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Mudanças climáticas no Cerrado brasileiro: suas origens e impactos para biodiversidade

Doutorando: Gabriel Selbach Hofmann

PORTO ALEGRE, SETEMBRO DE 2024

Mudanças climáticas no Cerrado brasileiro: suas origens e impactos para biodiversidade

Gabriel Selbach Hofmann

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I had a dream, which was not all a dream.
The bright sun was extinguish'd, and the stars
Did wander darkling in the eternal space,
Rayless, and pathless, and the icy earth
Swung blind and blackening in the moonless air;
Morn came and went—and came, and brought no day,
And men forgot their passions in the dread
Of this their desolation and all hearts
Were chill'd into a selfish prayer for light:
[...]
The world was void,
The populous and the powerful was a lump,
Seasonless, herbless, treeless, manless, lifeless—
A lump of death—a chaos of hard clay.
The rivers, lakes and ocean all stood still,
And nothing stirr'd within their silent depths;
Ships sailorless lay rotting on the sea,
And their masts fell down piecemeal: as they dropp'd
They slept on the abyss without a surge—
The waves were dead; the tides were in their grave,
The moon, their mistress, had expir'd before;
The winds were wither'd in the stagnant air,
And the clouds perish'd; Darkness had no need
Of aid from them—She was the Universe.

Lord Byron

Trechos do poema *Darkness*, escrito em 1816, o ano sem verão, durante uma mudança climática abrupta causada pela erupção do monte Tambora, na Indonésia.

DEDICATÓRIAS

Esta tese de doutorado é dedicada aos três mestres mais importantes na minha formação acadêmica e profissional:

Heinrich Hasenack, meu primeiro orientador, provavelmente a pessoa mais generosa que conheci em minha vida.

Eliseu José Weber, o mais sábio e exigente profissional e com quem tive o privilégio de aprender.

Luís Flamarion B. de Oliveira, meu maior incentivador, aquele que me ensinou o poder da análise de dados e a nunca me conformar com as injustiças socioambientais que marcam nosso tempo.

Por fim, na esperança que ela possa conhecer futuramente o esplendor e a riqueza dos sertões do Brasil, também dedico este trabalho à minha amada filha Serena Menguer Hofmann.

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Ao meu coorientador Manoel F. Cardoso pela sua amizade, parceria e incansável dedicação aos nossos manuscritos.

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A todos companheiros das inesquecíveis reuniões científicas na Serra da Bocaina e dos trabalhos de campo em Mambaí, onde muitas das análises usadas nessa tese foram pensadas e discutidas. Neste quesito, um agradecimento especial para Leandro de O. Salles, Peter M. de Toledo e Francisco B. Pontual por catalisarem estes processos.

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RESUMO

As mudanças climáticas representam o maior desafio da humanidade no século XXI, especialmente no que concerne a conciliação entre a demanda crescente por alimentos e energia com a conservação dos ecossistemas. O Cerrado brasileiro, segunda maior ecorregião da América do Sul, é reconhecido como um hotspot global de biodiversidade e também como um grande centro de produção de grãos, de proteína animal e de energia hidroelétrica. Esta tese de doutorado investiga a origem e a extensão das mudanças climáticas que atualmente já afetam esta ecorregião, bem como seus potenciais impactos para biodiversidade. Este documento é composto por cinco capítulos, onde os principais resultados são apresentados em três artigos científicos. O primeiro artigo demonstra de que maneiro o Cerrado está se tornando mais quente e mais seco. A gigantesca conversão de vegetação nativa em lavouras e pastagens desempenham um papel central na redução da evapotranspiração durante a estação seca, levando a um pronunciado aquecimento e redução da umidade relativa. O segundo artigo descreve uma significativa redução da precipitação pluvial e da frequência de dias chuvosos nos setores norte e central do Cerrado para todos os períodos do ano exceto para início da estação seca. Os resultados indicam uma clara tendência de prolongamento e intensificação da estação seca, causando amplos impactos socioambientais que transcendem os limites do Cerrado. Estas descobertas estão associadas com a intensificação do Anticiclone Subtropical do Atlântico Sul, que vem alterando a circulação atmosférica e aumentando a subsidência na região. O terceiro artigo revisa a mudança climática no Cerrado e projeta os possíveis impactos em diferentes grupos taxonômicos da biodiversidade terrestre. Ao longo dos últimos cinco mil anos, a grande previsibilidade da temperatura e do regime pluviométrico moldaram as estratégias de história de vida e a estrutura das comunidades. As mudanças climáticas estão agora remodelando as comunidades ecológicas, levando à homogeneização biótica. O impacto da mudança climática na sociedade e na biodiversidade já são amplos, e sua mitigação irá demandar a substituição do atual modelo de produção agropecuária no Cerrado por práticas mais sustentáveis.

Palavras-chave: hotspots globais de biodiversidade; savanas; mudanças de uso e cobertura do solo; evapotranspitação; aquecimento regional; Anticiclone Subtropical do Atlântico Sul; Sistema de Monção da América do Sul.

ABSTRACT

Climate change represents the greatest challenge for humanity in the 21st century, especially concerning the need to reconcile increased food and energy production with the conservation of ecosystems. The Brazilian Cerrado, the second-largest ecoregion in South America, is recognized as a global biodiversity hotspot and a great center for grain, animal protein, and hydroelectric power production. This doctoral thesis investigates the origin and extent of climate change currently affecting this ecoregion, as well as its potential impacts on biodiversity. This document consists of five chapters, with the key findings presented across three scientific papers. The first paper demonstrated that the Cerrado is becoming significantly hotter and drier. The massive conversion of native vegetation to pasture and cropland plays a key role in driving regional climate change by reducing evapotranspiration during the dry season, leading to pronounced warming and decreased relative humidity. The second article described a significant reduction in rainfall and frequency of rainy days in the northern and central Cerrado regions for all periods except at the beginning of the dry season. Our results indicate a clear trend of dry season lengthening and intensification, resulting in widespread environmental and social impacts that transcend the Cerrado boundaries. These findings are associated with the intensification of the South Atlantic Subtropical Anticyclone, which has been shifting atmospheric circulation and raising regional subsidence. The third article reviews the climate change in the Cerrado and projects possible impacts on different taxonomic groups of terrestrial biodiversity. Over the past 5,000 years, the Cerrado’s predictable temperature and water cycles shaped species' life history strategies and community structure. Climate change is now reshaping ecological communities, leading to biotic homogenization. The impacts of climate change on society and biodiversity are already wide, and its mitigation will require the replacement of the current agricultural production model in the Cerrado by more sustainable practices.

Keywords: global biodiversity hotspots; savanna; land use and land cover changes; evapotranspiration, regional warming; South Atlantic Subtropical Anticyclone; South American Monsoon System.

APRESENTAÇÃO

“*Gabriel, os ratos do cerrado na Bolívia estão desaparecendo por falta de orvalho!”*

Foi através desta mensagem inusitada, enviada por e-mail pelo meu orientador a época (2013), Luiz Flamarion B. de Oliveira, que esta tese iniciou seu longo processo de “gestação”. A mensagem se referia o trabalho publicado pela mastozoóloga Louise H. Emmons, em 2009, na revista Biotrópica. O artigo intitulado “*Long-Term Variation in Small Mammal Abundance in Forest and Savanna of Bolivian Cerrado*” analisa o curioso episódio de uma extinção local de população de roedores durante uma estação seca do Cerrado. Ao final da seção de discussão, Emmons incluiu uma hipótese de que o episódio da mortalidade dos roedores estava associado à densa fumaça de incêndios florestais que cobriu a região por um longo período naquele ano. Segundo a autora, esta fumaça teria elevado a temperatura noturna, impedindo a formação de orvalho, que é uma importante fonte de água para pequenos animais, levando-os a morte por falta de água”. Embora essa conclusão não tivesse qualquer embasamento de dados, a autora desafiava outros cientistas esclarecerem essa questão. Depois de ler este artigo, ainda demorei cerca de três anos para mergulhar de cabeça no tema de mudanças climática no Cerrado, pois naquele momento estava envolvido em projetos que atuavam em outras ecorregiões brasileiras.

Foi somente entre 2015 e 2017 que realizei verdadeiramente meus primeiros trabalhos no Cerrado, na região de Mambaí, que se localiza próxima a tríplice fronteira entre os estados de Goiás, Minas Gerais e Bahia. Lá, pela primeira vez, tomei conhecimento da magnitude da devastação promovida agronegócio nas chapadas do Oeste da Bahia. Me faltam adjetivos para descrever o que se passa naquela região, de forma que nem fotografias e imagens de satélite são capazes de transmitir tamanha desolação. Tenho certeza que nem o mais urbano dos brasileiros deixaria de notar aquela tragédia socioambiental. Foi a partir daí que comecei a coletar as primeiras informações sobre os diferentes temas desta tese. Novos trabalhos de campo foram surgindo, centro/norte de Goiás, Tocantins, além de longas viagens atravessando Minas Gerais e Goiás em quase toda sua extensão. Nestas jornadas, fui conhecendo grandes pesquisadores que me incentivaram sempre a prosseguir em frente. Através de uma iniciativa dos pesquisadores Leandro de O. Salles (Museu Nacional) e Peter M. de Toledo

(INPE), realizamos uma série de reuniões com diversos pesquisadores de diferentes áreas do conhecimento para criação de grupo de pesquisas e formalizações de projetos. Foi em uma destas ocasiões que conheci o coorientador desta tese Manoel F. Cardoso. Juntos, passamos a analisar sistematicamente banco de dados climáticos na área do Cerrado, resultando em um improvisado workshop de dados na Serra da Bocaina, munícipio de Bananal (SP). Os resultados obtidos desse seminário foram o embrião do que chamamos "*Projeto Orvalho*", ainda tendo em mente o artigo de Louise Emmons.

