all taxa is within 'biofriendly', 18% within PAs, 17% within 'other', 16% within 'restore' and 13% within 'anthropic' – Figure 76). Both results show the great proportion of refugia in Cerrado that falls within 'biofriendly' land use class, highlighting the importance of the areas not currently protected for long-term biodiversity conservation planning that considers the projected impacts of future climate change on the biota of this biome.

Currently PAs within Cerrado cover 10% of the biome's total land area (~ 203,645km^2 - Table 9). Considering the lowest future global warming level analysed by this research, up to 60% of Cerrado PAs' land area is projected as potential future climatic cross-taxon refugia for least any two taxa (Figure 77 – note that the Y-axis goes up to 61), corresponding to 6% of the biome's total land area (Figure 76). However, under the same future warming scenario, just over 11% of the PAs' land area is identified as refugia for all five taxa (Figure 77), a decrease that represents 5% of the biome's total land area.

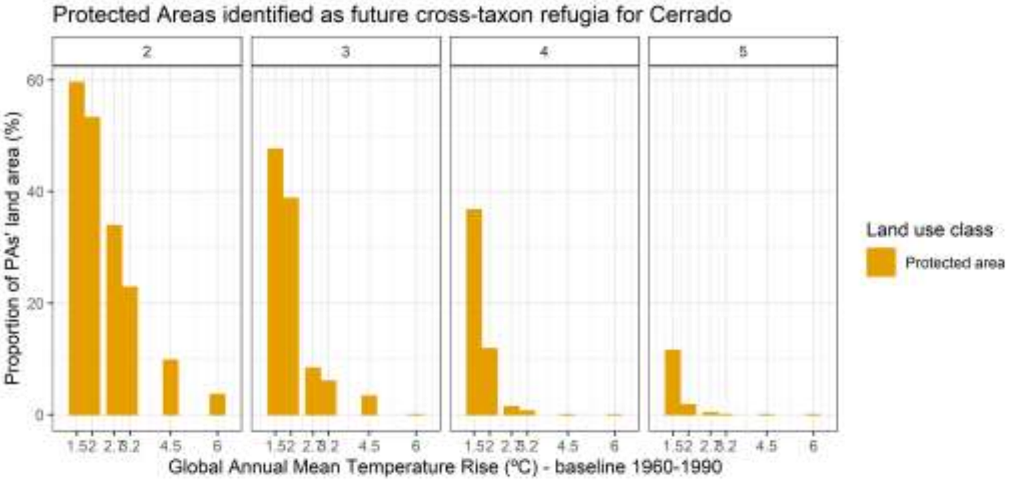

Figure 77: Proportion of the protected areas' land area within Cerrado identified as future climatic cross-taxon refugia for any combination of two or more taxa under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Number of taxa that are simultaneously been included in the refugia analysis is shown on the top of each box.

Moreover, in higher levels global warming, only a very small proportion of the PAs' land area within Cerrado has potential to act as refugia for all five taxa: 2% in a 2.0ºC warmer world and 0.3% if warming reaches 2.7ºC above pre-industrial times (Figure 77). In addition, other sharp decreases in the potential of Cerrado's PAs to act as refugia are also observed when the level of global warming increases:

- From 1.5ºC to 2.0ºC – refugia for four taxa decreases from 37% of the PAs' land area within Cerrado to 12% (68% decrease).
- From 2.0ºC to 2.7ºC – refugia for four taxa decreases from 12% of the PAs' land area within Cerrado to 1% (88% decrease); refugia for three taxa decreases from 39% of the PAs' land area within Cerrado to 8% (78% decrease); and refugia for two taxa decreases from 53% of the PAs' land area within Cerrado to 34% (36% decrease).

Regarding the geographical location of the PAs within Cerrado that are projected as potential cross-taxon refugia, they are mainly on the border with other biomes, as the Amazon, Atlantic Forest, Caatinga, or Pantanal (Figure 65). These PAs partially protect most locations identified as refugia simultaneously for at least two taxa in Cerrado, apart from refugia on the central-south (resilient up to 3.2ºC warmer world) and central (resilient up to 4.5ºC warmer world) portions of the biome (see chapter 4 Figure 47). The latter refugia are mainly covered by native vegetation despite being almost completely not protected, and hence need to be included in future long-term conservation planning measures.

Deforestation is a major threat not exclusive of Cerrado, yet national efforts to halt deforestation has proven to not be as successful for this biome as they were for the Amazon (Strassburg et al. 2017; Sano et al. 2019). In addition, future loss of natural habitat in Cerrado was projected to overlap with locations projected to remain with the highest number of plant species under despite future climate change (Velazco et al. 2019). Moreover, legal deforestation is conceivable in the northern Cerrado (Vieira, Pressey, and Loyola 2019) potentially taking place in locations identified as future refugia for all taxa under 1.5ºC scenario (Figure 67). Yet, Cerrado's PA network was found to be efficient in avoiding the degradation and conversion of the ecosystems in this biome between 2002 and 2009 (Carranza et al. 2014) but note that findings from Françoso et al. (2015) contradict this statement for sustainable use PAs, calling for the creation of areas with higher levels of restriction). Nevertheless, all studies above mentioned and other (Borges and Loyola 2020) support the need to expand the current PA network in this biome.

However, Cerrado currently has 10% of its land area protected as Conservation Units or Indigenous Lands (Table 9) and between 16 and 21% protected under the Forest Code (with native vegetation and in total, respectively - Table 7). Consequently, the current national commitment of protecting at least 17% of this biome has been achieved, and probably also the area-based target defined under the CBD for next decade. Thus, unless a very ambitious area-based protection goal is agreed for the next decade (i.e., greater than 30%), or Brazil commits to increase the current PA network regardless of the current amount already protected, there might be a lack of political willingness to expand the current PA network in this biome.

Finally, if future long-term conservation planning utterly aims to “safeguard ecosystems, species and genetic diversity” whilst tackling future climate change, it is important to create new PAs or OECMs that can effectively reduce the rate of deforestation and ecosystem degradation on this biome and that could promote the connectivity of the current PAs, especially among the ones identified as future climatic cross-taxon refugia.

i. Pampa

The projections for Pampa regarding its potential to act as future climatic cross-taxon refugia are the most optimistic among the Brazilian biomes (see chapter 4 Figure 47). If global warming does not exceed.4.5 ºC above pre-industrial times, ~ 100% of this biome’s land area is identified as future climatic cross-taxon refugia simultaneously for at least 2 taxa.

Considering that Pampa’s current PA network represents barely 3% of its land area (roughly 530k km^2), the vast majority of the land area identified as refugia in this biome is not currently protected. Moreover, Pampa is the only biome that falls short from reaching the national target of having at least 17% of its land area protected by 2020 even if the areas protected under the FC (FC-PAs) are included (Table 7). For such goal to be achieved in this biome, not only the FC-PAs must be verified and restored (if needed), but also 351,051km^2 of new PAs or OECMs would need to be created or expanded from the current ones (i.e., an expansion of the PA network equivalent to 2% of the biome’s land area). Therefore, it is inevitable to plan the expansion of Pampa’s current PA network if current or future area-based conservation commitments made by Brazil are to be met.

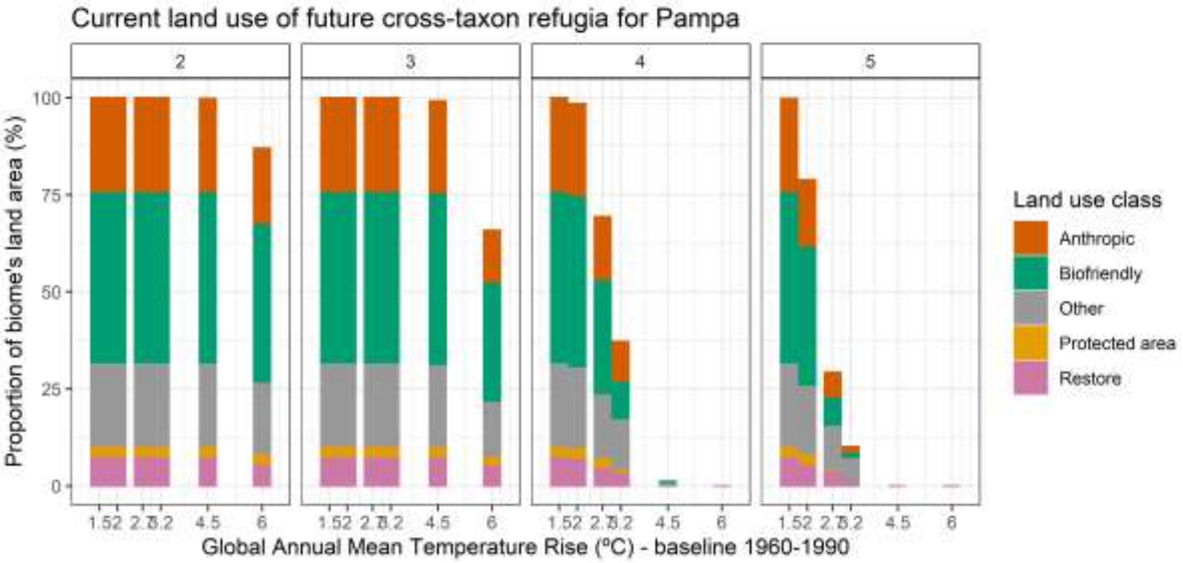

Figure 78: Current land use and size (expressed as a percentage of the biome’s total land area) of the locations in Pampa projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) simultanously, under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Considered land use classes: anthropic (orange), biofriendly (green), other (grey), protected area (yellow) and restore (pink), described in details on section 4.a of this chapter.

In addition to the poor coverage, it has been suggested that Pampa’s current PAs are ineffectively protecting medium-sized mammal species and that expanding the PA network in areas currently with native grassland would be advantageous for these species (de Lima et al. 2020). Pampa PAs’ efficiency could also be threatened by future climate change if levels of warming exceed 2.7ºC above the baseline. In this scenario, the proportion of the land area currently within Pampa PA network that has refugia potential for all five taxa sharply decreases (Figure 79), failing to protect the vast majority of the cross-taxon refugia for five taxa identified in the eastern region (compare chapter 4 Figure 48 with Figure 65).

However, if the global mean temperature is kept below 2.0ºC above pre-industrial levels, 35-44% of Pampa’s land area currently has native vegetation and is projected as cross-taxon refugia for all five taxa at the same time (44% in the +1.5ºC scenario and 35% in the +2.0ºC scenario), and around 7% of the biome still has this advantageous combination if warming levels do not exceed 2.7ºC (Figure 78). Therefore, in these three future climate scenarios, it is possible to expand Pampa's PA network exclusively in areas that are projected to be most resilient to future climate change.

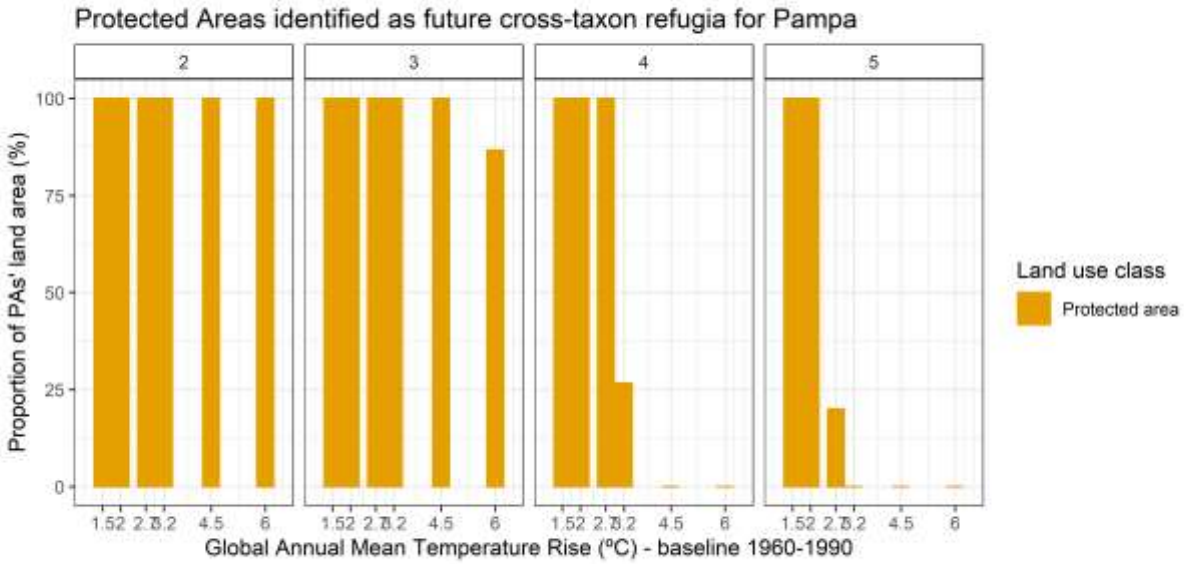

Figure 79: Proportion of the protected areas' land area within Pampa identified as future climatic cross-taxon refugia for any combination of two or more taxa under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Number of taxa that are simultaneously been included in the refugia analysis is shown on the top of each box.

Moreover, the geographical location of sites within Pampa currently with native vegetation that are projected as future climatic cross-taxon refugia for five taxa under the two lower future warming levels generally correspond to the ones identified as conservation priorities in order to preserve the variety of vegetation types of this biome (de Lima, Crouzeilles, and Vieira 2020). In addition, protecting these refugia with native vegetation would also benefit medium-sized mammal species (de Lima et al. 2020). However, it is worth mentioning that a considerable part of the most resilient eastern refugia for five taxa (up to 3.2ºC warmer) does not have native vegetation or fragments of native vegetation (i.e., areas to restore) but is yet in a region classified as of extremely high biological importance (MMA 2018b).

In conclusion, it is worth considering Pampa's great potential to act as future climatic cross-taxon refugia (see chapter 4 Figure 47, Figure 57 and Figure 58) whilst planning future conservation measures in this biome, prioritising the locations where the most resilient and most complete refugia (i.e., the ones that include the highest number of taxa) are identified, especially if they that match locations identified as conservation priority by other studies (e.g., the eastern part of the biome).

j. Pantanal

Pantanal has a unique situation regarding the current land use of future refugia for at least two taxa under the lowest level of warming investigated by this study: almost 70% of this biome's land area is refugia not currently protected and covered by native vegetation (land use class 'biofriendly' in Figure 80), the highest proportion among all biomes. On the other hand, Pantanal's potential to act as cross-taxon refugia is drastically lower if refugia for all five taxa is considered under the same future warming scenario. In this case, only 5% of Pantanal's land area is identified as refugia for all taxa with native vegetation but not protected, the third lowest relative amount of land area identified under this scenario among all biomes (Cerrado has the lowest – 3%, followed by the Amazon – 4%) and the lowest absolute land area as this type of refugia (~ 7,518km^2).