Em 2020, ingressei no Programa de Pós-Graduação da Universidade Federal do Rio Grande do Sul com objetivo de finalmente me dedicar a este projeto. Sob orientação de Francisco E. Aquino (ou simplesmente *Chico*), meu antigo professor de climatologia durante a graduação, conseguimos publicar o nosso primeiro artigo (Capítulo 2 desta tese), em 2021. Neste primeiro manuscrito, exploramos as mudanças de temperatura e umidade do ar no Cerrado brasileiro, sob uma perspectiva de mudança de uso e cobertura do solo, abordando também a questão da provável diminuição do orvalho em uma seção inteiramente dedicadas as implicações ecológicas da mudança climática que havíamos descrito. Este artigo teve grande impacto na sociedade, tendo sido tema de diversas matérias em veículos de imprensa. Nossa ideia era seguir aprofundando nas relações entre o aumento de temperatura e o uso do solo, mas nossos planos foram interrompidos pela pandemia de COVID-19, que encerrou as atividades presenciais na universidade por quase dois anos. Sem a possibilidade de usar a estrutura da universidade para nossa pesquisa, não tivemos outra alternativa senão mergulhamos novamente em bancos de dados. Desta vez, por sugestão nosso companheiro Eliseu J. Weber, nos debruçamos intensivamente sobre os dados de chuva. Em 2023, publicamos nosso segundo artigo (terceiro capítulo desta tese) e, novamente, fomos surpreendidos pela boa repercussão do trabalho.

Por fim, a partir da colaboração de uma série de amigos de longa data, abordamos mais profundamente os impactos das mudanças climáticas na biodiversidade de Cerrado. Esta é uma tarefa extremamente difícil, visto que uma grande parte da altíssima biodiversidade do Cerrado sequer é conhecida. Além disso, ao contrário dos bancos de dados meteorológicos que possuem um farto material para análise no tempo e espaço, no Cerrado não existem programas de monitoramento de dados biológicos de longa duração, tornando quase impossível a tarefa de compreender os efeitos das mudanças climáticas na biodiversidade da região. Com a ajuda inestimável destes colegas, concluímos um terceiro manuscrito (capítulo 4 desta tese), que será encaminhado para publicação após a defesa e correções sugeridas pela banca. Além destes três artigos, esta tese conta ainda com uma seção inicial de introdução geral, onde resumimos os principais temas abordados em nosso trabalho, além de uma breve seção de considerações finais. Encerro esta seção agradecendo mais uma vez a todos que contribuíram direta e indiretamente nesta longa jornada.

Gabriel Selbach Hofmann

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CAPÍTULO 1: INTRODUÇÃO GERAL

Veado-campeiro (*Ozotoceros bezoarticus*) em vegetação de campo limpo, no Parque Nacional da Serra da Canastra, Minas Gerais. Região das nascentes do rio São Francisco. Foto: Igor P. Coelho

O domínio dos cerrados é um espaço territorial marcadamente planáltico em sua área core. Paradoxalmente, é dotado de solos em geral pobres, porém condições topográficas e climáticas bastante favoráveis.

Aziz Ab'Sáber

Trecho extraído do livro Os Domínios da Natureza no Brasil

1.1. BREVE INTRODUÇÃO ÀS MUDANÇAS CLIMÁTICAS

Desde a descoberta dos Ciclos Glaciais passados, ainda na primeira metade do século XIX, a humanidade tomou consciência de que o clima na Terra está longe de ser constante e de que os padrões climáticos ao longo do tempo geológico foram muito diferentes dos atuais. O avanço da climatologia, em especial do aprimoramento dos modelos climáticos e dos métodos de observação indireta do clima (proxies climáticos), tem permitido quantificar a extensão das mudanças climáticas ao longo do tempo e identificar os principais fatores que provocam alterações no sistema climático regional/global (HANSEN *et al.*, 2005). Os fatores que impulsionam as mudanças climáticas são conhecidos como forçantes e têm em comum o fato de alterarem positiva ou negativamente o balanço de radiação e de energia da Terra. Enquanto algumas forçantes climáticas atuam em escalas temporais que variam de milhões (ex. Tectônicas de Placas) ou milhares de anos (ex. Periodicidades Astronômicas, conhecidas como forçantes de Milankovich), outras podem alterar o clima do Planeta em períodos de tempo mais curtos, como décadas (ex. ciclo de Manchas Solares), ou até mesmo anos (ex. grandes erupções vulcânicas, como registrado por Lord Byron no poema *Darkness*, que abre essa tese de doutorado) (BARRY; CHORLEY, 2013).

Ao longo das últimas décadas, as emissões antropogênicas de gases estufa, especialmente de dióxido de carbono (CO_2), metano (CH_4), óxido nitroso (N_2O) e ozônio (O_3), vêm sendo identificadas como a principal forçante para as mudanças climáticas recentes (período Pós-Revolução Industrial) (FARMER; COOK, 2013). Embora o vapor da água (H_2O) seja responsável por quase dois terços do efeito natural da Terra, sua presença na atmosfera não é considerada uma fonte causadora do aquecimento global devido ao seu curto tempo de permanência na atmosfera durante o ciclo hidrológico. O mesmo não ocorre com CO_2, CH_4 e N_2O, que possuem ciclos longos, permanecendo décadas ou até mesmo séculos na atmosfera (AL-GHUSSAIN, 2019). Além do ciclo longo, o CO_2 desempenha um papel central no aquecimento global recente devido a sua elevada concentração na atmosfera quando comparado aos demais gases estufa (mais de duzentas vezes superior ao CH_4 e mil vezes maior que N_2O). Passados quase 10 anos do acordo firmado em Paris durante a Conferência das Nações Unidas sobre as Mudanças Climáticas (COP21), as metas definidas para redução da emissão de gases estufa e demais ações para o combate às mudanças climáticas ainda estão longe serem atingidas.

Em 2018, o Relatório Especial do Painel Intergovernamental sobre Mudanças Climáticas (IPCC) estimou que, entre 2030 e 2052, a temperatura média global da superfície deverá ser 1,5 °C superior aos índices que eram registrados da era pré-industrial. Década após década as agências climáticas vêm registrando novos recordes sucessivos de temperatura global. A figura 1 mostra que 2023 foi o ano mais quente desde o início das medições sistemáticas em 1850, quando a temperatura global chegou a 1.18°C acima da média do século XX de 13,9°C (NOAA; 2024). O último ano em que a temperatura global esteve abaixo da média do século XX foi em 1976, sendo os 10 anos mais quentes já registrados ocorreram justamente ao longo da última década (2014-2023). Até o momento, o efeito mais reportado das mudanças climáticas globais é o aquecimento das zonas de alta latitude e grande continentalidade do Hemisfério Norte, cujas implicações ambientais incluem desde o derretimento de gelo no Ártico e geleiras de montanhas, mudanças no início e na duração das estações do ano, alteração nos padrões de crescimento e fenologia vegetal, entre outros (VOSE *et al.*, 2005; SCHWARTZ; AHAS, 2006; MAHLSTEIN; KNUTTI, 2012; PENG, *et al.*, 2013). No entanto, as regiões tropicais e o Hemisfério Sul também são amplamente afetados pelas mudanças climáticas. Especificamente em relação as áreas topicais, algumas das alterações mais importantes envolvem os padrões regionais de precipitação em decorrência de mudanças nas circulações de Walker e Hadley (NEELIN *et al.*, 2006; CHOI et al. 2014; LAU; KIM 2015; DINEZIO et al., 2013).

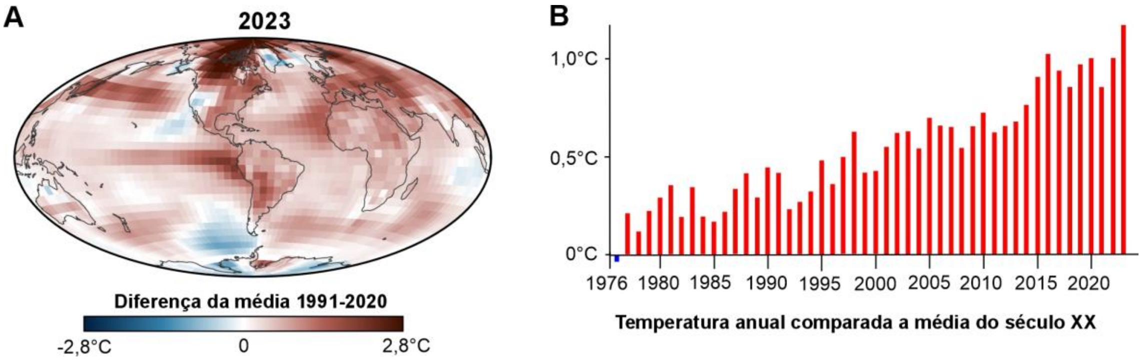

Figura 1. Anomalia global de temperatura do ano 2023 em relação a série histórica. Onde: A) Distribuição espacial dos desvios de temperatura no Planeta durante o ano de 2023. B) Temperatura média anual comparada a média global de 13,9°C no século XX. Fonte: Modificado de National Oceanic and Atmospheric Administration- NOAA (2024).

A influência das ações humanas nas forçantes climáticas não se restringe a emissão de gases estufa e/ou aerossóis na atmosfera. A supressão de vegetação nativa, tanto florestal quanto campestre, para expansão de pastagens, áreas urbanas e agrícolas também atua como uma importante forçante climática, proporcionando alterações significativas, especialmente em escalas locais e regionais (FOLEY *et al.*, 2005). As alterações climáticas associadas às mudanças no uso e cobertura do solo se dão em função de alterações nos balanços de radiação (principalmente devido à mudança no albedo das superfícies) e de energia, em razão de alterações nos fluxos de calor sensível, latente e no solo (SNYDER; DELIRE; FOLEY, 2004). Consequentemente, as mudanças no uso e cobertura do solo também levam a um forte impacto no balanço hídrico local, alterando padrões de evapotranspiração, escoamento e infiltração de água no solo (RAMANKUTTY; FOLEY, 1999). Assim, a substituição de superfície modifica as complexas interações solo-vegetação-atmosfera e, portanto, os seus efeitos podem atenuar ou amplificar as mudanças climáticas globais causadas pela emissão de gases estufa e aerossóis (BONAN, 2008). Nas últimas décadas, estudos teóricos vêm simulando as consequências da remoção da cobertura vegetal original dos diversos biomas terrestres em função de diferentes formas de uso do solo, como, por exemplo, pastagens (HOFFMANN; JACKSON, 2000), agricultura (BOUNOUA *et al.*, 2002) e solo exposto (SNYDER; DELIRE; FOLEY, 2004). Estas simulações demonstram que as consequências climáticas da substituição de superfícies diferem significativamente entre os diferentes biomas terrestres. Por exemplo, diante de uma hipotética supressão massiva das florestas tropicais, temperadas e boreais e posterior conversão em solo exposto, todas as formações sofreriam um aumento significativo do albedo superficial e redução do saldo de radiação, mas enquanto as florestas tropicais tenderiam a um forte aumento de temperatura, as florestas temperadas e boreais tenderiam a um pronunciado resfriamento anual (SNYDER; DELIRE; FOLEY, 2004).