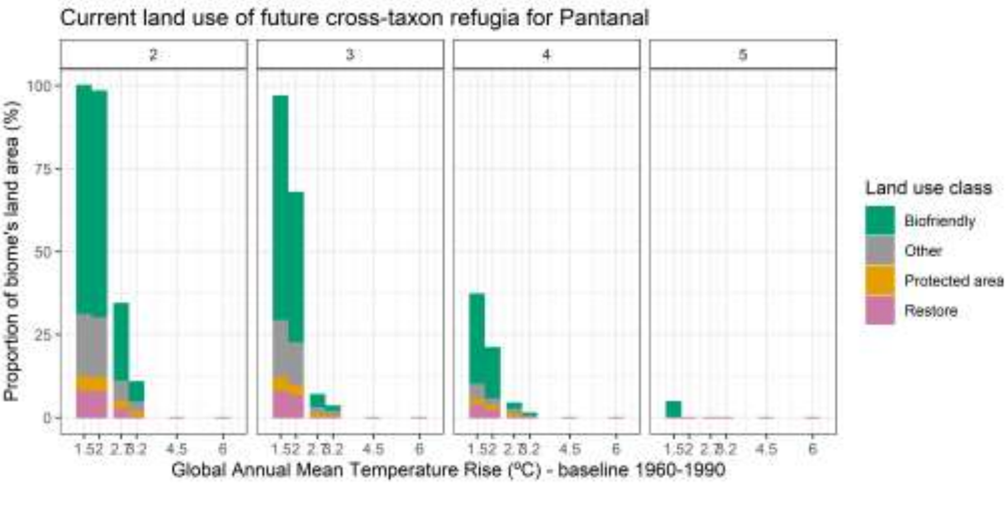

Figure 80: Current land use and size (expressed as a percentage of the biome's total land area) of the locations in Pantanal projected to have the potential to act as future climatic cross-taxon refugia for any combination of 2 to 4 taxa and for all 5 taxa (Amphibia, Aves, Mammalia, Reptilia, Plantae) simultanously, under six levels future of global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Considered land use classes: anthropic (orange), biofriendly (green), other (grey), protected area (yellow) and restore (pink), described in details on section 4.a of this chapter.

Regarding the amount of land area currently protected, Pantanal is almost as not protected as Pampa, with just 4% of its land area within PAs (Table 10). Moreover, the projections of future climatic cross-taxon refugia for Pantanal biome are worrying (see chapter 4 section 6.f), as there only are locations projected as refugia for plants in this biome up to 1.5ºC above the baseline (see chapter 4 Figure 43 and Figure 60). Therefore, it comes as no surprise that the PAs within Pantanal only have the potential to act as refugia simultaneously for five taxa if the Paris Agreement 1.5ºC target is delivered (Figure 81).

However, projections about Pantanal PAs' potential to act as refugia show a different picture if cross-taxon refugia for any two taxa is considered. In this case, the complete land area within Pantanal PA network is projected as refugia for any two taxa if global warming is limited to below 2.0ºC above pre-industrial levels (Figure 81). And if efforts to deliver the Paris Agreement targets fail and global warming reaches 2.7ºC above pre-industrial times, more than half of the PAs land area within this biome is still identified as refugia for any two taxa (Figure 81). Moreover, under the same future climate scenario, 20% of the land area of Pantanal's PAs is projected as cross-taxon refugia for the four vertebrate taxa (Figure 81), suggesting that in this level of warming, Pantanal's PA network has a better potential to act as cross-taxon refugia for more taxa than the PAs in the Amazon, Caatinga or Cerrado, even though this biome's PA network is smaller and outnumbered (but note that PAs in Caatinga and Cerrado remain with a small proportion of their land area identified as refugia for four taxa under 3.2ºC warmer scenario while PAs in Pantanal completely lose this potential at this future warming level).

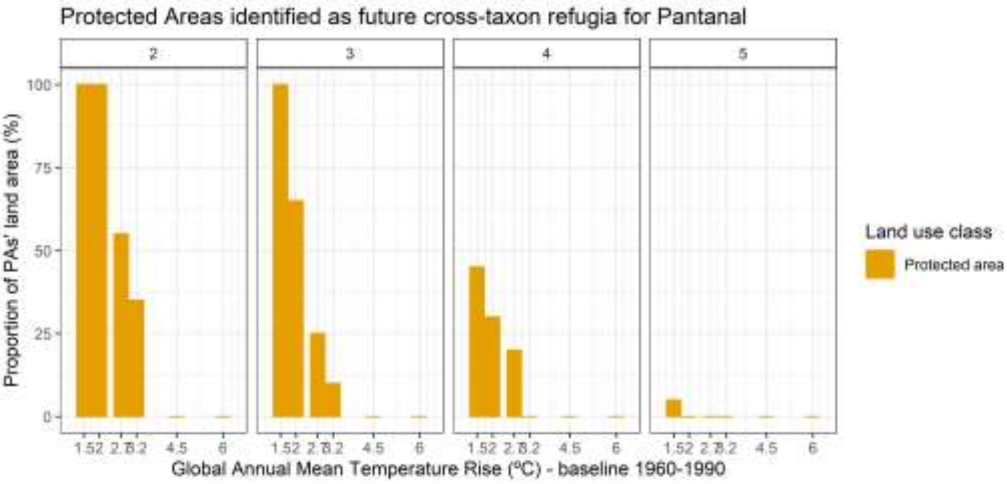

Figure 81: Proportion of the protected areas' land area within Pantanal identified as future climatic cross-taxon refugia for any combination of two or more taxa under six levels of future

global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Number of taxa that are simultaneously been included in the refugia analysis is shown on the top of each box.

Regarding the national commitment of having at least 17% of the land area of each non-Amazonian biome protected by 2020 assumed under the CBD, Pantanal's situation is unique. Pantanal is the only biome where the area covered by the PA network is almost six times smaller than the area protected under the Forest Code (Table 7). That means that in addition t the current 4% within PAs, Pantanal potentially has another 25-27% of its land area protected under the Forest Code (FC-PAs Table 7). Consequently, including the areas protected under the Forest Code guarantees the achievement of the current, and probably also the future, area-based protection targets.

Nevertheless, if future conservation planning intends to foster biota in Pantanal despite future climate change, the protection of the central-west and the extreme south refugia patches needs to be prioritized, irrespective of their status under the Forest Code and the lack of overlapping with the locations considered as priority by the latest national assessment (MMA 2018b). These locations are identified as future cross-taxon refugia for all taxa if global warming is limited to below 1.5ºC, or for all animal taxa if future warming exceeds 1.5 but remains below 2.0ºC (see chapter 4 section 6.f and Figure 47), they slightly overlap with current PAs (see Appendix section 2.b) what would enhance the resilience of the biota already protected, and have native vegetation (Figure 67).

k. Final remarks

Overall, the locations identified as future climatic cross-taxon refugia are projected to get smaller and more unevenly distributed throughout Brazil as the global mean temperature rises (key message from chapter 4). In all biomes within Brazil, future refugia are mainly outside current PAs even though they are still covered by native vegetation (except refugia in the Atlantic Forest – see subsections 5.a to 5.f). Due to the highly fragmented status of the Atlantic Forest, refugia in this biome mainly fall within converted areas that currently have native vegetation remnants (Figure 72) and classified by this study as suitable for restoration measures.

Moreover, the current PA network potential to act as future refugia decreases (Figure 64, Figure 65, Figure 70, Figure 72, Figure 74. Figure 76, Figure 78 , and Figure 81 -

except for the PAs in Pampa regarding the refugia projections for any two and any three taxa - Figure 81) and the PAs identified as refugia become less connected in higher levels of global warming (see section ‘current PA’s potential as future refugia’ and Figure 65). In addition, if the same level of future global warming is under analysis, PAs potential to act as future climatic cross-taxon refugia is lower for refugia that include higher number of taxa (Figure 64, Figure 65, Figure 70, Figure 72, Figure 74. Figure 76, Figure 78 and Figure 81 - except for the PAs in Pampa regarding the refugia projections for 1.5 ºC and 2.0ºC - Figure 81).

The threat that future changes in climate pose to PAs has been investigated by studies of other regions, countries, and continents. An analysis of 22 large PAs in North America under a future scenario of high level of warming (RCP 8.5) found that half of these PAs might have “substantially different vegetation” communities by the end of this century due to future climatic conditions (Holsinger et al. 2019). This chapter shows that the current plant assemblage within Brazilian PAs might not persist under future conditions of climate. Therefore, it is also possible to hypothesise that other plant species more compatible with the future climatic conditions could disperse and take the place of the ones currently within each Brazilian PA. Considering the refugia results for other taxa, it is possible to hypothesise “disruption of the current species assemblages” within each Brazilian PA, similar to the findings for PAs in Quebec, Canada (Berteaux et al. 2018). As future changes in climate are not the only threat to biota within PAs, projections of future land-use change can help identify PAs that will experience higher combined pressures, such as the ones within the Amazon (Asamoah, Beaumont, and Maina 2021) stressing the importance of strong and enforced legislation to tackle the climate and biodiversity crises.

The results presented here show a difference in the refugia potential among PAs of each biome, regardless of the disparity of protection currently present. Whilst PAs within Pantanal have the lowest relative (5%) and absolute (300 km^2) amount of land area identified as future refugia for all five taxa in the lowest warming scenario investigated (Figure 81), the complete land area covered by the PAs in Pampa is projected as future refugia for all taxa if global warming does not exceed 2.0ºC above pre-industrial times (Figure 79 - but note that the PAs cover only 3% of this biome, an area equivalent to 5,295 km^2). Moreover, if the global mean temperature reaches 3.2ºC warmer than the baseline, only the part of the Brazilian PA network that falls within the Atlantic Forest is projected to have the potential to act as future refugia for all five taxa (i.e., the complete land area of the PA network within the other biomes is no longer identified as refugia for all taxa if the mean global temperature reaches 3.2ºC above the baseline – Figure 65 and Figure 73). Therefore, keeping global warming below 1.5ºC above pre-industrial levels is essential to have a higher proportion of the Brazilian PAs' land area with potential to act as future climatic cross-taxon refugia (Figure 71 and Figure 81) and to endeavour safeguarding at least part of the locations identified as future climatic cross-taxon refugia for five taxa in all Brazilian biomes (Figure 65Figure 65).

This spatial variance in exposure of PAs to future changes in climate has also been assessed for different parts of the world and globally (but note that in this thesis sensitivity was evaluated). Within Europe's Natura 2000 sites, the ones located in the Alpine region were projected to experience higher levels of novel and disappearing climatic conditions than the sites in other regions (Nila et al. 2019). Globally, the amount of land area that is currently protected and projected to have climates in the future suitable for tropical and subtropical moist broadleaf forests, grasslands, savannas, and shrublands; boreal forests; and tundra is projected to substantially decrease. While PAs are projected to have more land area exposed to "cool (~4° to 15°C) and hot (>25°C) climates", favouring the biota associated with those (Elsen et al. 2020).

The expansion of the current Brazilian PA network has been often suggested as an urgent need to protect biota and to achieve the national commitment under CBD. However, if FC-PAs are considered, only Pampa would still need to increase its PAs coverage to achieve the 17% of protection, target aspired for 2020.In addition to Pampa, the Atlantic Forest and Caatinga would need to increase their PAs coverage to meet 30% of protection, the most likely target for CBD's post-2020 framework. Despite the advantage that the FC-PAs offer to reach the national target, the accuracy of their size and their aptitude to foster biodiversity have yet to be verified.

Nevertheless, the results presented in this chapter indicate that it would be advantageous to adopt different conservation measures while planning climate-smart biodiversity conservation efforts for each Brazilian biome. In this thesis, locations that are projected to be most resilient to future changes in climate, i.e., future climatic cross-taxon refugia, and that currently still hold native vegetation are considered suitable for PA network expansion. For the Amazon and Pantanal, for example, an expansion of the current PA network (either through the creation of new PAs or through the expansion of current ones) could safeguard large portions of the locations identified as refugia, promote their connectivity, and consequently enhance the resilience of the ecosystems within them. This thesis shows that the amount of land area considered suitable for PA creation or expansion decreases with higher levels of global warming. And that is observed for Brazil and for all biomes, although less pronounced for the most southern one, Pampa. Regarding Pampa, the results of this thesis contrasts one of the findings of a global study that investigated the land area of locations projected to have a more stable climate (lower changes) and currently with low indices of human modification (considered as intact areas) (Dobrowski et al. 2021). Different from this thesis, Dobrowski et al. (2021) found that Pampa has lower opportunity for expanding PA network than the tropical regions of Brazil. This difference can be explained by the methods used by each study. While Dobrowski et al. (2021) only considered suitable for PA expansion locations projected to undergo less changes in climatic conditions, this thesis has assessed the sensitivity of the biota within these locations to the climatic changes they are projected to be exposed to. Similar differences are observed during the identification of refugia (e.g., Michalak et al. (2020)) and have been discussed in chapter 4 section 6.g “Final remarks” of this thesis.

For the Atlantic Forest, this research shows that most refugia would benefit from restoration actions, corroborating with Dobrowski et al. (2021) that this biome has low potential for expanding PAs on climate stable and intact areas. However, there are very resilient refugia still mainly covered by this biome’s native vegetation, highlighting the urgency to protect these from other threats to biodiversity such as land-use change. For the other biomes (Caatinga, Cerrado and Pampa) a mixture of protection and restoring measures seems optimal to promote biodiversity conservation despite future climate change.

6. Discussion points

a. CBD area-based conservation target and the Brazilian Forest Code

In 2010 the CBD called its parties to increase their terrestrial protected area (PA) and other effective area-based conservation measures (OECMs) network to cover at least 17% of their total land area (CBD 2010). At that time, Brazil, which was still seen as an international environmental leader (Loyola 2014), committed to have 30% of the Amazon land area protected and 17% of the other biomes (national target 11 (Brazil 2013)).

On Brazil's 6th National Report (Brazil 2020b), it is stated that the country will consider its four types of PAs and OECMs (Conservation Units - UCs, Indigenous lands - TIs, Quilombola territories, and areas protected under the Brazilian Forest Code) 'as long as they maintain native vegetation' to account for its national target 11. However, the technical report of the national targets' indicators that complements the country 6th national report only has measurable indicators related to the area extent of UCs (MMA 2019). Therefore, to what extent Brazil will consider the other PAs and OECMs to meet this target is still unclear.

The results presented on this chapter for the first-time shed light on the impact that including the areas protected under the Forest Code recently added to SICAR could have on Brazil's progress towards its current protection targets and how this could impact the political willingness to expand the current network of PAs (here considered as the combination of UCs and TIs) if a new area-based protection target is agreed for the next decade under the CBD post-2020 global biodiversity framework. If Brazil includes Indigenous lands and areas protected under the Forest Code as indicators towards achieving current and future area-based conservation targets, the country will not need much effort to deliver the most ambitious target of having half of its land area protected (Table 11). And breaking down this number per biome, Brazil is very comfortable to increase its sub-national area-based conservation target for all biomes except for Caatinga and Pampa, the only regions that do not achieve 17% of protection as states in the current target (national target 11 (Brazil 2013)).

Table 11: Proportion of land area within Brazil and within Brazilian terrestrial biomes that could be considered towards the achievement of targets set under CBD. Column "UCs and/or TIs" refers to currently protected areas eihter considered by this study (Conservation Units, UCs, and Indigenous Lands, TIs) or to the UCs regirstred in the national system (whichever is higher); column FC-PAs refers to areas protected under the Forest Code (areas of permanent protection, APP and legal reserves, RL) that the land owner has registred in SICAR and declared to currently have native vegetation.

	UCs and/or TIs (%)	FC-PAs (%)	TOTAL (%)
Brazil	27	18.5	45.5
Amazon	48	16.6	64.6
Atlantic Forest	10	9.1	19.1
Caatinga	9	4.8	13.8
Cerrado	10	15.8	25.8
Pampa	3	7.8	10.8
Pantanal	5	25.3	30.3

Therefore, the analysis performed by this study goes beyond previous studies regarding Brazil's progress in terrestrial area-based protection that completely ignored the national plans to include other PAs and OECMs as part of the target (Pacheco et al. 2018, Vieira et al. 2019). Considering the total values presented on Table 11, Atlantic Forest, Caatinga and Pampa are the biomes that would still need to considerably increase their PAs network to meet a potential post-2020 target of having 30% of land protected by 2030.

For the Atlantic Forest, this research shows that an expansion of the PA network of around 11% would be needed. In addition, it shows that if the Paris Agreement 1.5ºC target is delivered, this expansion could protect almost all future climatic cross-taxon refugia for at least four taxa that currently have native vegetation (i.e., 'biofriendly' land use class, representing in the 1.5ºC scenario 11.5% of the biome's land area) located throughout the central and on the south-eastern parts of the biome (Figure 65). This would increase the protection of important sites for biodiversity, such as some of the putative Quaternary refugia (Carnaval et al. 2009; Porto, Carnaval, and da Rocha 2013) and of some priority areas for conservation along the central and southern coast of this biome identified by previous study (Zwiener et al. 2017) or listed on the latest national assessment (MMA 2018b).

Moreover, this study presents that a planned expansion of Caatinga's current PA network to incorporate part of the locations identified as refugia for all taxa under the 1.5ºC scenario that currently have native vegetation (Figure 67) could address the lack of connectivity and the spatial unevenness of protection in Caatinga. In addition, these refugia currently not protected overlap with areas identified as of very high biological importance on the latest national assessment (MMA 2018b), an analysis that included the need to promote landscape connectivity as one of the conservation targets (Fonseca et al. 2017).

This research also shows Pampa's great potential to act as future climatic cross-taxon refugia. If the global mean temperature is kept below 2.0ºC above pre-industrial levels, 35-44% of Pampa's land area currently has native vegetation and is projected as cross-taxon refugia for all five taxa at the same time. Therefore, future conservation measures in this biome can prioritise the locations projected as the most resilient and most complete refugia (i.e., the ones that include the highest number of taxa), especially refugia that match locations identified as conservation priority by other studies (e.g., the eastern part of the biome).

However, the findings presented here emphasise that the validation of the size, geographical location and land cover of the areas protected under the Forest Code is of extremely importance if these areas are to be included as part of the effort to deliver the current national target 11 or future one agreed under the post-2020 framework.

b. Caveats

This research consists of a spatial analysis of the intersection of locations identified as future climatic cross-taxon refugia for terrestrial biota in Brazil and the country's current land use and protection status. Due to the nature of this analysis and the spatial resolution adopted, small Protected Areas (PAs) were not included and hence led to minor discrepancies between the proportion of land area categorized as protected by this study and the official data from the Brazilian Ministry of the Environment (MMA 2018a) for the Atlantic Forest, Caatinga and Cerrado. Moreover, all different categories of Brazilian PAs were treated equally, as the main aim of this research is to evaluate their potential to act as future refugia as a network.

It is worth noting that while deforestation and ecosystem degradation are undoubtedly lower inside PAs than elsewhere, they are not completely absent within the PA network (Françoso et al. 2015; Lapola et al. 2020; Walker et al. 2020). Therefore, in addition to the threat that future climate change is projected to pose to biota within PAs (as outside them), future land-use change can also undermine the PAs (or any location) potential to foster biota and, more importantly, to act as future climate change refugia. A global analysis showed that this could be the case for PAs identified as putative refugia throughout eastern Europe, Scandinavia, eastern North America, Southeast Asia and eastern Africa (Asamoah, Beaumont, and Maina 2021). Land-use projections that consider the Brazilian context and legislation should be used to investigate the interaction of these threats to the Brazilian biota. Nevertheless, it is worth highlighting that there is empirical evidence of PAs performance since 1970s showing that observed declines on species number inside PAs are often lower than outside, and that PAs have been used as stepping-stones while species colonize new locations. Therefore, it is generally considered that PAs have been and are likely to continue to be crucial for long-term biodiversity conservation despite changes in climate (Thomas and Gillingham 2015).

At the same time, PAs in Brazil are in constant threat to be downsized, downgraded, degazetted, and / or reclassified (Bernard, Penna, and Araujo 2014; Brazil 2020b). Considering this, the results regarding the PAs' potential to act as refugia presented in this chapter should be seen as conservative as they are based on the assumptions that the current PA network remains with the same areal extent and with native vegetation. In addition, this research's findings regarding the PAs' potential to act as future refugia fills the gap left by previous assessment of the Brazilian PAs' vulnerability to future climate change considered the amount of non-native vegetation inside PAs and on their buffer zones (Lapola et al. 2020) by analysing projections of the impacts of climate change on terrestrial vertebrate and plant species potential geographical ranges.

Future land use change is also a concern in light of the projections of climate change impacts on crop species. Projections suggest that the changes in climate suitability will displace some important crops to the southern part of Brazil (Zilli et al. 2020), a region that is already the most populated and hence vegetation is more fragmented, possibly overlapping with areas identified in this thesis as future refugia. This research did not consider the impacts that climate change might cause on the current land use (such as displacement of crop cultures presented in the discussion section of this chapter) or that native vegetation might still be lost due to legal and illegal deforestation and ecosystems conversion. Moreover, the impacts that the full implementation of the Brazilian 2012 Forest Code and its derived programs and policies (CAR – national registry of rural private properties, CRA – quotas of environmental reserves, PRAD – projects aimed at recovering degraded areas, Proveg – national policy of native vegetation recovery) were not included.

Finally, results presented in this chapter should not be seen as an imperative of where to restore or protect but rather as a starting point. Future climatic cross-taxon refugia should be combined with other spatial data, such as the ones derived from the Forest Code after validation, topography, other biodiversity indicators (e.g., Local Biodiversity Intactness Index, Key Biodiversity Areas – KBA), and spatial data on carbon storage, to identify the locations where the synergies for biodiversity conservation, sustainable development, and tackling climate change are the greatest.

7. Key messages

The current land use of the areas identified as future climatic cross-taxon refugia varies depending on biome, taxonomic group, and level of global warming.

In general, the majority of the area identified as future climatic cross-taxon refugia for terrestrial biodiversity in Brazil is located in non- protected areas with natural vegetation (except in the Atlantic Forest), highlighting the importance of the expansion of the current PA network to safeguard these refugia from deforestation and degradation. While in the Atlantic Forest, future climatic cross-taxon refugia are mainly located in areas outside the current PA network that have been converted and hence would need restoration or reforestation actions to appropriately promote biodiversity conservation.

In addition, only if future warming is kept below 1.5ºC above pre-industrial levels, will there be PAs in all biomes with the potential to act as refugia for all five taxa, underscoring the importance of strengthening the global efforts to deliver the Paris Agreement targets.

These findings demonstrate that it will be essential to combine different conservation strategies to face the current and future challenges posed by future climate change to biodiversity in Brazil.

Chapter 6: Final remarks

This chapter presents as final remarks of this thesis the key messages of this research, and then an overall discussion followed by the overall conclusions. The key messages represent the main findings of the thesis relevant for the comparison between narratives that consider an increase in the global annual mean temperature of 1.5ºC and 2.7ºC above pre-industrial levels. These two levels of future warming were chosen to represent the ultimate temperature goal of the Paris Agreement ('to pursue efforts to limit warming to 1.5ºC') and 2.7ºC corresponding to the more optimistic interpretation of the current NDCs pledges, and to simplify the discussion presented here. The discussion covers the state of the art of the nexus of climate change, biodiversity conservation and land use in Brazil, how this research has contributed and advanced this field, questions that are left unanswered, and the main caveats. Finally, the conclusion section of this chapter shows how this thesis is successful in achieving its overarching aim and specific objectives.

1. Key messages

a. Projected changes for bioclimatic variables

1.1-Parts of Brazil are projected to experience an increase in the minimum temperature of the coldest month and in the maximum temperature of the warmest month greater than the global annual average increase in temperature. Moreover, the size of these patches and the degree of warming that they will experience above the global annual mean is higher on a 2.7ºC than on a 1. 5ºC warmer world compared to pre-industrial times (chapter 3).

a-Parts of the Amazon and Cerrado are projected to experience warming up to 1.5 times higher than the global annual mean increase in temperature for the minimum temperature of the coldest month, up to 2 times higher for the maximum temperature of the warmest month with global warming up to 1.5ºC in relation to pre-industrial levels. While in a 2.7ºC warmer world, parts of Amazon, Atlantic Forest, Cerrado and Pantanal are projected to experience warming up to 2.5 times higher than the global annual mean increase in temperature for the minimum temperature of the coldest month and the maximum temperature of the warmest month.

b-Regardless of the direction of change (i.e., if projections suggest an increase or a decrease in relation to observed levels), projected changes in annual total precipitation for Brazil are higher at 2.7ºC compared to 1.5ºC of global warming. In addition, more parts of the country are projected to get drier on the driest quarter on a 2.7ºC than on a 1. 5ºC warmer world compared to pre-industrial times(chapter 3).

c-The projected decreases in the total annual precipitation and in precipitation for the wettest and drier quarters for small parts of the northern Amazon and of the northern and central-eastern regions of the Atlantic Forest are higher at 2.7ºC compared to 1.5ºC of global warming (medium to high consistency). At the same time, projected increases in the three above mentioned bioclimatic variables for the south-eastern part of Atlantic Forest along with the eastern part of Pampa are higher quarter on a 2.7ºC than on a 1. 5ºC warmer world compared to pre-industrial times (medium to high consistency).

b. Size and geographical location of future climatic cross-taxon refugia

1.2-Comparing future climatic cross-taxon refugia for terrestrial biota in Brazil at 1.5ºC and 2.7ºC of global warming, the amount of land area projected as potential refugia decreases as the global mean annual temperature rises. In addition, refugia shrink faster in the tropical part of Brazil, that currently has more PAs (e.g., Amazon), than in the subtropical one, that has already been completely or partially converted (e.g., Atlantic Forest). Moreover, the rate of decrease is higher for refugia for all five taxa compared to refugia for two or more taxa (chapters 4 and 5).

a-The size of the land area identified as potential future climatic cross-taxon refugia for at least two taxa in Brazil shrinks 56% if global warming exceeds 1.5ºC and reaches 2.7ºC above pre-industrial levels, almost completely disappearing in the Amazon. This may suggest a tipping-point in the Amazon for significant ecosystem change at lower levels of global warming than the 3-4ºC suggested by Lenton et al. (2008) and Salazar and Nobre (2010) (see discussion in chapter 4 section 6.a). If refugia for all taxa is considered, a higher decrease in land area with refugia potential is projected under increased levels of global warming. On a 1.5ºC warmer world, approximately 17% of Brazil’s land area, including parts of within all biomes, has potential to act as future climatic cross-taxon refugia for all five taxa compared to only 3% (82% of decrease) on a 2.7ºC warmer world, restricted mainly to the Atlantic Forest and Pampa.

c. Protected areas potential to act as future climatic cross-taxon refugia

1.3-Any increase in global warming can jeopardize the Brazilian PAs potential to act as future climatic cross-taxon refugia for two or more taxa in Brazil, and only if future warming is kept below 1.5ºC above pre-industrial levels, will there be PAs in all biomes with the potential to act as refugia for all five taxa (chapter 5).

a-Even if global warming is limited to 1.5ºC above pre-industrial levels, less than half of the current Brazilian PAs' land area is projected as potential future climatic cross-taxon refugia for two or more taxa, and only 8% is identified as refugia for all five taxa simultaneously. The proportion of Brazilian PAs land area identified as future climatic cross-taxon refugia decreases to 9-1% on the 2.7ºC warmer scenario, depending on how many taxa are simultaneously considered (9% for two or more taxa and 1% for all five taxa). Moreover, limiting global warming to 1.5ºC compared to 2.7ºC is projected to increase the number and the geographical evenness of Brazilian PAs identified as potential future climatic cross-taxon refugia.

d. Current protection status of future climatic cross-taxon refugia

1.4-Locations in Brazil identified as potential future climatic cross-taxon refugia are largely unprotected. Moreover, the proportion of refugia that lie within Brazilian PAs is higher at 1.5ºC of global warming compared to 2.7ºC (chapter 5).

a-Considering refugia for two or more taxa under a 1.5ºC warmer world, 18% of the land area identified as this type of refugia is within Brazilian PAs. This proportion decreases to 9% of refugia within PAs if global warming reaches 2.7ºC above pre-industrial levels. Similar reduction in the proportion of refugia within PAs is observed for refugia for all five taxa. Under a 1.5ºC warmer world, 13% of the land area identified as this type of refugia is within Brazilian PAs, but this proportion decreases to 9% if global warming reaches 2.7ºC above pre-industrial levels.

e. Potential of future climatic cross-taxon refugia to be employed in conservation measures

1.5-There is an urgent need to protect locations projected as potential future climatic cross-taxon refugia in Brazil that fall outside PAs and hold native vegetation (chapter5).

a-At 1.5ºC of global warming, between 7 and 25% of the Brazilian land area is projected as future climatic cross-taxon refugia currently outside PAs but with native vegetation (for all five taxa and for two or more taxa, respectively), compared with 1 - 11% at 2.7°C. Therefore, limiting global warming to 1.5°C compared to 2.7ºC increases the amount and geographical distribution of refugia in Brazil with native vegetation that if protected could help the country promote long-term climate-smart biodiversity conservation in all biomes and avoid carbon emissions from deforestation and ecosystem degradation.

b-In a 1.5ºC warmer world, key places where refugia need to be protected are: refugia on the northern and north-west portions of the Amazon, the northern refugia on Caatinga, refugia in the border of Cerrado and the Amazon and Cerrado and Atlantic Forest, the most northern refugia in the Atlantic Forest, the ones in the central and southern coast of this biome, refugia in the western part of Pantanal, and refugia on the eastern coast of Pampa.