Avaliar estas simulações climáticas através de estudos empíricos com dados de campo é um passo fundamental para compreensão das reais consequências das ações antrópicas nos biomas terrestres. Estas tentativas são relativamente recentes, mas estudos conduzidos nas pradarias da América do Norte, onde ao longo do século XX ocorreu uma massiva supressão da cobertura vegetal original para expansão de áreas agrícolas (especialmente das culturas irrigadas), vêm corroborando as previsões fornecidas pelos modelos teóricos. Tanto as pradarias norte-americanas quanto canadenses vêm registrando um resfriamento regional e a um significativo aumento da precipitação pluvial nos meses de primavera/verão (ALTER *et al.*, 2018; BETTS *et al.*, 2013), tendência oposta ao que seria esperado para as altas latitudes do Hemisfério Norte levando em conta somente os modelos climáticos baseados em cenários de aumento de emissões de gases estufa. Portanto, estes estudos demonstram que, em escalas regionais, os efeitos produzidos pelas mudanças no uso e cobertura do solo podem superar aqueles produzidos pelas demais forçantes climáticas.

No Brasil, até o início das atividades acadêmicas desta tese de doutorado, em 2019, a maior parte dos estudos relacionando mudanças climáticas e alterações do uso e cobertura do solo tinha sido conduzida em ecorregiões florestais, como Mata Atlântica e Amazônia. Especificamente em relação à Amazônia, a ampla conversão de floresta em outras formas de uso, principalmente por pastagens, tem sido acompanhada de uma pronunciada redução da evapotranspiração seguida de um intenso aquecimento regional (MALHI; WRIGHT; NIN, 2004; SAMPAIO *et al.*, 2007; ALMEIDA *et al.* 2017). Adicionalmente, estes estudos também vêm encontrando uma tendência de forte queda na formação de nuvens e da precipitação pluvial, especialmente durante os meses que marcam o final do período seco, onde as chuvas são mais dependentes do transporte vertical de umidade proveniente da evapotranspiração e convecção local (MALHI *et al.*, 2008; MARENGO, 2004; MARENGO *et al.* 2018; DEBERTOLI *et al*. 2015). No Cerrado, até 2019, este tipo de estudo ainda se restringia ao plano teórico (COSTA; PIRES, 2010) ou estudos conduzidos em áreas localizadas (LOARIE et al. 2011; SPERA et al. 2016). Embora possam resultar em fortes impactos socioambientais e econômicos nas próximas décadas, as consequências climáticas das mudanças do uso nas demais ecorregiões brasileiras seguem sendo um tema pouco explorado até os dias de hoje.

1.2 O CERRADO BRASILEIRO

O Cerrado brasileiro é a segunda maior ecorregião da América do Sul, sendo também considerada um *hotspot* mundial de biodiversidade, com grande número de endemismos, tanto da flora quanto da fauna (MYERS *et al.*, 2000). Originalmente, o Cerrado se estendia por cerca de dois milhões de quilômetros quadrados, ~22% do território brasileiro (JEPSON, 2005; RATTER; BRIDGEWATER; RIBEIRO, 2006). Em território boliviano, a vegetação de cerrado se prolonga por boa parte da região conhecida como *Los Llanos de Chiquitos* (ou *Chiquitania*), onde representa uma zona de transição entre o Chaco boliviano e a Floresta Amazônica (HASENACK *et al.*, 2017; HUECK, 1972). No Brasil, o Cerrado ocorre desde as regiões equatoriais até o paralelo 25°S, ocupando a integralidade ou partes do território de 10 dos 26 estados brasileiros e estando presente nas cinco regiões do Brasil. O cerrado é vegetação predominante em toda a Região Centro-Oeste do Brasil (Mato Grosso, Mato Grosso do Sul, Goiás e Distrito Federal), mas também ocupa parte dos territórios das Regiões Sul (no extremo norte do Paraná), Sudeste (porção central de São Paulo e oeste de Minas Gerais), Nordeste (oeste da Bahia e sul do Maranhão e Piauí) e Norte, onde cobre a maior parte do Tocantins (Figura 2). Ao longo da sua distribuição do Cerrado as altitudes variam de cotas próximas ao nível do mar (Região da Mata dos Cocais, no Maranhão e Piauí) até 1800 metros (RATTER; BRIDGEWATER; RIBEIRO, 2006).

Figura 2. Distribuição do Cerrado brasileiro segundo o Mapa do Biomas do Brasil (IBGE, 2004).

1.3 USO DE TERMOS E CONCEITOS ASSOCIADOS AO CERRADO

Antes de realizar um aprofundamento sobre as principais características e fatores ambientais que determinam a ocorrência do Cerrado, bem como das suas diferentes fitofisionomias, é de importante esclarecer alguns pontos a respeito da termologia e dos conceitos empregados ao longo desta tese, na medida em que a utilização de alguns destes termos têm sido motivo de um intenso debate. O Cerrado brasileiro tem sido mencionado na literatura cientifica internacional como *the Neotropical Savanna* (ou seja, a Savana Neotropical), estando, portando, incluído no grande grupo de vegetação classificado como “savana”. Esta classificação do Cerrado como uma savana é bastante antiga, podendo ser encontrada na literatura científica e mapas cartográficos há pelo menos 70 anos, estando presente na obra de diversos autores brasileiros e estrangeiros (COLE, 1960; HUECK, 1972; WALTER; BRECKLE, 1986). No entanto, desde as décadas de 1960 e 1970, importantes autores têm contestado a inclusão do Cerrado na categoria savana, sugerindo, em alguns casos, que este fosse considerado um tipo de vegetação *sui generis*. Entre as principais razões elencadas para este questionamento estão a elevada riqueza de espécies do Cerrado, em comparação com as demais savanas tropicais no Mundo, e a sua grande diversidade de fitofisionomias, que variam desde campos abertos até florestas densas (WALTER, 2006). Adicionalmente, existem também particularidades em relação à origem desta formação vegetal, além de importantes diferenças funcionais e fisiológicas das espécies de plantas do Cerrado brasileiro, cuja maior parte das árvores possui folhas largas e perenes, em contraste com a savana africana, por exemplo, onde as espécies arbóreas costumam ser caducifólias e possuírem folhas pequenas (GRAEFF, 2015; RIZZINI, 1997). A obra de Carlos Toledo Rizzini traz ainda um elemento adicional importante, sugerindo que as fisionomias savânicas do cerrado atual (mais notoriamente o cerrado *stricto senso*) seriam na verdade um produto da ação antrópica, especialmente pelo uso do fogo, que teria levado a uma degradação gradual do Cerradão (fitofisionomia florestal do Cerrado que seria a condição clímax da região) até transformá-las nas vegetações baixas e esparsas que conhecemos atualmente. Esta ideia é atualmente conhecida como teoria Rizzini-Lund-Aubréville, e pode ser consultada diversos trabalhos da extensa obra de Rizzini e também em sínteses presentes em Ratter *et al*. (2006) e Graeff (2015).

Essa discussão também se deve, pelo menos em parte, ao próprio conceito de savana em si. A falta de clareza na definição de savana foi, por exemplo, a principal razão declarada por Goodland e Ferri para que não empregassem o termo para se referirem ao Cerrado (GOODLAND; FERRI, 1979). O termo savana é uma palavra de origem ameríndia, e que apareceu na literatura pela primeira vez em 1535 em língua espanhola (*sabana* ou *sabána*) quando foi utilizada por Gonzalo Fernández de Oviedo y Valdés (1478-1557) para descrever "uma terra sem árvores, mas com muita grama e ervas" (COLE, 1960). Deste modo, esta definição original claramente vai de encontro ao significado da palavra cerrado, que na língua portuguesa remete a noção de vegetação densa e fechada. Ocorre que, até a metade do século XIX, o termo savana era utilizado apenas para designar alguns tipos de vegetação Caribenha e, principalmente, os Llanos da Venezuela e da Colômbia (WALTER, 2006). Foi somente em 1872 que o naturalista August Grisebach propôs diferenciar as savanas das estepes (outro tipo de vegetação essencialmente composto por gramíneas) pela presença de elementos arbustivos e arbóreos nas savanas, uma ideia que permanece difundida na literatura até os dias de hoje (WALTER, 2006).

Desde então, o termo savana passou a ser amplamente empregado na literatura, sendo utilizado para designar diversos tipos de vegetação fisionomicamente semelhantes, mas que se estruturam em função de diferentes fatores ecológicos (WALTER; BRECKLE, 1986). Ao longo do tempo, pesquisadores de todo o mundo têm se dedicado a difícil tarefa de estabelecer definições conceituais sobre as savanas, bem como propor diferentes formas de classificação e definição dos fatores associados à sua distribuição. As definições são amplas, havendo uma excelente síntese em Walter (2006). Dentre estes conceitos, o que será adotado nesta obra é apresentado por Heinrich Walter, que diz: "*as savanas são sistemas ecológicos formados por pradarias tropicais, nas quais algumas espécies isoladas de lenhosas vivem em competição com gramíneas e outras herbáceas*" (WALTER, 1986). Ressalta-se que, nesta definição, as savanas tropicais são separadas das vegetações de mesma fisionomia semelhante que se encontra em latitudes médias e/ou subtropicais, havendo também no texto original do autor uma ampla formalização das condições climáticas necessárias para sua existência, como a manutenção das temperaturas elevadas durante todo o ano e existência de uma estação seca de inverno bem definida.