1.6-Limiting global warming to 1.5ºC compared to 2.7ºC gives Brazil the opportunity to choose from locations in four biomes identified as future climatic cross-taxon refugia for five taxa with restoration potential (i.e., with remnants of native vegetation) the ones with the best cost-benefit whilist meeting its current 12Mha restoration pledge (chapter 5).

a-Under a 1.5ºC warmer world, 3% of Brazil's land area is projected as future climatic cross-taxon refugia for five taxa with restoration potential, an area two times larger than the current Brazilian restoration pledge under the Bonn Challenge (12Mha, ~ 1,4% of the country's land area). In comparison, only 0.7% of Brazil's land area is projected as refugia for five taxa with restoration potential if global warming reaches 2.7ºC above pre-industrial times.

b-Moreover, if global warming is limited to 1.5ºC, most of the future climatic cross-taxon refugia for five taxa with potential to be restored are throughout the Atlantic Forest (65% of the land area of these refugia), but there is a considerable amount throughout Caatinga (22% refugia), and a smaller proportion in northern part of Cerrado (7% refugia) and in the eastern and western borders of Pampa (5% refugia). While if global warming reaches 2.7ºC above pre-industrial levels, this type of refugia with potential to be restored is only found in the central and southern parts of the Atlantic Forest (88% of the land area of these refugia) and in the eastern part of Pampa (12% refugia).

2. Discussion

The research here presented investigates the nexus of climate change, biodiversity conservation and land-use to: (a) identify and analyse the locations in Brazil and in each Brazilian biome that are projected as potential future climatic cross-taxon refugia for terrestrial species of five taxa (Amphibia, Aves, Mammalia, Plantae, and Reptilia), (b) examine the extent to which the current Brazilian PA network has potential to act as future climatic cross-taxon refugia, and (c) demonstrate how refugia outside PAs can be used to plan conservation measures, such as the expansion of the PA network and ecosystem restoration, for each Brazilian biome.

a. Contributions to the field

Specifically, this research shows that locations identified as potential future climatic cross-taxon refugia for terrestrial biota in Brazil do not always match locations projected to undergo less change in bioclimatic variables (chapters 3 and 4). This shows the added benefit of the use of SDMs, such as Maxent, in identifying future climate change refugia, as compared to the simpler approach used by Borges and Loyola (2020) which considered only Cerrado and did not conduct a SDM exercise or consider species individually, and also used an average of four climate models only. Therefore, it is unsurprising that many of the locations identified as refugia by this previous study (Borges and Loyola 2020) are not identified as future climatic cross-taxon refugia with native vegetation by this research, similarly to the miss-match found by Michalak et al. (2020) for North America when comparing different approaches to identify refugia. The former considered refugia as locations projected to undergo the lowest levels of future climatic changes and to remain with highest levels of native vegetation, an approach to identify refugia that does not take into consideration information about species. Even though the previous study used land-use projections for 2050, there is an overall matching of the areas considered to hold native vegetation by both studies (this thesis and Borges and Loyola (2020)). Therefore, it is interesting to highlight that the differences between the locations identified as refugia by each study come from the different definition of refugia and methodologies adopted while identifying them. As an example, the previous study has identified that under RCP 8.5 by 2050 (representing an increase in the global mean temperature between 2.6-4.8ºC (Collins 2013)) there would still be refugia in the extreme west part of the Cerrado biome (border with the Amazon) and along its border with Pantanal. This research shows that under these same warming levels the first region is not projected as refugia or to remain climatically suitable for at least 50% of its current species for any of the five taxa separately (chapter 4, Figures10 to 14). And that under these same warming levels, the second region is projected as potential refugia only for reptiles (chapter 4, Figures10 to 14). This suggests that the Cerrado is more sensitive to future climate change than Warszawski et al. (2013) which indicated a threshold of 3-4ºC of global warming for an ecosystem transition.

Considering that this research uses projections of potential refugia that are based on future potential geographical ranges delivered from SDMs that combine the projected changes in bioclimatic variables and species climatic tolerances, the definition of refugia adopted by this research is more complex than the one used by Borges and Loyola (2020), and it represents areas that will remain climatically suitable for the modelled biota under different levels of future climatic changes. Moreover, the research presented here adopts a more robust approach to the bioclimatic modelling than the previous study. Here future projections derived from 21 GCMs are independently considered for each of the six future warming levels and the level of agreement on the projected changes for the bioclimatic variables is shown (chapter 3). In the previous study, an average of the projected changes derived from four GCMs under RCP8.5 by 2050 was used. Due to the large spread of the projections of change for the bioclimatic variables (as seen in chapter 3), adopting few GCMs or using their average has been discouraged by several other studies, as it fails to capture the range of plausible future climate scenarios and their impacts on biota (Buisson et al. 2010; Porfirio et al. 2014; Araújo et al. 2019).

Finally, the research here presented sheds light on the recommendation made by the previous study (Borges and Loyola 2020) to restore all areas in Cerrado that hold less native vegetation and projected to undergo less climatic changes. The research presented in this thesis provides further detail by showing that: (a) the southern areas in Cerrado are currently already vastly converted (e.g., to cropland), what would increase the cost of restoration, and (b) with exception of the northern part of the biome, all the other areas suggested by Borges and Loyola (2020) for restoration actions are projected to remain climatically suitable for up to only 50% of their current plant species, what could jeopardize any attempt of restoration that is not carefully planned (chapter 4 Figure 13). In fact, the results presented in this thesis corroborate with the alarming projections that southern areas of Cerrado are at risk of a severe ecosystem change if global warming reaches 3-4ºC above pre-industrial levels (Warszawski et al. 2013). As a conclusion, further research is needed to identify the best conservation strategy to enhance diversity, connectivity, and hence the resilience of the biota of these regions of Cerrado. Future studies could identify the Flora projected to have the best chances of survival under future climatic conditions, explore their potential for restoration actions, and how they could improve the landscape in order to support the projected species ranges shifts caused by future climate change.

This research also shows that the amount of land area identified as potential future climatic cross-taxon refugia in Brazil decreases as the global mean temperature rises, and that rate of decline is higher in the tropical part of Brazil, that currently has more PAs and more native vegetation (e.g., Amazon), than in the subtropical one, that has already been completely or partially converted (e.g., Atlantic Forest – chapters 4 and 5). The results presented in this thesis provide further insight to the findings that tropical forests are more sensitive to changes in land-use and climate than temperate ones (Newbold et al. 2020), showing that the sensitivity to climate change also varies between tropical forests (Amazon and Atlantic Forest).

In addition, this finding corroborates with the only other study which attempts to identify conservation priorities not specific to a single taxon across the whole country taking into account climate change. It uses a regional climate model driven by two global climate models to identify areas with high probability of being exposed to drought due to future climate change (Kasecker et al. 2018). It has mainly pinpointed priority municipalities to implement and monitor climate change adaptation measures in the tropical part of the country due to their extensive natural vegetation cover, high levels of poverty, and high probability of being exposed to drought due to future climate change. Some of them match locations identified as potential refugia for all five taxa in the tropical part of Brazil under the two lowest levels of future warming (1.5 and 2.0ºC above baseline). These municipalities that were identified as conservation priorities and are projected to hold potential refugia (north and northwest of the Amazon, noth Cerrado, central and western Caatinga, and northern Atlantic Forest) would be ideal locations for the expansion or creation of PAs or OECMs that allow sustainable activies within their boundaries aiming to alliviate poverty of local communities. This example shows that the knowledge about the locations with potential to act as future climatic cross-taxon refugia can provide aditional guidance for conservation planning that aims to deliver Nature-based Solutions (NbS – for definition see chapter 5 section 1) benefiting biodiversity, climate, and society. Therefore, by combining results from both studies (Kasecker et al. (2018) and this thesis), it is possible to identify where refugia with native vegetation could be employed as NbS and deliver some of the societal goals to the most needed (sharing the land between biodiversity and people) and where refugia should be spared and fully protected (options for land sharing and land sparing are discussed in chapter 5).

Other existing studies have focused on the use of species distribution models and / or environmental niche models to spatially identify conservation priorities in Brazil under climate change (e.g., Loyola et al. (2012), de Oliveira et al. (2012), Ribeiro, Sales, and Loyola (2018), Vasconcelos and Prado (2019)). All these studies have covered far fewer species than this thesis being restricted a single taxon, apart from de Oliveira et al. (2012) that considered 32 vertebrate species, and / or to one or two biomes, except Loyola et al. (2012) that considered Brazil. Most of these studies did not include the full range of uncertainty in climate projection, nor did they spam the full range of potential global warming levels between 1.5ºC and 6.0ºC. However, it is useful to make a comparison with some of these earlier studies.

For example, Vasconcelos and Prado (2019) looked at anuran species in the Atlantic Forest (350 species) and Cerrado (155 species). In common with this thesis, they identified the Atlantic Forest as particularly important for protecting biodiversity under climate change and that Cerrado is at greater risk under future changes in climate. However, unlike this thesis, Vasconcelos and Prado (2019) considered that species can follow their suitable climate without limitation (usually referred as ‘full-dispersal’ or ‘unlimited dispersal’ – see explanation on chapter 2 section 3.c and discussion at end of chapter 4) and used this to show that species ranges are shifting towards the Atlantic Forest, particularly at higher levels of global warming. Hence it showed that the number of grid cells identified as conservation priority for anuran species increases in the Atlantic Forest and decreases in Cerrado as levels of future climate change increase (Vasconcelos and Prado 2019).

Other examples are the analysis of conservation measures that take into consideration the future climatic suitability of Caatinga for 32 endemic vertebrate species (de Oliveira et al. 2012) and of the Amazon for 256 mammal species (Ribeiro, Sales, and Loyola 2018) under future climate change. The former used future climate projections up to the end of the century from three GCMs under two future climate change scenarios to force the seven different algorithms to model future potential species ranges. The latter used future climate projections from three GCMs up to 2050 under one future climate change scenario to force one algorithm to model future potential species ranges (Maxent, same as used by the WI). Therefore, in addition to the lower number of species considered by both studies in comparison to this thesis (that included 316 mammal species for the Amazon and 1377 vertebrate species for Caatinga), they also considered a lower range of uncertainty in climate projection, and lower range of future global warming levels.

In common with this thesis, de Oliveira et al. (2012) found that if future climatic cross-taxon refugia is to be included in future long-term conservation planning for Caatinga, efforts should focus on protecting locations that currently hold native vegetation (see chapter 5 section 5.g Figure 13). This thesis goes beyond this previous finding by showing that only if the 2.0ºC Paris Agreement temperature target is met, there will be refugia for plants in Caatinga, underscoring the importance of protecting these refugia to simultaneously promote climate change mitigation and adaptation.

Ribeiro, Sales, and Loyola (2018) projections of locations in the Amazon that will remain climatically suitable for mammal species (referred as species metric) in 2050 derived from three GCMs under one high emission scenario (corresponding to an increase of 2.0ºC±0.4ºC) generally match the ones presented in this thesis (see chapter 4 section 4.b Figure 40 panels 1.5ºC and 2.0ºC). However, in contrast with this thesis, Ribeiro, Sales, and Loyola (2018) considered as refugia the locations projected to experience lower climate anomalies, less climate extremes and lower climate change velocity (referred as climate change metrics). Further differences between the methodologies adopted by this previous research and this thesis to identify priority areas for future conservation planning in this biome should be mentioned. The previous study used a prioritization software (Zonation (Moilanen et al. 2005)) and weights for species and climate change metrics for the prioritization process, such as 'weights for species according to their conservation status' (Ribeiro, Sales, and Loyola 2018). It means that Ribeiro, Sales, and Loyola (2018) used other metrics in addition to refugia to identify the priority locations for conservation of refugia for mammals in the Amazon. Therefore, not surprisingly the locations identified by Ribeiro, Sales, and Loyola (2018) as 'extremely high priority' for conservation of refugia for mammal species in the Amazon do not match the locations identified as refugia for the same taxon and biome by this thesis (see chapter 4 section 4.b Figure 40). At the same time, this thesis goes beyond the previous study by analysing the locations projected to remain climatically suitable for most species under a broader range of future climate scenarios for other taxa in the same biome (and in all other Brazilian biomes), mapping the locations identified as future climatic cross-taxon refugia for the country. Hence, a good follow up to this thesis includes the use prioritization / approach or systematic conservation software, such as Zonation, Marxan, prioritizr or ResNet to identify the most cost-efficient refugia to be protected or restored.

A final example is the analysis performed by Loyola et al. (2012) that investigated the locations in Brazil projected to remain climatically suitable for 55 marsupial species under future climate change, considering the abovementioned unlimited dispersal. In addition to the low number of species included in this previous analysis, it used future projections for 2050 derived from only four GCMs under two future climate scenarios. In comparison, this thesis considers results of future potential geographical range of 367 mammal species in Brazil, derived from 21 GCMs under six levels of future global warming. Nevertheless, the areas presented in this thesis as future climate change refugia for mammals (see chapter 4 section 4.b Figure 40) under the lowest levels of future global warming investigated by this thesis (1.5ºC and 2.0ºC above pre-industrial levels) overall match the locations identified by Loyola et al. (2012) to remain climatically suitable for most marsupial species (north-west of Amazon, central and southern part of the Atlantic Forest, most of Caatinga, north and west of Cerrado, most of Pampa and south of Pantanal). On the other hand, by analysing the locations that are projected to remain climatically suitable simultaneously for several taxa, this thesis shows that even in a 1.5ºC warmer world far fewer and smaller locations are projected as refugia for all taxa, especially smaller in Caatinga, Cerrado and Pantanal (see chapter 4 section 6 Figure 45 and Figure 46). If future conservation measures aim to safeguard most of all biota, it is important to considering a broad range of taxa in refugia identification.

The results of this research also show locations that if restored could improve biota's resilience to future climate change (chapter 5). This conservation measure is specifically imporant for potential future climatic cross-taxon refugia identified by this research in the Atlantic Forest, a biome that has been extremely degraded and fragmented, currently holding just 8-11% of its original extension (depending if "intermediate secondary forests and small fragments" are considered or not - Colombo and Joly (2010)) in which more than 80% of the remaining fragments have less than 50ha (Ribeiro et al. 2009).Therefore, it is not surprising that for this biome the locations identified by this research as cross-taxon refugia (regardless of the number of taxa included) mainly fall within the land category 'restore' (areas with native vegetation remnants – chapter 5), corroborating with a statement made by previous analysis of conservation priorities for the Atlantic Forest under future climate change (Zwiener et al. 2017): 'restoration actions are urgently needed' in this biome. This latter study used species distribution modelling to identify future climate change refugia for 2255 woody plant species in the Atlantic Forest only.

This research goes beyond Zwiener et al. (2017) by providing spatially explicit information of where such restoration actions could take place to recover locations where the full range of taxa (and not only plants) are identified to be most resilient to future climate change. The maps in this thesis have presented the locations projected by at least 11 GCMs (out of 21) to remain climatically suitable for at least 75% of the current species of at least two out of five taxa under six future levels of global warming. In contrast Zwiener et al. (2017) consider only three GCMs and two scenarios, failing to capture the full range of climate projections as is done in this thesis. Therefore, this thesis provides decision makers a range of possible future climate scenarios and the locations that are projected to remain climatically suitable for one taxon or several taxa (chapter 4), and the current land-use of the latter (chapter 5).