Uma nova polêmica em relação ao emprego de nomenclaturas associadas ao Cerrado brasileiro surgiu nas últimas décadas, quando se passou a utilizar a denominação de "Bioma Cerrado". Esta denominação do Cerrado como um bioma já aparecia em alguns trabalhos entre o final da década de 1990 e o início dos anos 2000 (OLIVEIRA; MARQUIS, 2002; RATTER; RIBEIRO; BRIDGEWATER, 1997), mas ganhou grande difusão em 2004, quando uma cooperação entre o Instituto Brasileiro de Geografia e Estatística (IBGE) e o Ministério do Meio Ambiente (MMA) lançou o Mapa de Biomas do Brasil na escala 1:5.000.000, separando o território brasileiro em seis biomas terrestres: Amazônia, Mata Atlântica, Caatinga, Cerrado, Pantanal e Pampa (IBGE, 2004). A demanda deste produto teve origem no Ministério do Meio Ambiente, que necessitava de um mapa oficial das regiões naturais brasileiras para formulação de legislações específicas (IBGE, 2019). Até aquele momento, tanto os técnicos dos diferentes órgãos do serviço público quanto os diversos grupos de pesquisa espalhados pelo Brasil usavam produtos distintos, com nomenclaturas, conceitos e/ou limites diferentes, sendo o mais popular à época o mapa de ecorregiões da World Wide Fund for Nature (WWF), que aqui mencionamos como Olson et al. (2001). Na medida em que o IBGE é o órgão oficial para realização da cartografia brasileira, coube a esta instituição atender a demanda do MMA e produzir este novo mapa. Nos anos seguintes da publicação do mapa de Biomas do Brasil pelo IBGE, esta terminologia/divisão territorial passou a ser adotada oficialmente tanto em nível federal quanto estadual, sendo posteriormente utilizada na formulação de novos projetos de lei, criação de programas de mapeamento de remanescentes e monitoramento da biodiversidade. Além disso, esta nova nomenclatura também passou a ser incluída em programas escolares e livros didáticos em todo Brasil. Em 2019, o IBGE lançou uma atualização do Mapa dos Biomas do Brasil e seus limites, com a nova versão sendo compatível com escala 1:250.000 (IBGE, 2019).

Atualmente, a ideia de Biomas do Brasil se encontra profundamente enraizada tanto na academia quanto sociedade brasileira, embora existam contestações a respeito da aplicação do conceito de bioma pelo IBGE (BATALHA, 2011; COUTINHO, 2006). Em sua síntese, o IBGE considerou o bioma como: "*grande conjunto de vida vegetal e animal caracterizado pelo tipo de vegetação dominante*' (IBGE, 2004). No caso particular do Cerrado, o IBGE menciona em sua nota técnica anexa ao Mapa de Biomas do Brasil que os principais critérios técnicos para sua delimitação são: "*predominância das formações com fitofisionomias savânicas que caracterizam o bioma, como uma consequência clima, solos e fogo, fatores que auxiliam na sua identificação*" (IBGE, 2004). Em 2011, valendo-se de uma ampla revisão realizada por Coutinho (2006), o professor Marco Antônio Batalha, um dos maiores pesquisadores da atualidade sobre a vegetação do Cerrado brasileiro, lançou um artigo expondo a forma errônea com que o conceito de bioma tem sido utilizado no Brasil. Sua principal crítica residiu no fato de que a interpretação do IBGE segue uma conotação essencialmente florística, quando deveria ser fisionômica e funcional (BATALHA, 2011). Assim, na visão de Batalha, se o conceito de bioma fosse aplicado corretamente, o Cerrado brasileiro (*lato sensu*) seria composto por três biomas:

(i) campo tropical (campo limpo), (ii) a savana (campo sujo, campo cerrado e cerrado *stricto sensu*) e (iii) floresta estacional (cerradão) (BATALHA, 2011).

Embora se reconheça o mérito e a qualidade do produto cartográficos produzido pelo IBGE, especialmente dada à grande dificuldade de se estabelecer e mapear unidades que consigam contemplar/agrupar toda biodiversidade brasileira satisfatoriamente em poucas categorias discretas, aqui também se considera válidos os argumentos apresentados por Batalha (2011). Deste modo, sempre que possível, se evitará mencionar o Cerrado brasileiro como um bioma (ou seja, Bioma Cerrado), tanto nesta tese quanto nos produtos derivados dela. Neste sentido, em razão de seu uso tradicional na língua inglesa, quando da redação de artigos científicos internacionais, o Cerrado brasileiro será mencionado como uma ecorregião (*ecoregion ou ecological region*) (BAILEY, 2009; OLSON *et al.*, 2001). Já em português, como sugerido por Batalha (2011), a palavra “cerrado” será empregada em três formas distintas: (i) Cerrado brasileiro, com letra C em maiúsculo, para se referir o domínio fitogeográfico e/ou o recorte territorial utilizado como área de estudo; (ii) cerrado, com letra c minúscula, para referir o tipo vegetacional no seu sentido mais amplo (*lato sensu*), que, portanto, contempla todas as suas diferentes fitofisionomias; (iii) cerrado *stricto sensu* para referir a fitofisionomia savânica mais comum do Cerrado brasileiro. Desta maneira, o uso do termo “Bioma Cerrado” será mantido apenas para designar dados e produtos gerados por terceiros, como a base cartográfica oficial do IBGE ou os produtos e dados gerados pelo Projeto MapBiomas, por exemplo.

1.4 BIODIVERSIDADE DO CERRADO

O Cerrado é reconhecido na literatura científica como a savana mais biodiversa do Planeta, sendo a diversidade de algumas de suas localidades similar aquelas encontradas em áreas de florestas tropicais, como Amazônia e Mata Atlântica (FURLEY, 1999; AGUILAR *et al.*, 2015). Embora a quantidade de espécies que habitam o Cerrado seja ainda desconhecida, documentos de divulgação das agências brasileiras e Organizações Não-Governamentais estimam que o número seja superior a 320 mil (EMBRAPA, 2024; WWF, 2024). O número de espécies descritas no Cerrado vem aumentando exponencialmente nas últimas duas décadas devido ao avanço do uso de técnicas moleculares em estudos filogenéticos no Brasil, atualização das revisões taxonômicas, e aumento de amostragens científicas em diferentes subregiões (COLLI;

VIEIRA; DIANESE, 2020). Para efeitos de comparação, no final do século XX, as estimativas encontradas na literatura científica mencionavam a existência de cerca de 160 mil espécies para toda a ecorregião (RATTER; RIBEIRO; BRIDGEWATER, 1997). Este aumento do número de nova espécies descritas é mais significativo em alguns grupos específicos, como plantas, que até 2005 eram estimadas em cerca de 7 mil e hoje já ultrapassam 12.800 espécies (KLINK; MACHADO, 2005; FLORA E FUNGA DO BRASIL, 2024). A biodiversidade do Cerrado segue, portanto, sendo um tema mal compreendido (COLLI; VIEIRA; DIANESE, 2020). É provável que as estimativas de riqueza de espécies e número de endemismos sigam aumentando nas próximas décadas, especialmente com avanço do conhecimento em grupos ainda pouco conhecidos como, por exemplo, protozoários, bactérias, fungos e invertebrados.

A origem da diversidade do Cerrado é atribuída em grande parte sua história muito antiga e a flutuações climáticas ocorridas durante o Pleistoceno e o Holoceno, épocas marcadas pela alternância entre períodos glaciais e interglaciais, e que produziram grandes variações climáticas em toda Região Tropical do Brasil (SALGADO-LABOURIAU *et al.*, 1997; BEHLING; HOOGHIMSTRA, 2001; LEDRU *et al.*, 2006; STÍKIS et al., 2018). De modo geral, acredita-se que durante os períodos glaciais as condições climáticas mais secas e/ou frias favoreceram a expansão das diferentes formações campestres e savânicas do Cerrado e da Caatinga, ocorrendo uma posterior retração destas formações para expansão das florestas tropicais durante fases mais quente e úmidas (SALGADO-LABOURIAU *et al.*, 1997; FURLEY, 1999). Estes movimentos de contração e expansão das diferentes formações vegetais teria promovido a fragmentação e o isolamento de manchas destas diferentes fisionomias por longos períodos, levando à evolução de muitas espécies microendêmicas nos *pools* de genes isolados (RATTER; RIBEIRO; BRIDGEWATER, 1997). As variações climáticas e os consequentes movimentos de expansão e retração das savanas e florestas também podem estar associados a extinções na região, particularmente da megafauna (ex. preguiças e tatus gigantes) que habitava o Cerrado até parte final do Pleistoceno (DOUGHTY; FAURBY; SVENNING, 2016; SALLES et al., 2016). Ao longo dos últimos 5 mil, as variações climáticas na região do Cerrado se estabilizaram, dando origem as condições quentes e de precipitação com distribuição sazonal que conhecemos hoje (BEHLING; HOOGHIMSTRA, 2001; LEDRU *et al.*, 2006), levando a estruturação das comunidades e estratégias de vida atuais. A concentração de grande número de espécies endêmicas em regiões específicas, como, por exemplo, a Serra do Espinhaço, Chapadas dos Veadeiros e Guimarães e planície do Araguaia apoia a ideia do isolamento como fator importante para especiações ocorridas nestas regiões (AGUILAR *et al.*, 2015; VIEIRA-ALENCAR et al., 2023).

Os campos rupestres são exemplos dessa altíssima biodiversidade concentrada em áreas localizadas. Embora possuam uma baixíssima representatividade espacial no Cerrado, ocorrendo principalmente em os topos de serras e *inselbergs*, os campos rupestres abrigam mais de 5 mil espécies de plantas, com elevada proporção de espécies endêmicas (ALVES; KOLBECK, 1994; FERNADES *et al.*, 2018). As espécies endêmicas nos campos rupestres não se restringem as plantas. Na região da Serra do Espinhaço, pelo menos 28 novas espécies de vertebrados (11 de anfíbios, 10 de répteis, 4 de aves e 1 de mamífero) foram recentemente descritas (ALVES *et al.*, 2014; FERNADES *et al.*, 2018). Vários fatores são elencados para explicar a elevada quantidade de espécies endêmicas dos campos rupestres, como, por exemplo, a possibilidade de que a topografia complexa das montanhas tenha possibilitado a formação de microrrefúgios interglaciais, mantendo condições climáticas favoráveis e evitando extinções para espécies mais adaptadas a ambientes áridos e frios durantes movimentos de retração deste tipo de vegetação (BARBOSA *et al.*, 2015). Contudo, esta hipótese para diversificação dos campos rupestres não é consensual, sendo tema de intensos questionamentos por estudos recentes (RAPINI *et al.*, 2021).

A diversidade no Cerrado não é homogênea nos principais grupos taxonômicos, sendo normalmente concentrada em alguns taxons específicos. Em plantas, por exemplo, a ampla maioria das espécies do Cerrado é composta por angiospermas, ocorrendo o mesmo com os mamíferos, onde a diversidade é altamente concentrada nas ordens Rodentia e Chiroptera (AGUILLAR *et al.*, 2004). Os números mais recentes dão conta de 12.829 espécies de plantas para o Cerrado, sendo 4.613 endêmicas (FLORA E FUNGA DO BRASIL, 2024). Entre os animais vertebrados os principais grupos taxonômicos do Cerrado são representados por: 204 espécies de anfíbios (124 endêmicas); 278 espécies de répteis (129 endêmicas); 1.200 espécies de peixes; 856 espécies de aves (28 espécies endêmicas); 251 espécies de mamíferos (42 endêmicas) (AGUILAR *et al.*, 2015; VIEIRA-ALENCAR et al., 2023; LOPES; SILVA, 2024). Os inventários sobre invertebrados são restritos a grupos ou locais muito específicos. Em seu website, a

Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) estima em mais de 90 mil espécies de invertebrados para o Cerrado (EMBRAPA, 2024), mas não apresenta dados ou referências que sustentem essa estimativa. Embora o conhecimento a respeito da diversidade de invertebrados seja muito restrito, é notório que existem centros de endemismos de alguns grupos de insetos no Cerrado, como, por exemplo, a região do rio Araguaia para o grupo Lepidoptera (BROWN; GIFFORD, 2002).

1.5 CARACTERÍSTICAS AMBIENTAIS DO CERRADO

Assim como as demais áreas de savanas tropicais do mundo, o Cerrado se encontra em uma zona de transição entre os biomas de florestas tropicais equatoriais, que no Brasil é representado pela Amazônia, e os desertos das regiões áridas e semiáridas subtropicais, que no Brasil não ocorrem devido sua posição geograficamente privilegiada junto à costa leste da América do Sul (WALTER, 1986). Além da posição geográfica, outras características ambientais e semelhança quanto ao uso do solo que aproximam o Cerrado das demais áreas de savana tropicais. Nesse contexto, o clima, os solos e o fogo atuam como os três filtros ambientais determinantes para ocorrência e estruturação das comunidades biológicas e das diferentes fitofisionomias do cerrado, influenciando a composição de espécies, tipos de adaptações, interações interespecíficas e características funcionais da vegetação.

1.6 CLIMA DO CERRADO

O clima funciona como o principal filtro ambiental para a ocorrência das savanas tropicais no mundo, na medida em que sua distribuição nos diferentes continentes coincide, na maioria das vezes, com zona do tipo climático Aw (ou seja, clima tropical com inverno seco), de acordo com a classificação climática de Köppen (WOODWARD, 2009) (Figura 3). O Aw é o segundo tipo climático mais representativo na Terra, cobrindo 11,5% das áreas continentais, e sendo caracterizado tanto pelas temperaturas elevadas durante todo o ano e também pela alternância de estações chuvosas e secas bem definidas (PEEL; FINLAYSON; MCMAHON, 2007). Nas áreas tropicais mais elevadas, as savanas também costumam ocorrer em condições mais frias, onde o tipo climático predominante se torna o Cwa ou Cwb, sendo a temperatura do mês mais quente de verão (superior ou inferior a 22°C) o fator determinante sua para separação destes dois tipos climáticos. Os dados climáticos registrados nas diferentes áreas de savanas mundiais mostram que a estação úmida e mais quente costuma durar entre cinco a sete meses de duração, tendo seu ápice no mês que sucede o solstício de verão (WALTER; BRECKLE, 1986). O fim da estação chuvosa geralmente é marcado por uma rápida transição para uma estação seca e mais fria. Em geral, a precipitação pluviométrica anual nas savanas costuma variar entre 800 e 1400 mm, com maiores volumes de chuva podendo ser observados nas zonas de transição com as florestas equatoriais (WALTER; BRECKLE, 1986).

No Cerrado, o tipo climático Aw predomina em quase toda sua área extensão, com temperaturas elevadas sendo registradas ao longo de todo ano e médias mensais que variam entre 18 e 26°C (ALVARES *et al.*, 2013). As exceções se encontram apenas nas áreas mais elevadas, como Serra do Espinhaço em Minas Geras, onde baixas temperaturas são registradas durante o inverno e o tipo climático é o Cwa ou Cwb (Figura 4A). A estação seca, que ocorre entre a segunda quinzena de maio e o equinócio de primavera no Hemisfério Sul, em setembro, tem origem na estabilidade gerada pelo Anticiclone Subtropical do Atlântico Sul (ASAS; também conhecido como Anticiclone de Santa Helena), um centro de alta pressão semipermanente que se forma no Atlântico Sul, no ramo subsidente da célula de Hadley (ALVES; EIDT, 2021; NIMER, 1979; REBOITA *et al.* 2019). Durante o inverno austral, este anticiclone se encontra fortalecido e posicionado próximo da costa brasileira na latitude do Trópico de Capricórnio (23°27’S), criando um fluxo de ar quente e úmido no sentido de leste para oeste que invade o interior do Brasil nas latitudes tropicais (REBOITA *et al.* 2019). No entanto, a natureza subsidente dessa massa de ar restringe o transporte vertical da umidade proveniente da evapotranspiração regional, impedindo o desenvolvimento de nuvens e a ocorrência de chuva. Existem pequenas variações na duração da estação e intensidade do período seco entre as diferentes regiões do Cerrado, sendo geralmente mais longas e intensa nas zonas core ou próximas à Caatinga (NIMER, 1979).

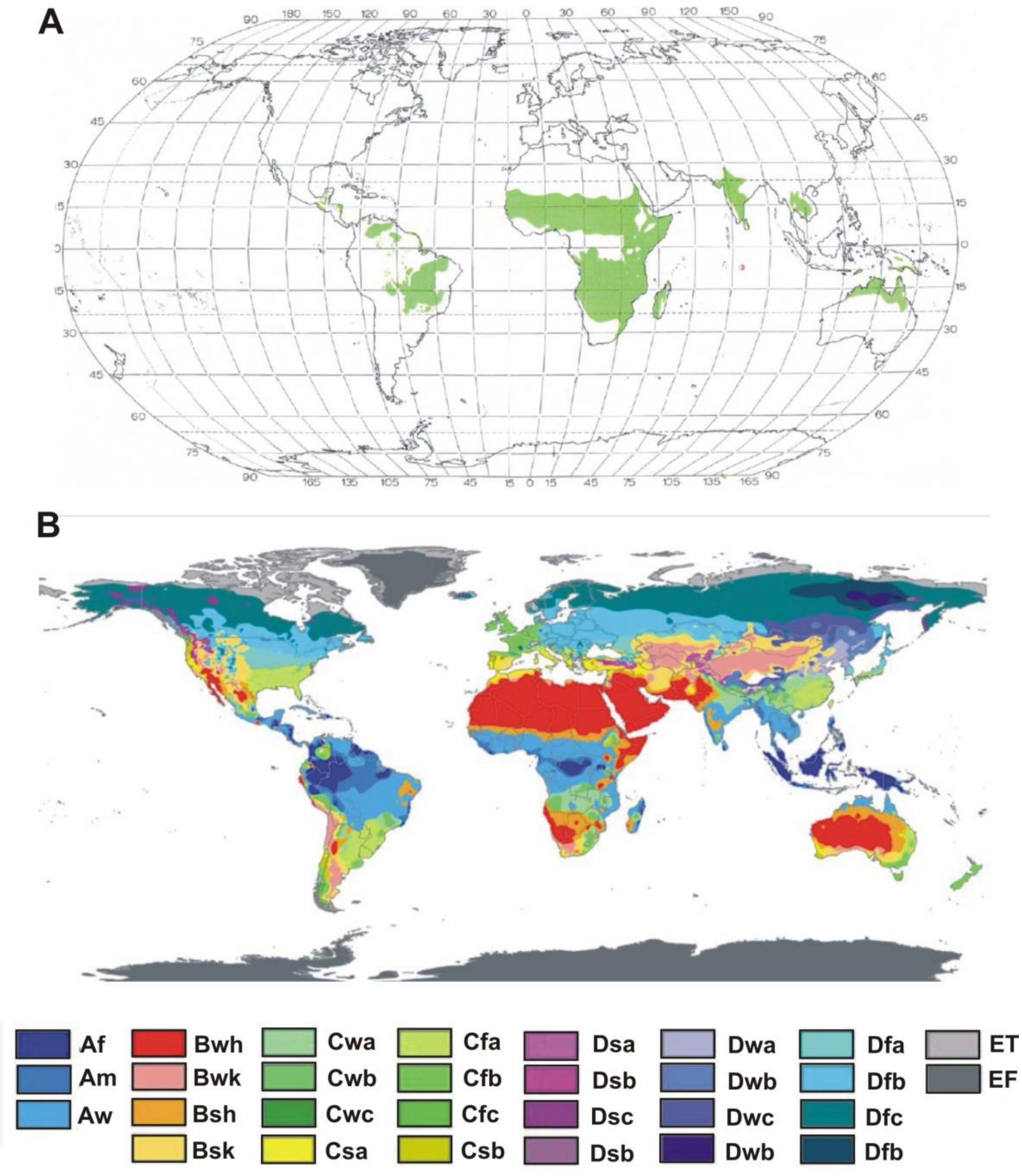

Figura 3. Associação entre as savanas tropicais no Mundo e o tipo climático Aw (tropical com inverno seco), segundo a classificação climática de Köppen. A- localização das diferentes áreas de savanas tropicais no mundo. Fonte: (BOURLIÉRE, 1983). B- Classificação climática de Köppen aplicada a todos os continentes da Terra. Fonte: (PEEL; FINLAYSON; MCMAHON, 2007).