In addition, when analysing the national commitment for area-based conservation in the Atlantic under the CBD, this thesis goes beyond the previous analysis (Zwiener et al. 2017) by: (i) considering that 9-15% of this biome is protected under the Forest Code; and (ii) considering 30% of protection as a possible post-2020 area-based target. On the other hand, Zwiener et al. (2017) included information on land cost, forecasted urbanization, cropland and pastureland, and the political willingness to promote biodiversity conservation to perform the prioritization exercise. In chapter 5 the analysis of ecosystem restoration is based on current land-use. Therefore, a further step of the analysis of refugia would be to investigate the overlap of future climatic cross-taxon refugia with future land-use projections taking into account shifts in agriculture (such as the ones from Brazil Zilli et al. (2020) briefly mentioned in chapter 5), and with current land cost or restoration cost (such as values presented by (Brancalion et al. 2019) or as the ones used by (Strassburg et al. 2020)) to plan conservation measures with the most benefits for biota and the least cost.

Finally, this research shows the extent to which future climate change will impact the climatic suitability of Brazilian PAs for the terrestrial biota currently present. It shows that only if global warming is limited to 1.5ºC there will be PAs in all biomes projected as potential future cross-taxon climatic refugia for all five taxa (chapter 5). The findings of the national analysis presented in this thesis corroborate with previous SDM-based assessments made for the Atlantic Forest and Cerrado that found that PAs in those biomes are projected to protect less species due to changes in climate suitability in the future (Lemes, Melo, and Loyola 2013; Ferro et al. 2014; Velazco et al. 2019), albeit these three studies all considered a limited number of climate change projections. It is worth noting that the first two of the three studies mentioned above considered that species ranges could expand from the original boundaries (usually referred to dispersal scenario) and found that even if an unlimited dispersal is considered, for many amphibian species the range contraction will exceed the range expansion (Lemes, Melo, and Loyola 2013), and for tiger moth species only few PAs on the southern part of the biome are projected to gain new species (Ferro et al. 2014).

Moreover, in contrast to these three previous studies that have used data on species from one taxon only (Velazco et al. (2019) investigated plants), the results of future cross-taxon refugia presented in this thesis summarise projections of ranges' contractions due to future climate change for thousands of species from a broad range of taxa, and hence are more robust.

Lapola et al. (2020) assessed the vulnerability of Brazilian PAs to future climate change by combining results from DGVM exercise (as a proxy of probability of habitat change within the PAs), projections of future changes in climate, past land-use changes and overall connectivity. Instead of summarizing their results in terms of specific levels of future global warming (as in this thesis), many possible climate scenarios are combined based on full range of GCMs and RCPs. This makes a direct comparison of the findings infeasible, however, Lapola et al. (2020) find that coastal PAs are less vulnerable to future climate change, indicating partially agreement with the findings of this thesis. Both agree that the PAs in the central and southern parts of the Atlantic Forest have potential to act as refugia. Lapola et al. (2020) recommended that future research should consider the possible impacts of future climate change on flora and fauna within PAs. Therefore, this thesis fills this gap left by this previous vulnerability assessment of the Brazilian PAs to future climate change that considered only habitat change as an impact of climate change on biota (Lapola et al. 2020). Nevertheless, all studies suggest that large-scale spatial planning that promotes connectivity between PAs (and for this study between refugia) through the creation of new PAs or OECMs with suitable land use would enhance the resilience of ecosystems within more vulnerable PAs. Future work aimed at investigating further the role of Brazilian PAs in a changing climate should include projections on terrestrial species' range shifts caused by future climate change in the analysis of the potential of PAs to act as future refugia.

b. Contributions to Brazilian conservation planning

The Brazilian National Adaption Plan (PNA in Portuguese) (Brasil 2016) was created by federal government in 2016 in partnership with academia, civil society, private sector and states government. Its overarching objective is to "promote reduction and management of climate-risk considering the effects of climate change, by taking full advantage of emerging opportunities, avoiding losses and damages, and building instruments to prepare natural, human, productive and infrastructure systems to adapt to climate change" (Brasil 2016). It also has three specific objectives assigned as responsibilities of the federal government. The specific objective 3 "Identify and propose measures to promote adaptation to and reduction of climate risk" has three goals related to Biodiversity and Ecosystems (goals 3.3, 3.4, and 3.5).

- Goal 3.3: Preparation of Ecosystem- based Adaptation strategy measures in areas at risk of extreme events and other climate change impacts.
- Goal 3.4: Modelling of the impact of climate change on biodiversity for use in public policies for conservation, recovery and sustainable use of biodiversity
- Goal 3.5: Deployment of monitoring in 50 federal Conservation Units, for evaluation and monitoring of the impacts of climate change on current and future biodiversity.

During the planning stage of this research (end of 2015), a partnership with the Brazilian Environmental Ministry through the Secretariat for Climate Change and Environmental Quality (SMCQ) was formed with the aim of contributing to the achievement of at least two of the three goals related to biodiversity and ecosystems. This partnership and the project proposal co-created by Brazilian Ministry, the PhD supervisory team and the PhD researcher are mentioned in the Annex (Brasil 2017b) of the 1st Monitoring and Evaluation Report (Brasil 2017a) (please note that although the report is available in English, its annex is only available in Portuguese, hence the two previously mentioned references). Unfortunately, the partnership became latent from early 2019 on and the collaboration project did not progress from the proposal stage.

Table 12 summarizes the planned (as included in the project proposal) and potential contributions of this research to the PNA, and these are explained below:

a) Analysis of projections of future change in climatic variables under several scenarios and based on multiple Global Circulation Models (GCMs) at higher resolution than the ones available through the IPCC to create maps showing areas projected to undergo higher levels of change – results of Chapter 3 feeding into goal 3.4 – planned on project proposal.
b) Analysis of projections of impacts of future climate change on terrestrial biota under several scenarios and based on multiple Global Circulation Models

(GCMs) to create maps of locations projected to be most resilient to future changes in climate, i.e., future climate change refugia – results of Chapters 4 and 5 feeding into goal 3.4 – planned on project proposal;

c) Sharing spatially explicit results related to future climate change projections and future climate change refugia to be included within the Brazilian Environmental Ministry geoservice (geo database) – results of Chapters 3, 4 and 5 feeding into goal 3.4 – planned on project proposal.

d) Analysis of future climate change refugia within Brazilian PAs to identify PAs that are most or least likely to be resilient to future changes in climate that could be validated through the ongoing field surveys. The National Biodiversity Monitoring Program (Programa Monitora, Brasil) is a long-term monitoring program of some Brazilian PAs that includes field surveys to collect information related to terrestrial birds, mammals and plant species within PAs boundaries. The findings of Chapter 5 of this thesis on the current PAs' potential to act as future climate change refugia could be paired with these filed surveys to:

    i. validate and monitor PAs identified as with high refugia potential (similarly to Morelli et al. (2017)) (feeding into goal 3.5 – potential interaction not planned on project proposal);

    i) validate PAs with the lowest potential to act as refugia and test adaptation measures that have the potential to increase ecosystem resilience, such as improving habitats condition and promoting connectivity with other PAs (also feeding into goal 3.5 – potential interaction not planned on project proposal).

Table 12: Brazilian National Adaptation Plan objective, goals, initiatives and indicators related to “Biodiversity and Ecosystems” (from Brasil 2016) and how this research could contribute to them.

Objective	Goal	Initiatives	Indicators	Contribution from this research
Objective 3. Identify and propose measures to promote adaptation to and reduction of climate risk	Goal 3.4 Modelling of the impact of climate change on biodiversity for use in public policies for conservation, recovery and sustainable use of biodiversity.	Identify the impact of climate change on biodiversity;	Number of scenarios and maps available in an appropriate format as inputs for public policies on biodiversity;	This thesis has created maps showing projections of future climate change and future climate change refugia based on 21 GCMs. All maps consider the same biome division, land use classification and PAs network as used by the Brazilian federal government.
		Promote incorporation of climate risk into current policies for conservation, restoration and sustainable use of biodiversity.	Number of public policies for biodiversity management that incorporate climate modelling;	Spatially explicit results from this thesis were going to be provided to the Ministry’s geoservice.
			Number of staff of governmental and non-governmental agencies trained.	Training on how to interpret and to use the results of this thesis was planned for key actors

	Goal 3.5 Deployment of monitoring in 50 federal Conservation Units, for in situ evaluation and monitoring of the impacts of climate change on current and future biodiversity.	Develop and implement an in situ programme for monitoring biodiversity in terrestrial ecosystems in 40 Conservation Units (CUs), covering different biomes, and in 10 CUs located in coastal marine ecosystems, with emphasis on critical ecosystems such as coral reefs and mangroves.	Number of Conservation Units with monitoring implemented and maintained per year	N/A
			Number of biodiversity diagnoses in monitored CUs;	N/A
			Number of reports and trend analyses on relationships between biodiversity and climate, including reports on specific formations/ taxons;	Identification of PAs that could be used to validate future climate change refugia analysis and to test adaptation measures that have the potential to increase climate resilience.
			Early-warning system deployed and number of warning reports issued since its deployment;	N/A

c. Limitations

It should be noted that as all analyses that build on results from SDMs, this research has some limitations that should be taken into account when incorporating the future climatic cross-taxon refugia results into conservation planning (also discussed at the end of chapter 4). First, the locations identified as potential future climatic cross-taxon refugia derive from the projections of refugia created by the Wallace Initiative (WI – explained in detail in chapter 2 section 3). The WI uses species' observed occurrence data from the Global Biodiversity Information Facility (GBIF – an online repository) and carries on the spatial bias on data collection observed (e.g., more occurrence data near roads and cities) for these data (Oliveira et al. 2016) .Therefore, the refugia identified by the WI represents the locations projected to remain climatically suitable for at least 75% of their current species regardless of the number of species currently there. It important to highlight by neglecting the species richness of a grid cell to identify it as potential single-taxon or cross-taxon refugia, the WI and this research avoid reinforcing the spatial bias on data collection.

Second, the WI refugia projections derive from SDMs that analysed the relation of the known occurrences of species and the observed values for the set of eight bioclimatic variables to project potential geographic distribution of each species under future conditions of climate change. This approach excludes the interactions between species, and between species and other abiotic elements (e.g., land-use, soil, etc) that often shape the species' range (Wisz et al. 2013) and their vulnerability to future changes in climate (Vogt et al. 2016). By analysing locations identified as potential future refugia simultaneously for several taxa and the current land-use of these locations, this research attempts to address these limitations and guarantee the maintenance of most current inter-specific interactions. However, further analysis is needed to evaluate the extent to which losing up to 25% of the current species could affect those interactions.

Third, the refugia projections are derived from SDMs forced by future projection of changes for bioclimatic variables. Although these variables better represent biota's climatic needs and constraints (Ramírez-Villegas and Bueno-Cabrera 2009), they fail to incorporate the negative impacts of future extreme climatic events, fire, and their interaction on biodiversity (Brando et al. 2014). Climate variability, such as droughts and warmer temperatures, can increase the frequency of natural fire events or the intensity of non-natural fire events (Jia et al. 2019). Fire on its own can accelerate shifts that would take decades to occur naturally (Davis et al. 2019). Moreover, future climate projections from the new phase of the Coupled Modelling Intercomparison Project (CMIP6) show a higher number of models agreeing on the direction of change for precipitation on the Amazon, especially regarding the drying trend of the eastern portion of the biome (Parsons 2020). Therefore, future studies are needed to investigate the risks that projections of extreme events, such as droughts, and fire could pose to the locations identified in this thesis as future climatic cross-taxon refugia.

Fourth, although this research acknowledges that climate change is one of the current five major threats and the one projected to be the leading driver of loss in the future, it neglects the impacts of other current or emerging drivers. Land-use change (LUC) is currently the leading driver of biodiversity loss globally (IPBES 2019) and, unless ecosystems degradation is controlled and deforestation is halted, LUC will continue to play a major role in the decline of nature. Recent research has shown a “doubling of gross tropical forest carbon loss worldwide from 0.97 ± 0.16 PgC yr−1 in 2001–2005 to 1.99 ± 0.13 PgC yr−1 in 2015–2019” (Feng et al. 2022). In Brazil, where deforestation rates are again rising (Qin et al. 2021; Feng et al. 2022), most of the deforestation that took place in early twenty-first century was caused by expansion of some type of agricultural land (Feng et al. 2022). In addition, projections suggest that the changes in climate suitability will displace some important crops to the southern part of the country (Zilli et al. 2020), a region that is already the most populated and hence where vegetation is more fragmented. More importantly, the most resilient future climatic cross-taxon refugia identified by this thesis are within the southern part of Brazil (Figure 47). Therefore, this potential overlap of future refugia and suitable areas for agriculture could increase the already fierce competition for land and consequently the opportunity cost of area-based biodiversity measures (PAs, OECMs and restoration). The protection or sustainable management of the locations identified in this thesis as future climate change refugia are be key to their resilience and persistence throughout a changing climate.

Moreover, it is worth noting that while deforestation and ecosystem degradation are undoubtedly lower inside PAs than elsewhere, they are not completely absent within the PA network (Françoso et al. 2015; Lapola et al. 2020; Walker et al. 2020). At the same time, PAs in Brazil are in constant threat to be downsized, downgraded, degazetted, and / or reclassified (Bernard, Penna, and Araujo 2014; Brazil 2020b). Considering this, the results regarding the PAs' potential to act as future climate change refugia presented in this thesis are conservative as they assume that the current PA network remains with the same areal extent and with native vegetation.

d. Future research priorities

Lastly, this research aims to demonstrate how locations with potential to act as future climatic cross-taxon refugia could be used in long-term conservation planning in Brazil. The results presented here represent a starting point that could be used in "integrated biodiversity-inclusive spatial planning" (as currently in discussion by Parties of the CBD for Target 1 of post-2020 global biodiversity framework) aiming to identify opportunities for conservation, restoration and sustainable management that will provide benefits for nature, climate and people.

In that sense, future climatic cross-taxon refugia should be combined with other spatial data related to biodiversity conservation, such as the ones derived from the Forest Code after validation, topography, other biodiversity indicators (e.g., Threatenend, endemic or small-ranged species, Local Biodiversity Intactness Index – LBII, Key Biodiversity Areas – KBA), spatial data related to carbon stocks and storage, including mangrove areas, , spatial data related to agriculture such as current and future climate suitablity for crops, spatial data related to projected climate, including climate extremes and fires, and spatial data related to economic growth (available for some cities and states through the ecological and economic zonning – ZEE) to identify the locations in Brazil and in each Brazilian biome where the synergies for biodiversity conservation, sustainable development, and tackling climate change are the greatest.

Several countries / regions have already perfomed such integrated spatial analysis exercise using one of the many tools available. Marxan has been used in marine areas of Australia and California (Marxan 2022). Costa Rica, Uganda, Haiti, Kazakhstan, Cambodia, Dominican Republic, Peru, and Colombia have developed a tailored spatial analysis in partnership with the United Nations Development Programe to "identify country's essential life support areas (ELSAs)" (UNDP 2022). All these projects have mapped the locations for conserving, restoring and sustainably managing nature while providing benefits for climate and people.

However, few, if not none, have included projections of impacts of future climate change on biota or future climate change refugia (areas projected as most resilient to future changes in climate). With the results from this thesis, Brazil has an opportunity to do a climate-smart integrated biodiversity-inclusive spatial analysis that includes resilient locations for climate change mitigation (through climate resilient areas for carbon storage – conservation or carbon sequestration – restoration). And it could go even further and include climate resilient areas for adaptation if future climate change refugia that considers species dispersal are identified.

In addition to the future reseach topics previously suggested, a good follow up to this study would be to get as many stakeholders involved in the planning and implementation process, included different sectors of the national, state, and local governments, organized civil society, private sector and indigenous and local communities.

3. Conclusions

This final section connects this thesis' key findings (in bold) with its specific objectives (bullet points) and highlights the importance and urgency of halting global warming.

The size and resilience of future climatic cross-taxon refugia in Brazil identified by this research vary according to the biome under analysis and the number of taxa included in the refugia.

- Research aim addressed: To analyse the proportion of Brazil and its biomes that is projected to remain climatically suitable for most of the terrestrial biodiversity they presently contain, by acting as future climatic cross-taxon refugia (chapter 4).

Locations in Brazil identified by this research as potential future climatic cross-taxon refugia for terrestrial biota are derived from SDMs projections of species future potential geographical range. These future climatic cross-taxon refugia do not always match locations projected to undergo less change in bioclimatic variables, as SDMs combine the projected changes in bioclimatic variables and species climatic tolerance to project areas that will remain climatically suitable despite future changes in climate.

Moreover, the size and resilience of future climatic cross-taxon refugia identified by this research vary according to the biome under analysis and the number of taxa included in the refugia. The Amazon is the biome that has the lowest relative extent projected to act as future climatic cross-taxon refugia for two or more taxa regardless of the warming level, while Pampa has almost 100% of its land surface identified as cross-taxon refugia for two or more taxa for all scenarios up to 4.5ºC warmer than pre-industrial levels. Finally, in a 4.5ºC warmer world, the Atlantic Forest is the only biome projected to host refugia for all five taxa.

Only if future warming is kept below 1.5ºC above pre-industrial levels, will there be PAs in all biomes with the potential to act as refugia for all five taxa.

- Research aim addressed: To identify, for each biome within Brazil, the extent to which the PA network is projected to have the potential to act as future climatic cross-taxon refugia for terrestrial biota under different levels of future global warming (chapter 5).

Future climatic cross-taxon refugia in Brazil are currently under different land uses, jurisdictions, and levels of protection. Regarding refugia within the current Brazilian PA network, only if future warming is kept below 1.5ºC above pre-industrial levels, will there be PAs in all biomes with the potential to act as refugia for all five taxa. If the mean global temperature reaches 2.7ºC above the baseline, just 1% of the current Brazilian PA network will remain with this potential, and mostly in the south of the Atlantic Forest and east Pampa.

This thesis explores the extent to which future climate change will impact the Brazilian PAs climatic suitability to the terrestrial biota they currently host and is included on the Wallace Initiative database. Therefore, this thesis' findings fill a gap left by previous vulnerability assessment that considered only habitat change as an impact of climate change on biota within PAs (Lapola et al. 2020). Nevertheless, both studies suggest that large-scale spatial planning that promotes connectivity between PAs (and for this study between refugia) through the creation of new PAs or OECMs with suitable land use would enhance the resilience of ecosystems within more vulnerable PAs. Future work aimed at investigating further the role of Brazilian PAs in a changing climate should include projections on terrestrial species' range shifts caused by future climate change.

Future climatic cross-taxon refugia in Brazil and in all Brazilian biomes fall mainly outside the current PA network, and most still hold native vegetation. This finding underscores the urgency of safeguarding these refugia from deforestation and degradation through the expansion of the current PA network.

Except in the Atlantic Forest, where future climatic cross-taxon refugia lie in areas that have already been partially converted, and hence would benefit from restoration actions to promote biodiversity conservation.

- Research aim addressed: To identify future climatic cross-taxon refugia in Brazil outside of the current Brazilian PA network where conservation efforts could be focused to (a) avoid deforestation or degradation (e.g., through new PAs or OECMs) or (b) restore degraded or converted ecosystems (chapter 5).
- Research aim addressed: To demonstrate how the location of future climatic refugia for terrestrial biota can be used to design area-based conservation planning in Brazil that takes into consideration future effects of climate change (overarching aim).

Concluding, this research demonstrates that future climatic cross-taxon refugia for terrestrial biota can be used as a starting-point while designing area-based conservation planning in Brazil that takes into consideration future effects of climate change. Moreover, due to the uneven geographical distribution of potential cross-taxon refugia in Brazil, the findings presented here emphasize the value of sub-national level biodiversity conservation targets and planning, and show that different parts of the country will require different measures to face the challenges posed by future climate change.

Although delivering the Paris Agreement's goals is crucial, it might not be enough for some taxa and places.

Still, tackling the ongoing climate crisis by delivering the Paris Agreement goals of keeping global warming to well below 2ºC and closer to 1.5ºC above pre-industrial times is crucial to alleviate future climate change impacts on biota of all biomes. Keeping global warming to no more than 1.5ºC above pre-industrial levels will enhance the prospects of having future climatic cross-taxon refugia for all five taxa in and outside PAs of all Brazilian biomes. Moreover, if global efforts fail to keep global warming to under 2.0ºC above pre-industrial levels, refugia are likely to become non-existent in the Amazon for amphibians, birds, and plants; in Caatinga for plants; in Cerrado for birds and plants; and in Pantanal for birds and plants. However, the extent to which even a 1.5ºC warmer world could impact species in some biomes still needs further investigation, as this thesis' approach is conservative and considers that species are not able to follow their suitable climate or adapt. This research shows that at this level of warming, less than half of the Amazon's land area is projected as future climatic cross-taxon refugia for two or more taxa and that only 6% is identified as refugia for all five taxa. These projections reinforce a disturbing warning regarding the future of the largest tropical rainforest (chapter 4 section 5.a and references therein) that should not be taken lightly, and research that assesses these impacts whilst considering species interactions and range shifts would be a good follow-up to this study.

Finally, considering refugia as 'safe havens' where 'biodiversity retreat to, persist in and can potentially expand from under changing environmental conditions' (Keppel et al. 2012) further research is needed to understand the role these locations could play if there is a temporary (maybe for few decades) overshooting in temperature.

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Appendix

1. Related to chapter 4

a. WI modelled current species richness for Brazil

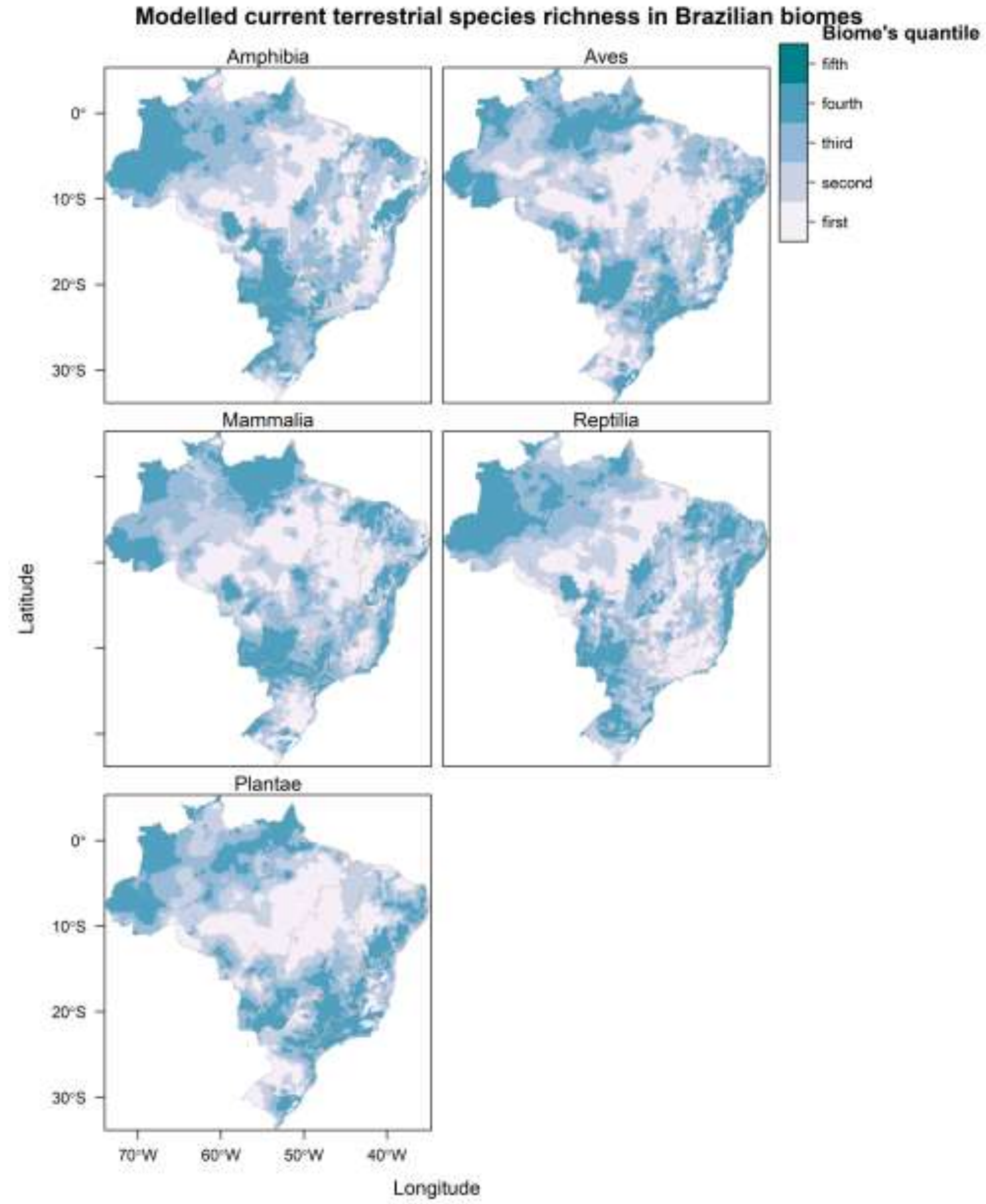

Figure 82: WI modelled current species richness for each taxon divided in quantiles based on biome's species richness for each taxon.

b. Complete WI 'future climatic refugia' dataset for Brazil

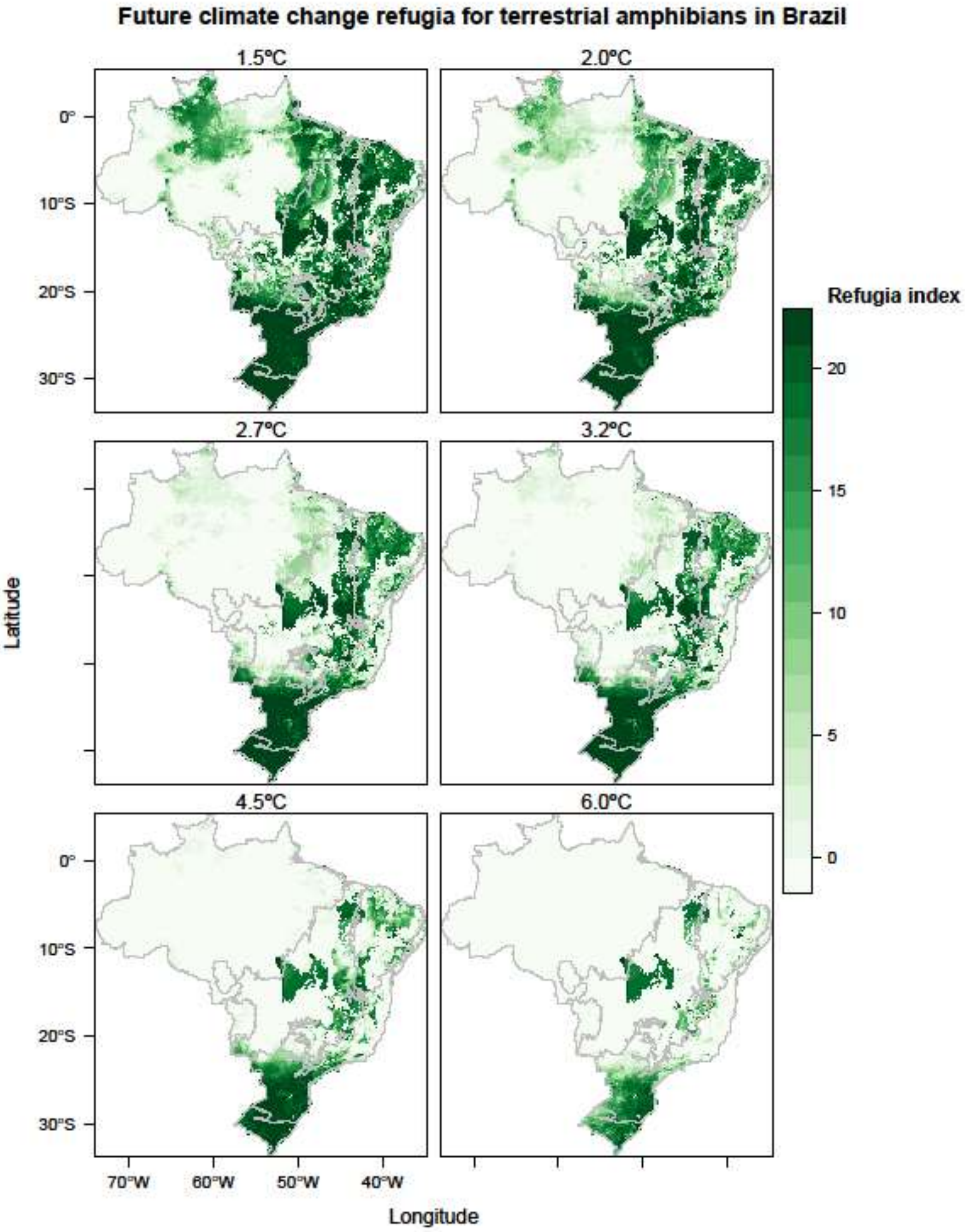

Figure 83: Locations projected to remain climatically suitable for at least 75% of the amphibian species included in the WI database and modelled to currently be there under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Refugia index represents the number of GCMs agreeing on the projection explained above.