Já o período chuvoso é uma consequência do regime de monção da América do Sul. Este regime está vinculado à atuação da Zona de Convergência Intertropical (ZCIT) em seu setor nordeste, e também a formação da Zona Convergência do Atlântico Sul (ZCAS), uma zona de baixa pressão que se forma esporadicamente e que cruza o Cerrado diagonalmente no sentido noroeste-sudeste (Figura 4B) (GAN; KOUSKY; ROPELEWSKI, 2004; MECHOSO *et al.*, 2005). O desenvolvimento do sistema de monção na América do Sul é marcado por uma inversão do vento zonal na Região Centro-Oeste do Brasil na altitude de 1500 metros (ou seja, em 850 hPa), o que ocorre entre o final de setembro e o início de novembro, quando o Hemisfério Sul se torna progressivamente mais aquecido em função da maior incidência de radiação solar, levando a um enfraquecimento do ASAS. Este, se desloca para uma posição mais austral (~28°S) e mais afastada do da América do Sul, diminuindo assim a sua influência sobre o Cerrado brasileiro (GRIMM, 2009; NIMER, 1979). Neste período, o aquecimento mais pronunciado da América do Sul em relação às áreas oceânicas adjacentes leva a um rebaixamento da pressão atmosférica sob o continente, o que favorece a penetração da ZCIT e o escoamento do ar úmido proveniente do oceano para o interior do Brasil (ALVES; EIDT, 2021). Ao penetrar no interior da Amazônia, esse ar úmido proveniente do Atlântico tropical é reciclado pela elevada evapotranspiração da Floresta Amazônica e mantém níveis elevados de umidade. Posteriormente, esse ar úmido flui da Amazônia para o Cerrado, elevando os níveis de umidade em todo o Brasil Central e Região Sul do Brasil (GAN; RODRIGUES; RAO, 2021). Na porção oeste do Cerrado, o fluxo de ar conhecido como Jato de Baixos Níveis (*South American Low-Level Jet*) também adiciona grande quantidade de umidade na região (MECHOSO *et al.*, 2005). A baixa pressão atmosférica e a umidade elevada no Cerrado durante esse período possibilitam o desenvolvimento de uma convecção profunda na região, mantendo precipitações elevadas e favorecendo a formação da ZCAS durante os meses de verão (GAN; KOUSKY; ROPELEWSKI, 2004). Portanto, a ZCAS funciona como uma grande faixa de convecção que contribui para o aumento das chuvas em diferentes regiões do Cerrado brasileiro durante os meses de verão. A partir do final de março, a convecção migra gradualmente para as zonas equatoriais e o transporte de umidade proveniente da Amazônia perde intensidade, marcando assim o final do período chuvoso no Cerrado (GAN; RODRIGUES; RAO, 2021).

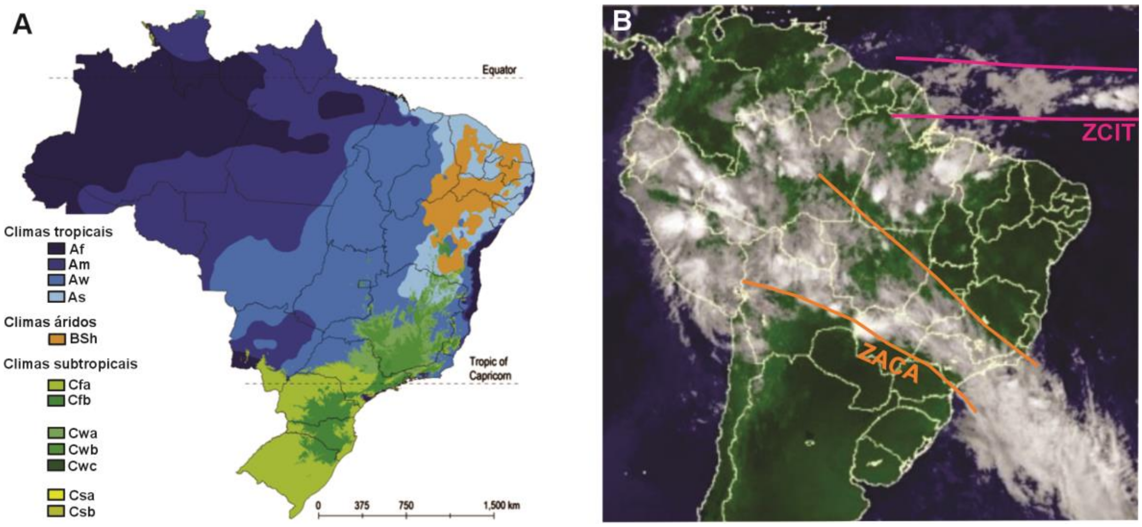

Figura 4. Classificação climática de Köppen aplicada ao território brasileiro e esquema como o Sistema de Monção da América do Sul durante o verão Austral. A- Predomínio do clima do tipo Aw e ocorrências do tipo Cwa e Cwb no setor sudeste Cerrado brasileiro (Fonte: modificado de Alvares et al. 2014). B- Imagem do satélite GOES em 04/02/2013 mostrando a formação da Zona de Convergência Intertropical sob o oceano Atlântico e o norte do Brasil (linhas em cor de rosa) e da Zona de Convergência do Atlântico Sul atravessando diagonalmente as regiões Norte, Centro-Oeste e Sudeste do Brasil (linhas cor de laranja) (Fonte: CPTEC-INPE).

A estação chuvosa no Cerrado brasileiro dura, em média, 190 dias (mínimo 150 e máximo 220 dias) (GAN; KOUSKY; ROPELEWSKI, 2004; NIMER, 1979). Considerando o polígono do definido pelo IBGE, os maiores volumes pluviométricos no Cerrado se encontram por volta de 2000 mm/anuais e são observados nas zonas de transição para Amazônia, como no norte do Mato Grosso e oeste de Tocantins. Já os menores índices se encontram na transição para a Caatinga, como norte de Minas Gerais e Oeste da Bahia e do Piauí, onde os totais anuais se encontram entre 1000 e 800 mm (ASSAD; EVANGELISTA, 1994; INMET, 1992; NOVAIS; FARIAS, 2021). De forma geral, o Cerrado costuma ser menos impactado por eventos de teleconexão do que outras regiões do Brasil como, por exemplo, a Região Sul. Contudo, as chuvas anuais nesta ecorregião também estão sujeitas a variações anuais em decorrência de diferentes eventos de teleconexão, que alteram a circulação atmosférica e causam anomalias pluviométricas na Região Tropical do Brasil (ALVES; EIDT, 2021; CARPENEDO; AMBRIZZI, 2020; SILVA; CARPENEDO, 2022).

Os efeitos meteorológicos causados pelos eventos de teleconexão no Cerrado são de difícil interpretação, existindo grande variação de tendências em suas diferentes sub-regiões (SILVA; CARPENEDO, 2021). Um exemplo desta complexidade é o evento El Niño 2015-2016, que resultou em forte redução de chuva em diversas localidades do Norte do Cerrado, particularmente na zona de transição com o Sul da Amazônia, mas que não provocou alterações significativas em outras sub-regiões (JIMÉNEZ-MUÑOZ *et al.* 2016; PRESTES *et al.* 2024). A Região Centro-Oeste do Brasil, que abriga uma expressiva área do Cerrado, parece ser mais afetada por anomalias na Temperatura da Superfície do Mar (TSM) no Atlântico Sul, pois essas podem alterar a circulação atmosférica, reduzindo a intensidade dos ventos alísios, diminuindo assim o fluxo de umidade que chega a região (ALVES; EIDT, 2021). Recentemente, estudos vêm demonstrando que as diferentes fases do Modo Anular Sul (*Southern Annular Mode*-SAM) causam alterações significativa tanto na extensão quanto na intensidade do SASA, refletindo em variações importantes nas regiões tropicais da América do Sul que incluem o Cerrado (CARPENEDO; AMBRIZZI, 2020; CARPENEDO; AMBRIZZI; SILVA, 2022).

1.7 RELAÇÕES ENTRE O TIPO DE SOLO E AS FITOFISIONOMIAS DO CERRADO

Como ocorre nas outras savanas do mundo, o Cerrado se encontra sob o escudo do antigo Gondwana, um terreno que desde a separação do supercontinente nunca mais foi coberto pelos oceanos. Desta forma, superfícies rochosas expostas têm estado constantemente sujeitas à erosão por milhões de anos, resultando e uma paisagem formada por planaltos antigos, onde os solos costumam ser pobres em nutrientes, especialmente fósforo (P), cálcio (Ca) e outros micronutrientes essenciais para maior parte das plantas (WALTER; BRECKLE, 1986; GRAEFF, 2015). Desta maneira, o solo funciona como um importante filtro ambiental para vegetação das savanas, de forma que a ocorrência das diferentes fitofisionomias do cerrado está intimamente relacionada com o nível de nutrientes no solo (GOODLAND; FERRI, 1979). Os solos do Cerrado costumam ser profundos e bem drenados, sendo que maior parte das espécies de plantas nativas não toleram alagamento (RATTER; RIBEIRO; BRIDGEWATER, 1997). Além disso, maioria dos solos é ácida, com baixa capacidade de troca catiônica e altos níveis de saturação de alumínio, que afetam diretamente os sistemas radiculares e indiretamente inibem a absorção de cálcio e fósforo pelas raízes das plantas (FURLEY; RATTER, 1988).