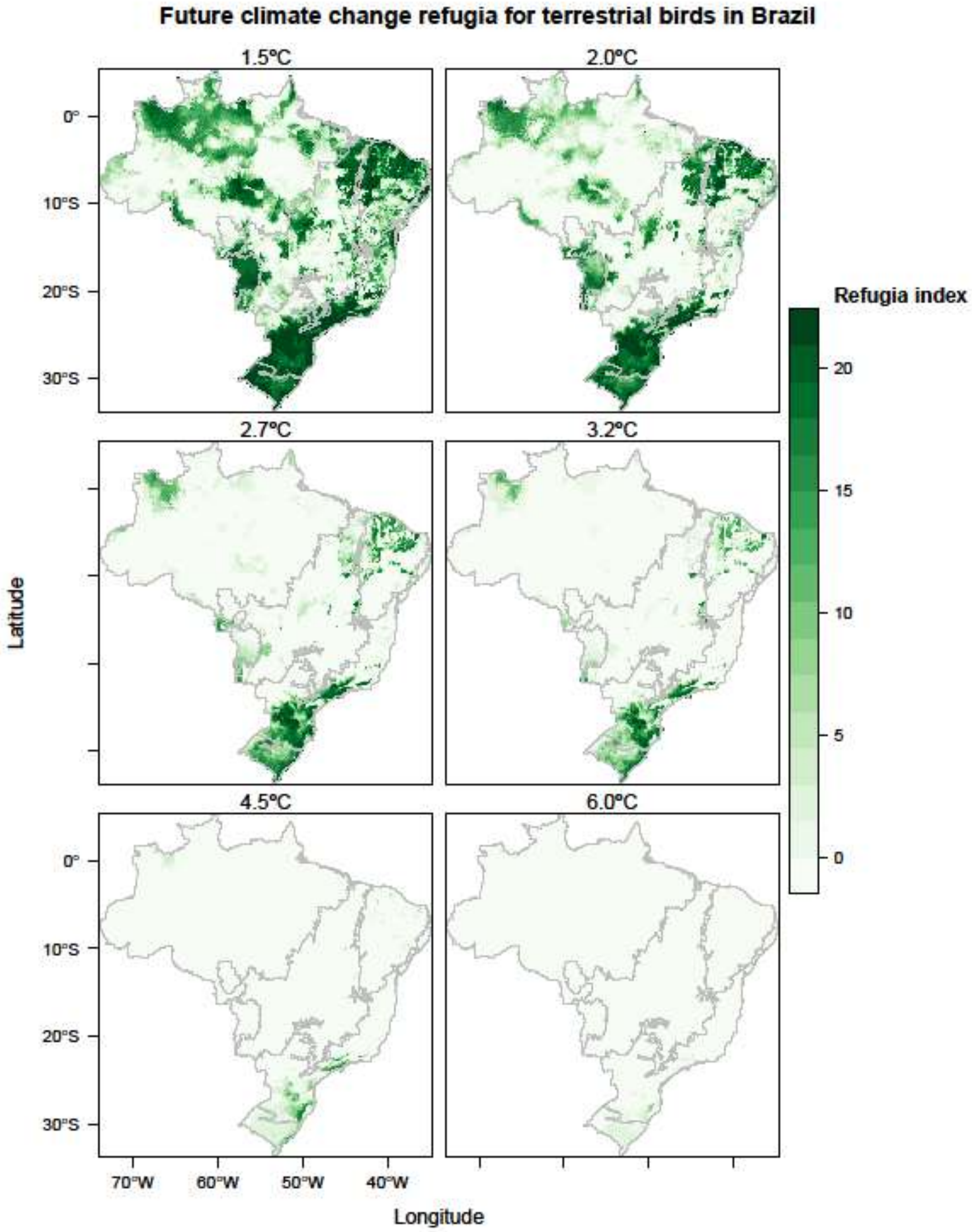

Figure 84: Locations projected to remain climatically suitable for at least 75% of the bird species included in the WI database and modelled to currently be there under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Refugia index represents the number of GCMs agreeing on the projection explained above.

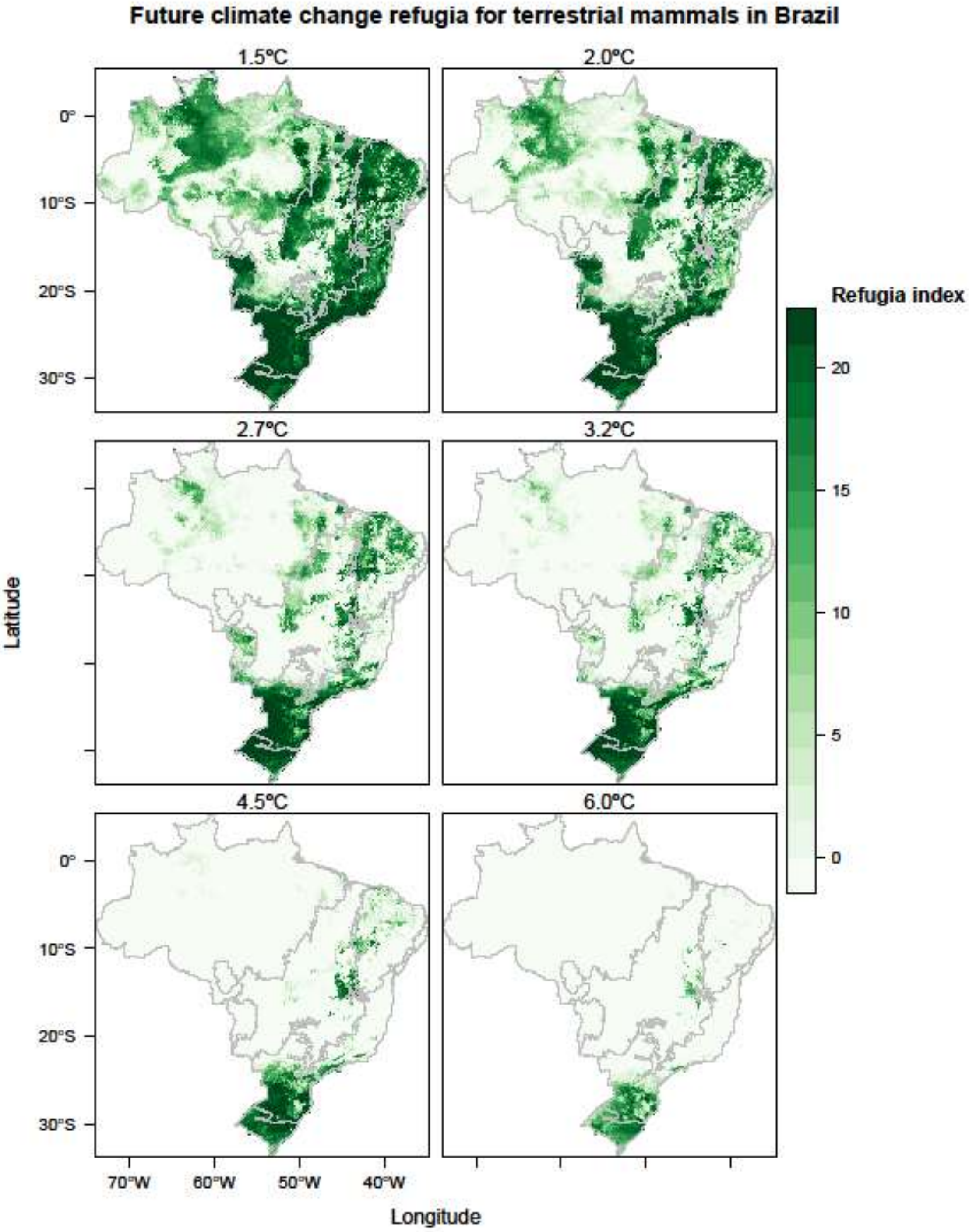

Figure 85: Locations projected to remain climatically suitable for at least 75% of the mammal species included in the WI database and modelled to currently be there under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Refugia index represents the number of GCMs agreeing on the projection explained above.

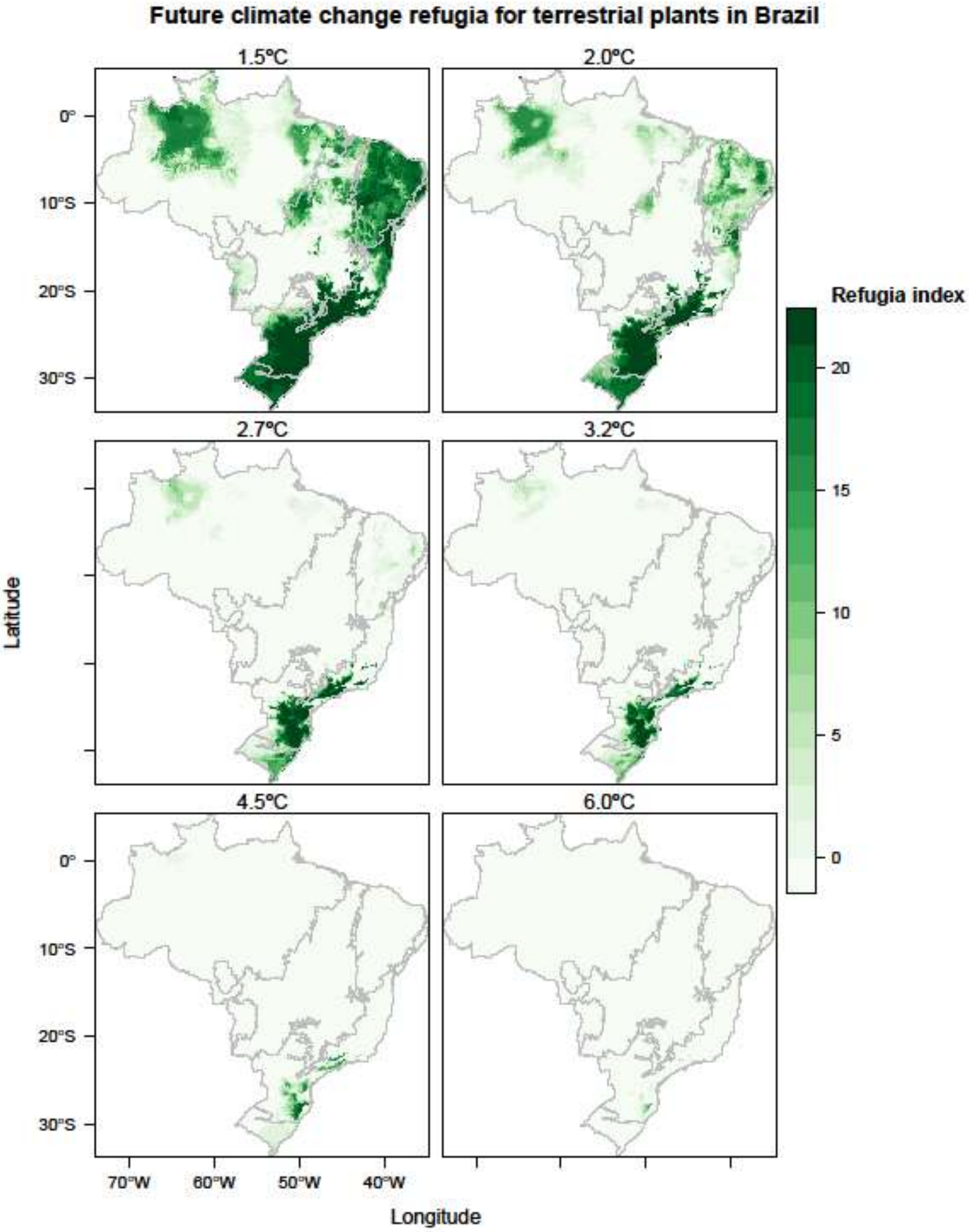

Figure 86: Locations projected to remain climatically suitable for at least 75% of the plant species included in the WI database and modelled to currently be there under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Refugia index represents the number of GCMs agreeing on the projection explained above.

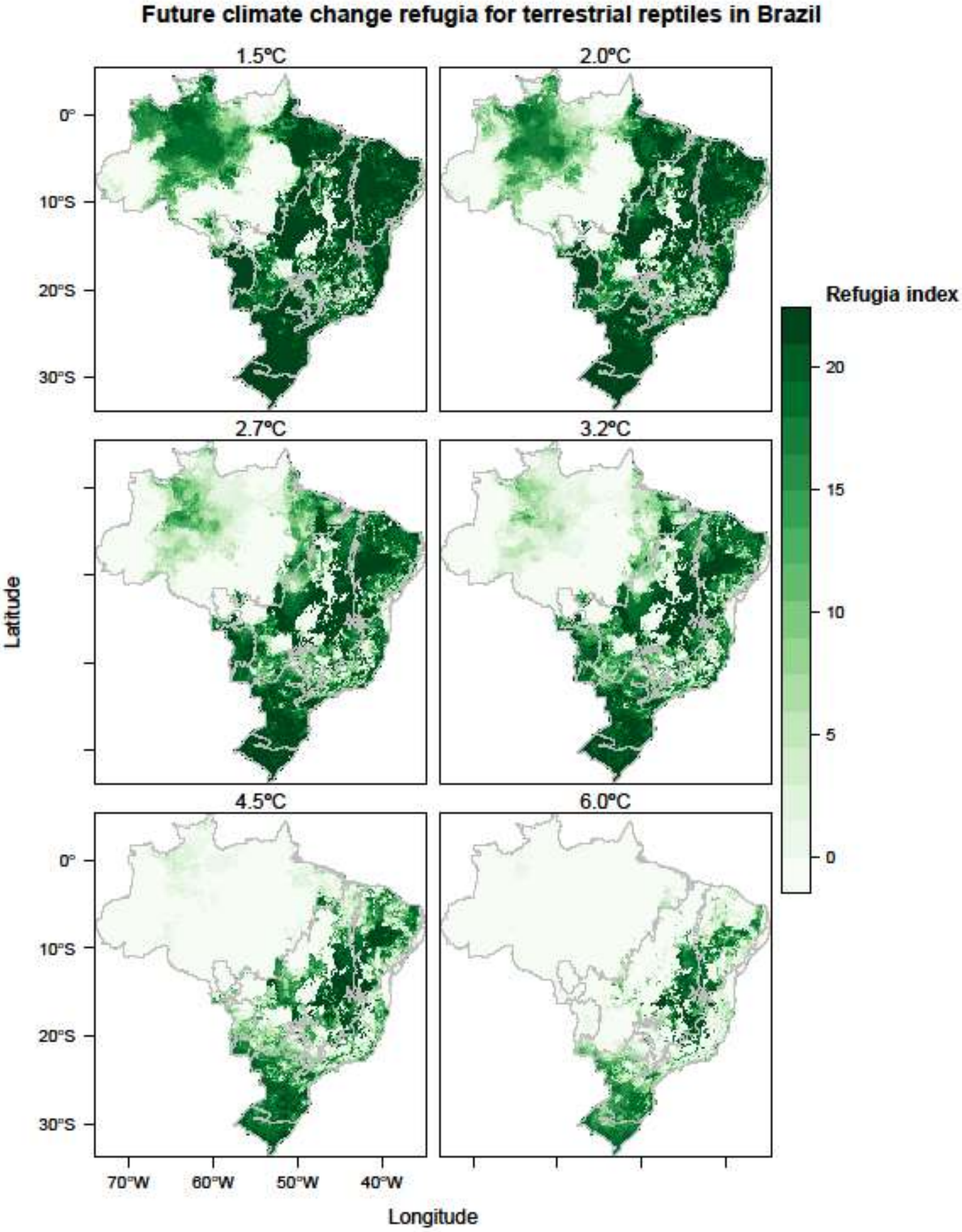

Figure 87: Locations projected to remain climatically suitable for at least 75% of the reptilie species included in the WI database and modelled to currently be there under six levels of future global warming (1.5, 2.0, 2.7, 3.2, 4.5, and 6.0ºC above pre-industrial levels). Refugia index represents the number of GCMs agreeing on the projection explained above.

2. Related to chapter 5

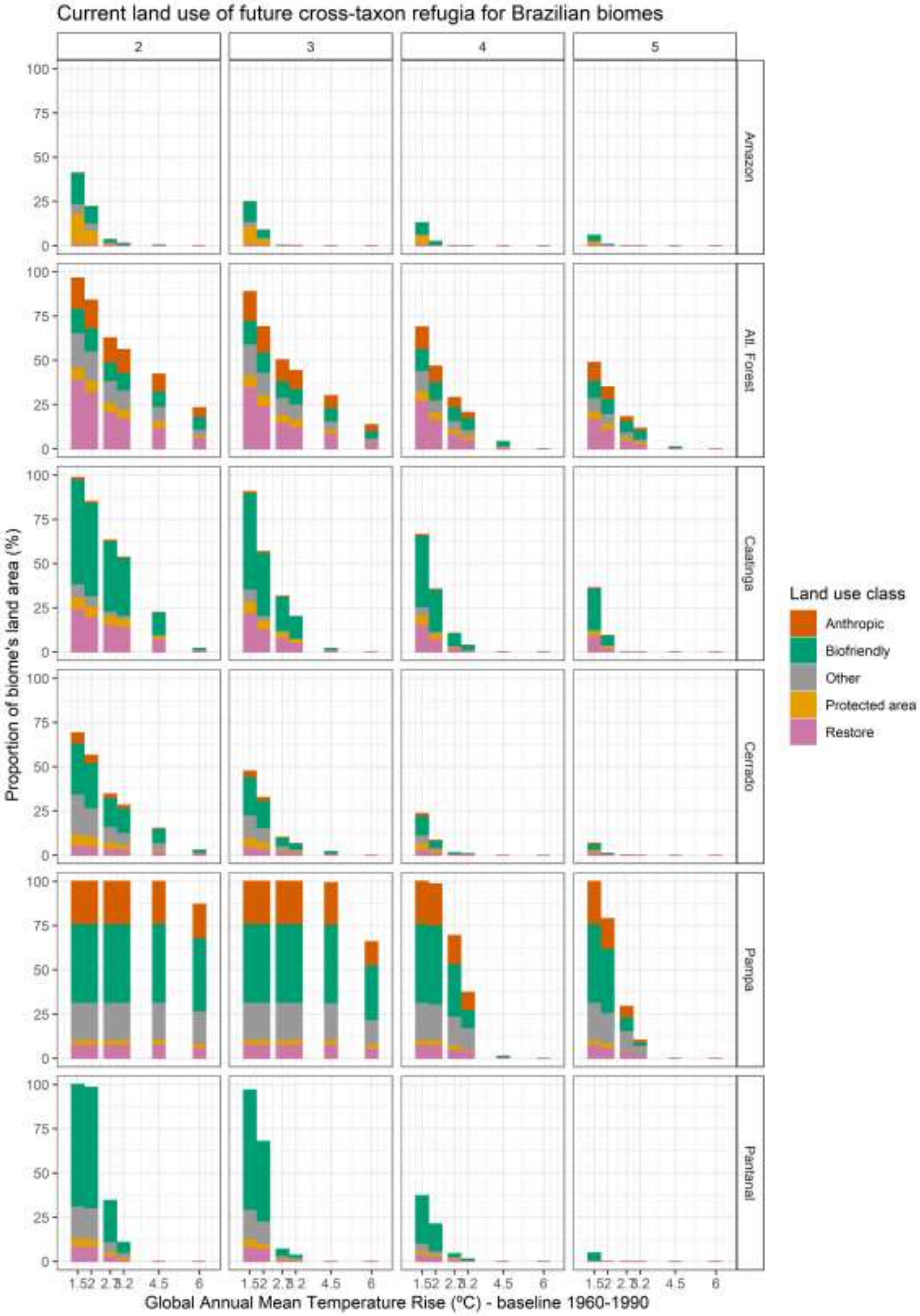

Figure 88: Figure combinig results presented in chapter 5 sections 5.e to 5.j.

a. PAs network potential to act as future climatic refugia for each taxon

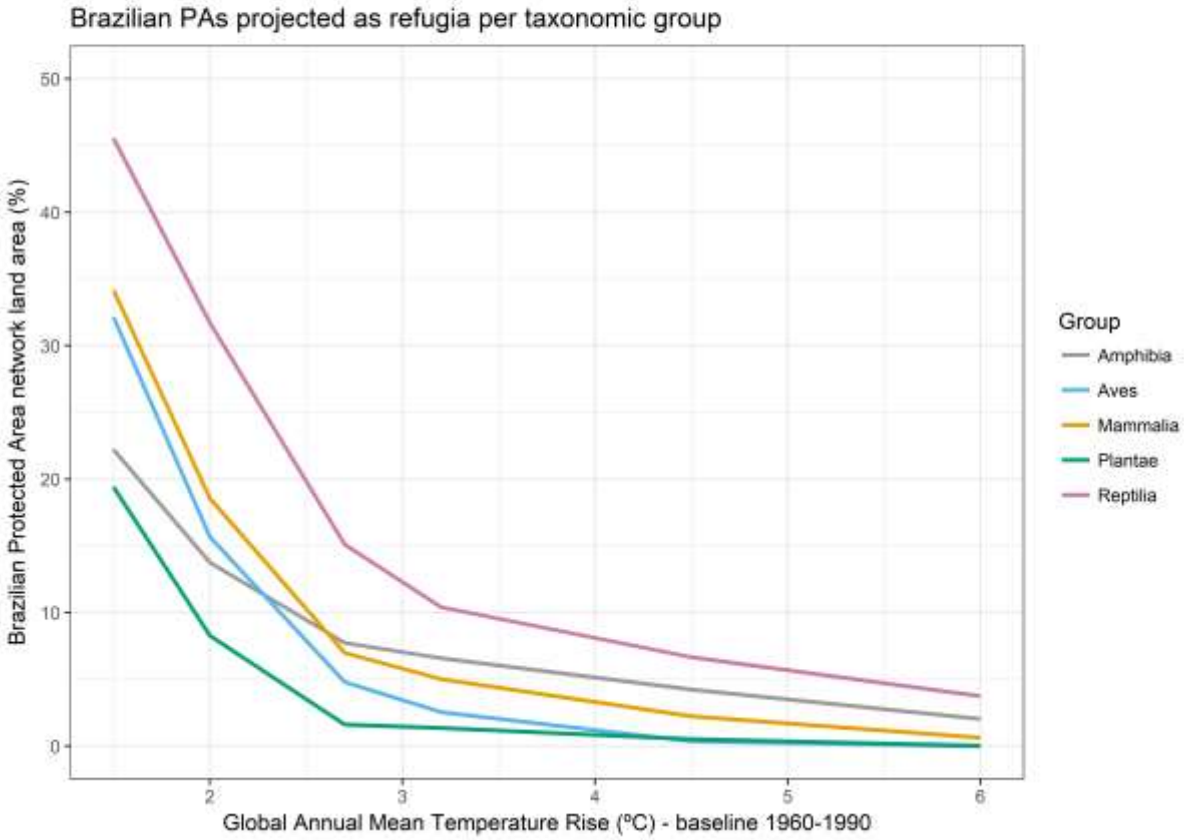

Figure 89: Proportion of the Brazilian PAs land area projected as future climate change refugia for each taxon individually under increased levels of global warming.

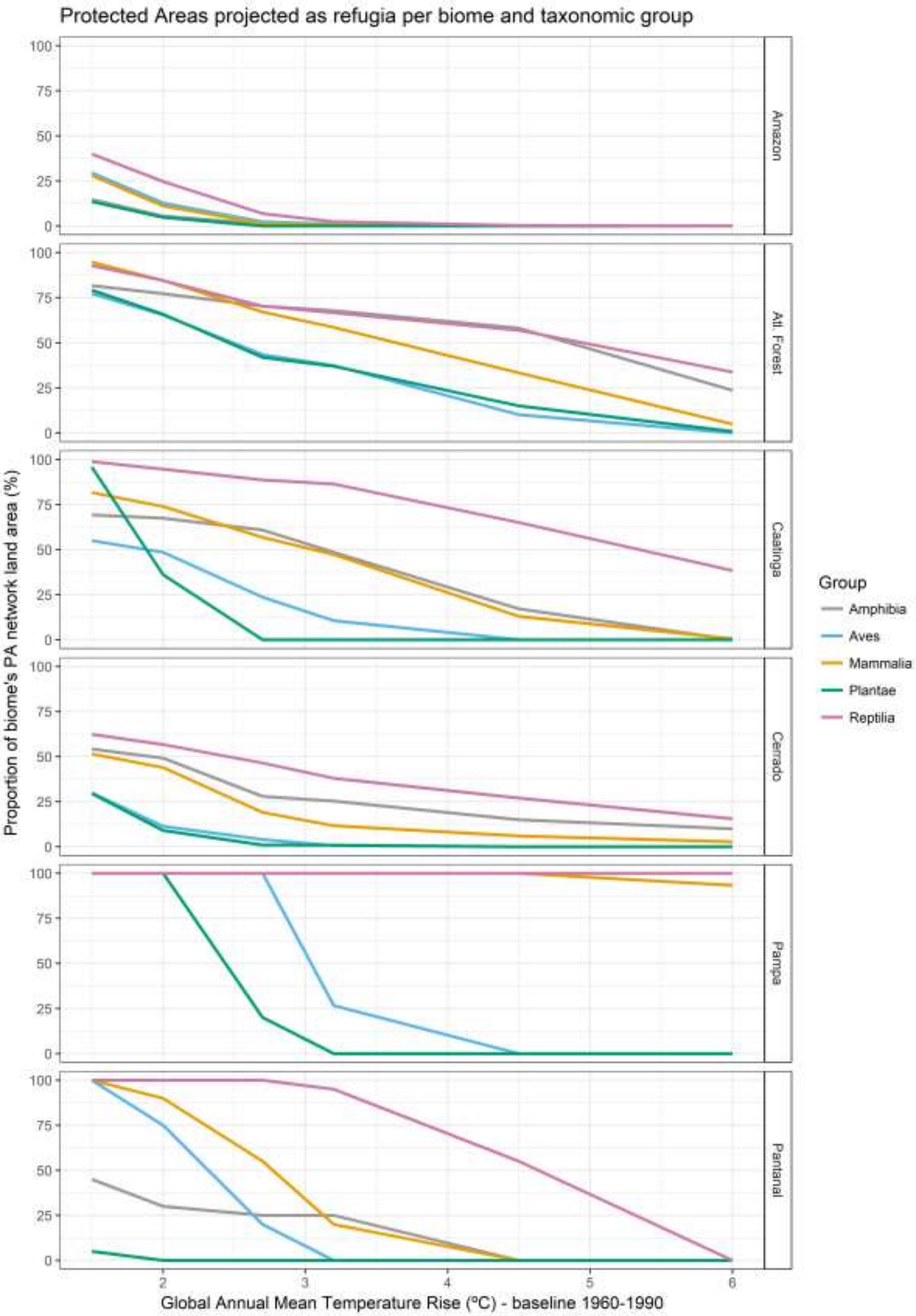

Figure 90: Proportion of each biome's PA network land area projected as future climate change refugia for each taxon individually under increased levels of global warming

b. Future climatic cross-taxon refugia and PAs boundaries

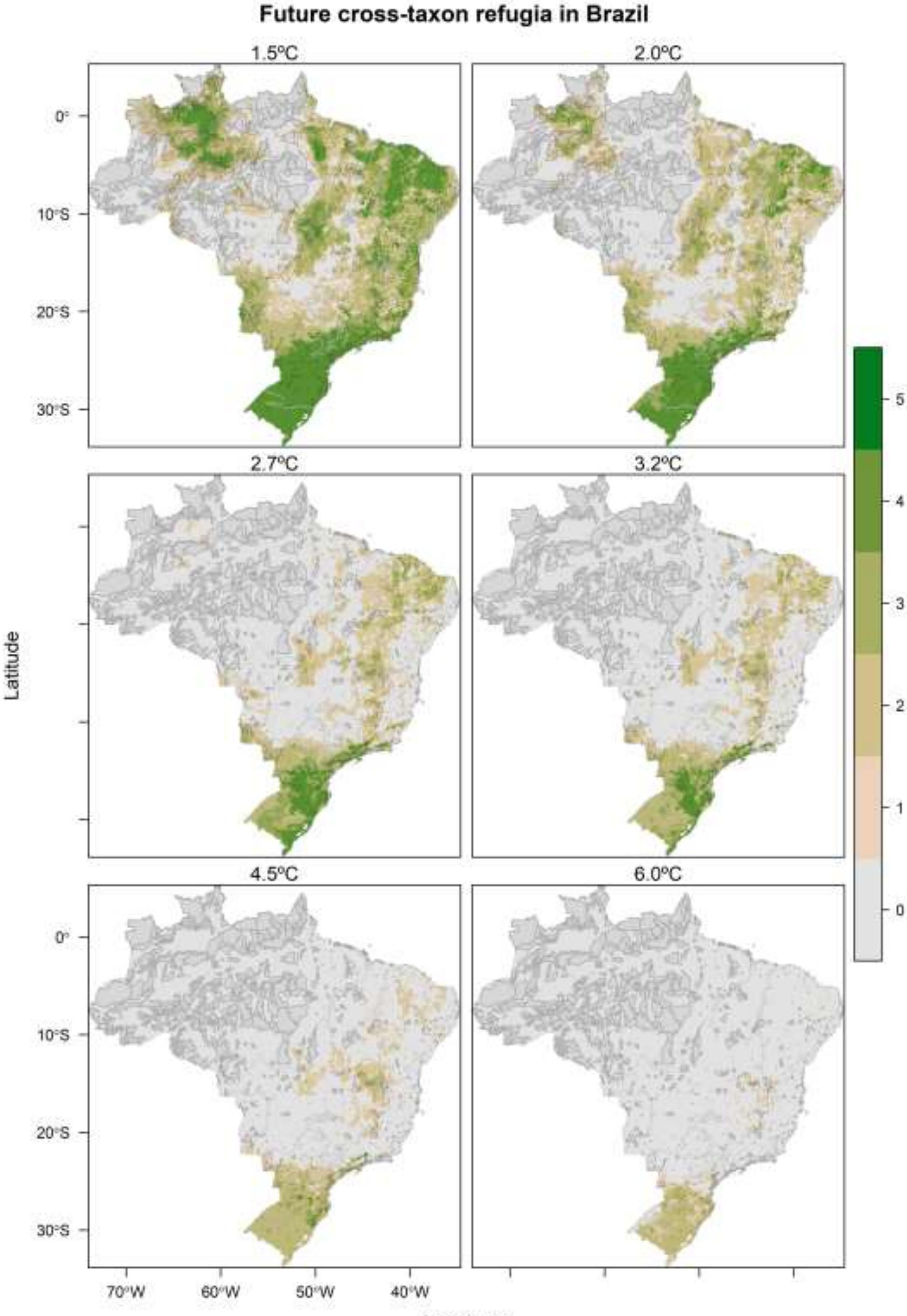

Figure 91: Future climatic cross-taxon refugia in Brazil as presented in chapter 4 Figure 47. Dark grey lines represent the current PAs boudaries, light grey lines represent the biomes boudaries.