No Cerrado predominam os latossolos, tanto para as áreas sedimentares como para os terrenos cristalinos (AB’SÁBER, 2003). Em geral, os latossolos são caracterizados pela elevada toxidade devido ao excesso de alumínio trivalente (Al^{3+}) (MOTTA; CURI; FRANZMEIER, 2002). Existem pelo menos três grandes grupos de latossolos no

Cerrado, o vermelho-escuro, o vermelho-amarelo e o roxo. Eles geralmente ocorrem em topografia plana ou suavemente ondulada e, portanto, embora não sejam naturalmente férteis do ponto de vista agronômico, permitem o uso da agricultura mecanizada e podem ser corrigidos com aplicação de calcário e outros fertilizantes (FURLEY; RATTER, 1988). Por essa razão, as áreas de topo plano dos chapadões do Cerrado têm se tornado áreas preferenciais para o estabelecimento grandes áreas de monocultura na região, especialmente para produção de soja. Outro tipo de solo comum no cerrado são os areais de quartzo que, embora profundos, também apresentam uma baixíssima fertilidade devido à alta concentração de alumínio. Ademais, existem ainda muitos outros tipos de solos, de forma que citá-los seria uma tarefa exaustiva e pouco relevante para a fluidez da leitura desta tese. Para acessar a todas as particularidades pedológicas desta região existem excelentes revisões disponíveis, como Motta et al. (2002), por exemplo.

A vegetação do cerrado é caracterizada pela ocorrência de diferentes fitofisionomias, que se encontram dentro em um gradiente que varia desde áreas campestres (ex. campos limpos, rupestres e sujos), passando pelas formações savânicas (ex. cerrado *stricto sensu* e veredas), até formações tipicamente florestais (ex. cerradão, matas ciliares e florestas secas) (GRAEFF, 2015). Como mencionado anteriormente, a maior parte das fitofisionomias possuem uma estreita relação com os solos, havendo capítulos de livros excelentes que se dedicam exclusivamente a detalhar estas relações (veja: RIBEIRO; WALTER, 2008; OLIVEIRA-FILHO; RATTER, 2002). Algumas destas associações são óbvias, como, por exemplo, os campos rupestres ocorrendo em áreas de solos rasos e pedregosos, as veredas ocorrendo em solos alagados e as florestas secas associadas aos afloramentos de calcário (GRAEFF, 2015). Em geral, o aumento da densidade da vegetação arbórea está associado aos solos mais férteis enquanto as áreas abertas dominadas por gramíneas se encontram em solos mais pobres (GOODLAND; FERRI, 1979), embora também existam áreas de Cerradão em terrenos com baixa fertilidade (RIZZINI, 1997). A Tabela 1 foi formulada Oliveira-Filho e Ratter (2002) e sintetiza a as principais relações entre as variações de umidade e fertilidade do solo e as principais fitofisionomias do Cerrado. Em nível de espécies, algumas plantas costumam ser excelentes indicadoras do tipo de solo que são encontradas. Em solos distróficos, por exemplo, são frequentes a ocorrências de espécies como *Ocotea spixiana* e *Hirtellag landulosa*, enquanto *Magonia pubescens* e *Terminalia argentea* costumam ocorrem em solos mesotróficos (FURLEY; RATTER, 1988).

Tabela 1. Principais Fisionomias do Cerrado e sua associação com os níveis de fertilidade do solo e regimes de águas subterrâneas (Fonte: OLIVEIRA-FILHO; RATTER, 2002).

Regime de águas subterrâneas	Fertilidade do solo em termos de saturação de bases		
	Baixo	Intermediário	Alto
Locais fortemente drenados com lençol freático profundo e déficit hídrico no nível do solo superficial	Campo Limpo, Campo Sujo, Cerrado Stricto Sensu ou fácies distróficas de Cerradão	Fácies mesotróficas de Cerradão ou Florestas Semideciduais nos interflúvios	Floresta Seca Decidual nos interflúvios e áreas inclinadas
Alta umidade do solo durante a maior parte do ano nas áreas de captação	Fácies distróficas de Cerradão ou florestas perenifólias nos vales	Fácies mesotróficas de Cerradão ou Florestas Semideciduais nos interflúvios	Floresta Seca Decidual e semidecidual nos vales
Permanentemente alagado a muito úmido ao longo dos cursos dos rios	Matas ciliares sempre verdes, florestas de galeria úmidas ou pantanosas, florestas aluviais		
Períodos sucessivos de alagamento do solo e forte déficit hídrico	Veredas, Campos Úmidos de planície, Campos Rupestres e Campos com Murundus		

1.8 HISTÓRICO DE OCUPAÇÃO DO CERRADO E O USO DO FOGO

O Cerrado brasileiro possui ocupação humana antiga, como comprovam os restos mortais de Luzia, um esqueleto humano de 11.500 anos, o mais antigo já encontrado no Brasil, tendo sido descoberto em Minas Gerais no município de Pedro Leopoldo, no sudeste do Cerrado (NEVES; PILÓ, 2008). Nos milhares de anos que se seguiram após a morte de Luzia, o Cerrado foi ocupado por dezenas de etnias indígenas, como os Xavantes do Mato Grosso, Guarajáras do Maranhão, os Javaés da região do Araguaia, os Avá-

Canoeiros da Ilha do Bananal e os Caxixós do oeste de Minas Gerais, entre outros. O registro de fogo e queimadas é quase tão antigo quanto à ocupação humana no Cerrado brasileiro, sendo este o terceiro e último grande filtro ambiental que molda a composição e estrutura da vegetação na região. Embora atualmente a maior parte das queimadas seja associada à atividade antrópica, o fogo também é um elemento natural e recorrente no Cerrado. Ao longo do seu processo evolutivo, a vegetação nativa do Cerrado desenvolveu diversas adaptações que permitem tolerar o regime de fogo (SIMON; PENNINGTON, 2012). Nos campos rupestres, por exemplo, existem pelo menos três espécies pirófitas, que dependem do fogo para sua reprodução (ALVES; SILVA, 2011). No entanto, evidências paleobotânicas e estratigráficas sugerem que as queimadas no Cerrado brasileiro se tornaram mais frequentes a cerca de 10 mil anos atrás, quando grupos indígenas se espalharam pela região (ALEXANDRE *et al.*, 1999; MISTRY *et al.*, 2005). Assim como observado em outras regiões da América do Sul (BEHLING; PILLAR; BAUERMANN, 2005; BEHLING *et al.*, 2007; BILBAO; LEAL; MÉNDEZ, 2010; VEBLEN *et al.*, 2003), os povos indígenas do Cerrado tradicionalmente utilizam o fogo para diversos propósitos, como, por exemplo, durante atividades de caça e guerras tribais, e também para controlar de espécies indesejáveis e para estimular a produção de frutas (COUTINHO, 1982; MIRANDA *et al.*, 2002; MISTRY, 1998).

A entrada dos povos ibéricos no Cerrado se deu tanto através de bandeiras e incursões a pé pelo seu setor leste, ou seja, a porção mais próxima do Oceano Atlântico, quanto pelo oeste, através da navegação fluvial pelo Rio Paraguai e seus afluentes. Em ambos os setores, a fundação das primeiras vilas e cidades esteve quase sempre associada à descoberta de ouro, diamantes ou outras minérios. São os casos de Cuiabá (em 1719) e Diamantino (em 1728) no Mato Grosso, Diamantina (em 1713) em Minas Gerais, Goiás Velho (em 1729) e Pirenópolis (em 1727) em Goiás, entre outros exemplos. Assim como os indígenas antes deles, os caboclos e quilombolas que povoaram as primeiras vilas e cidades do Cerrado também passaram a utilizar as queimadas com o propósito de manejar a vegetação/paisagem e abrir espaço para pastagens e agricultura de subsistência (PIVELLO, 2011). Ao longo do tempo, as queimadas continuaram sendo praticadas em todas as regiões do Cerrado. Segundo monitoramento realizado pelo Instituto Nacional de Pesquisas Espaciais (INPE), em média, anualmente são registrados mais de 68 mil focos de queimadas em todo Cerrado, sendo mais de 80% dos casos verificados entre os meses de julho e outubro (INPE, 2020). Além das queimadas, a extração de árvores para produção de madeira e carvão também é uma prática muito antiga e que perdura até os dias de hoje no Cerrado (RATTER; RIBEIRO; BRIDGEWATER, 1997).

Embora sua ocupação seja antiga, grande parte do Cerrado permaneceu com uma baixa densidade populacional até a metade do século passado. Ao longo do século XX, os diferentes governos que se sucederam no poder estabeleceram diversos planos de ocupação territorial e integração nacional, tendo na agricultura um pilar fundamental para o sucesso destas iniciativas. Este foi o caso do Governo Vargas (1930-1945), que mesmo adotando políticas que estimulavam a industrialização no Brasil, também procurou reunir as diversas propostas de integração nacional sob uma bandeira política chamada de “Marcha para Oeste" (BESKOW, 2007; LINHARES; SILVA, 1999). Foi neste contexto que se deu parte da colonização da Região Centro-Oeste do Brasil, principalmente na zona fronteira com o Paraguai e Bolívia, através da criação do Território Federal de Ponta Porã e das Colônias Agrícola Nacionais de Dourados, Taquari-Mirim e Ministro João Alberto (hoje Nova Xavantina), bem como a construção da Estrada de Ferro Noroeste do Brasil (NOB), entre Campo Grande e Porto Esperança, em Corumbá, e do Ramal de Ponta Porã (OLIVEIRA, 2013). Esta política nacional prosseguiu no governo de Juscelino Kubitschek e, posteriormente, foi amplamente estimulada durante o período da Ditadura Militar no Brasil (1964-1985), através de diversos programas e investimentos que acabaram por favorecer o setor do agronegócio. Entre eles está a criação do Sistema Nacional de Crédito Rural, em 1965, e das Superintendências do Desenvolvimento do Centro-Oeste (SUDECO) e da Amazônia (SUDAM), entre 1966 e 1967, além da fundação da Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), em 1973 (CARDOSO; TEIXEIRA, 2015; CHADDAD; JANK, 2006; PAIVA; SCHATTAN; FREITAS, 1976).

A partir da década de 1970, contando com a participação do Instituto Nacional de Colonização e Reforma Agrária, o processo de colonização liderado pelas “empresas colonizadoras” emergiu como principal estratégia para a fixação de população e ampliação agrícola no Centro-Oeste, sendo este expediente amplamente utilizado no estado de Mato Grosso (SILVA, 2010). De forma geral, estas empresas eram beneficiadas por subsídios governamentais e, após aquisição de grandes extensões de terras, passavam a fornecer infraestrutura básica e, em seguida, a comercializar lotes rurais e urbanos a partir de áreas próximas dos eixos rodoviários, como a BR163 Cuiabá-Santarém e BR070 (GALVÃO, 2013). Por fim, vários pesquisadores apontam a construção de Brasília como populacional do Cerrado (RATTER; RIBEIRO; BRIDGEWATER, 1997; SILVA, 2010). A partir dela se formou a chamada Região Integrada de Desenvolvimento do Distrito Federal e Entorno, que, segundos os levantamentos mais recentes, já se aproxima de uma população de cinco milhões de habitantes. Além disso, se deu a criação de uma extensa malha rodoviária que ajudou conduzir a urbanização de muitas novas localidades. O processo de ocupação do Cerrado ainda não está concluído e continua seguindo os passos do avanço das novas fronteiras agrícolas. Neste contexto, novos municípios seguem sendo criados e antigas cidades têm sido completamente transformadas pela chegada de recursos e de trabalhadores de outras regiões ligados ao agronegócio. Esse é o caso de Luís Eduardo Magalhães, município localizado no extremo oeste da Bahia, que ganhou destaque nacional pelo seu vertiginoso crescimento urbano e populacional, e tornando-se "a capital brasileira do agronegócio". Luís Eduardo Magalhães não é um caso isolado, havendo processo semelhante em muitas outras localidades desta nova fronteira agrícola aberta no Cerrado que hoje é conhecida como MATOPIBA, sigla que representa a junção das siglas dos estados do Maranhão, Tocantins, Piauí e Bahia, respectivamente (LAHSEN; BUSTAMANTE; DALLA-NORA, 2016).

1.9 O AVANÇO DO AGRONEGÓCIO NO CERRADO

Como citado na seção anterior, a partir da década de 1970, o Cerrado se transformou na principal fronteira agrícola brasileira (Figura 5). Além dos diversos programas e subsídios governamentais, outros fatores também contribuíram para isso. O baixo custo da terra, as chuvas abundantes durante os meses de verão, os solos profundos e dispostos terrenos suavemente ondulados, ou seja, perfeitos para mecanização, também foram fatores-chave no desenvolvimento de operações de agronegócios em grande escala na região (CAVALCANTI; JOLY, 2002). As limitações historicamente impostas pelos solos pobres e ácidos foram superadas pela aplicação em larga escala de calcário para correção de pH e outros fertilizantes químicos (MOTTA; CURI; FRANZMEIER, 2002). Desta forma, baseada principalmente na conversão de vegetação nativa em lavouras de soja, a agricultura comercial se expandiu rapidamente em quase todas as regiões do Cerrado. Entre 1994 e 2002, a taxa de áreas de vegetação nativa convertidas em lavouras chegou a ser de 18.000 km^2/ano (LAHSEN; BUSTAMANTE; DALLA-NORA, 2016). Embora em taxas mais reduzidas, as áreas agrícolas seguiram avançando sobre o Cerrado ao longo da última década, especialmente nas áreas de solo plano e na região do MATOPIBA (SANO, 2016). Atualmente, se estima que cerca de 47% da área original do Cerrado (93 milhões de hectares) já tenham sido convertidos em áreas agrícolas ou de pastagem (STRASSBURG *et al.*, 2017; MAPBIOMAS, 2024).

A pronunciada estiagem durante os meses de inverno e início da primavera se configura como um fator limitante para a produção de grãos na maior parte do Cerrado, pelo menos neste período do ano. No entanto, muitos produtores da região mantêm parte de suas áreas produtivas durante os meses do início do período seco através da irrigação por pivô central (Figura 5h) (OLIVEIRA *et al.*, 2004). Este método de irrigação apresenta um custo socioambiental potencialmente elevado, especialmente em razão da possível redução da vazão de rios e rebaixamento do nível/contaminação do lençol freático e de aquíferos (RATTER; RIBEIRO; BRIDGEWATER, 1997). Diante da impossibilidade de irrigação da maior parte das áreas produtivas durante a estação seca, muitos produtores têm adotado o sistema de plantio direto, onde, após a colheita dos grãos ao final da safra, a parte vegetativa das culturas não é removida das lavouras, fazendo assim com que o material orgânico seja reincorporado ao solo através do processo de decomposição biológica e a posterior mineralização dos nutrientes (BOER *et al.*, 2007). Durante o início do período da entressafra (meados do mês de abril, embora possa haver variação entre as diferentes localidades), o sistema de plantio direto empregado na região também costuma utilizar a semeadura das chamadas plantas de cobertura, normalmente espécies de gramíneas altamente tolerantes a estiagem e que produzem grande quantidade de biomassa, como, por exemplo, o milheto (*Pennisetum glaucum*) e o capim-pé-de-galinha (*Eleusine coracana*). A grande vantagem ambiental/econômica da utilização destas espécies é a redução do tempo em que o solo permanece descoberto, diminuindo a perda de solo pela erosão eólica ou através do escoamento superficial após as chuvas (SANO, 2016), além da manutenção do estoque de carbono orgânico e umidade no solo (NETO *et al.*, 2010). Contudo, nem todos os produtores adotam o plantio direto e, nestes casos, as lavouras permanecem em pousio, ou seja, com o solo descoberto durante os meses de estiagem (Figura 5e e f).

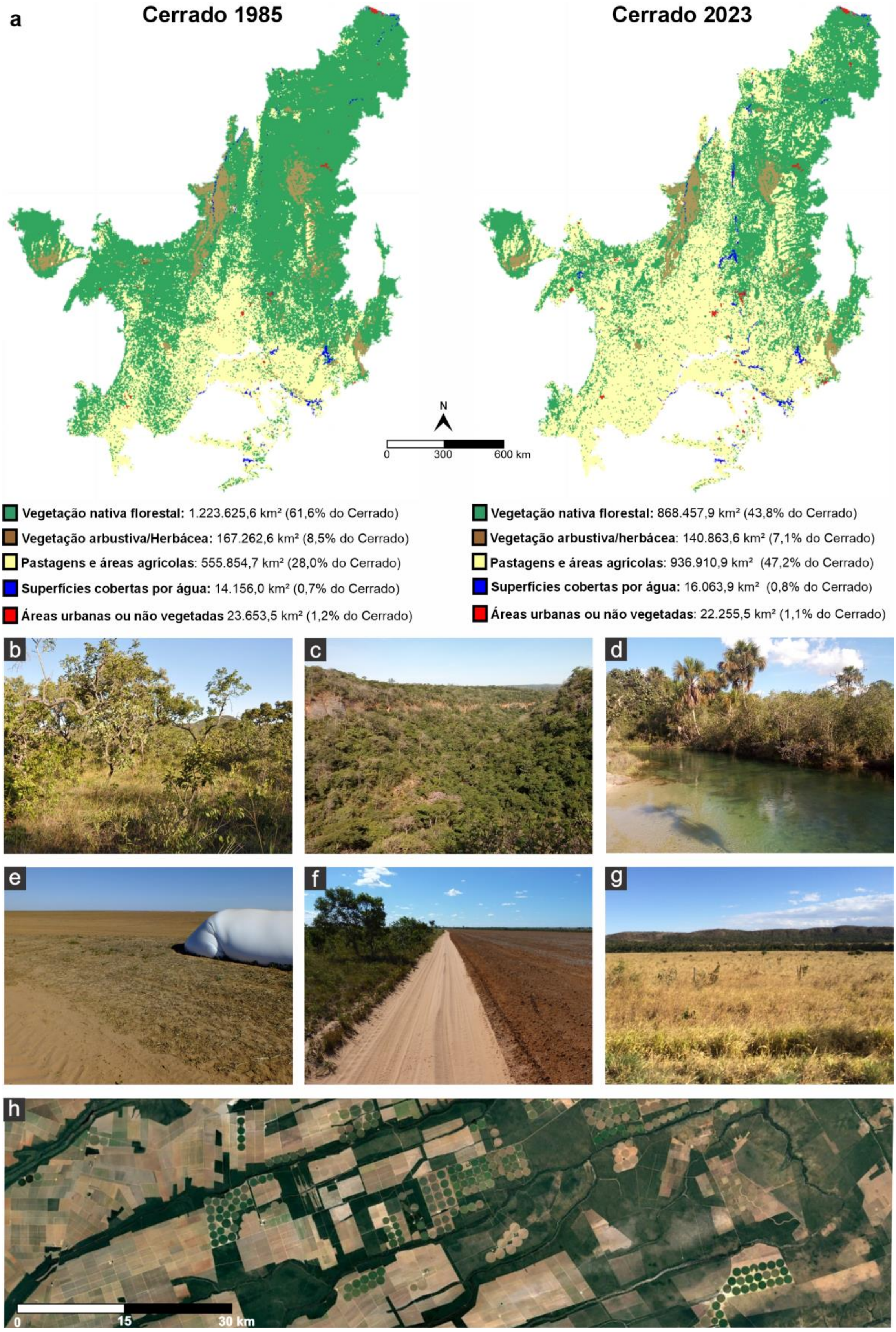

Figura 5. Mudanças atuais no uso e cobertura do solo no Cerrado brasileiro. a) Mapas de uso e cobertura solo do solo do Bioma Cerrado para os anos de 1985 e 2023(Fonte: Projeto MapBiomas – Coleção 9.0 da Série Anual de Mapas de Cobertura e Uso de Solo do Brasil, acessado em 13/09/2024 através do link: mapbiomas.org. b) área de Cerrado stricto sensu no norte de Goiás. c) Floresta Decídua estabelecida em afloramentos de calcário do Grupo Bambuí, em Mambaí (GO). d) Vereda

junto ao rio Paratudão, no Refúgio da Vida Silvestre Veredas do Oeste Baiano. e) Extensa área de agricultura comercial em pousio com a presença de um Silo Bag. f) Pequena estrada de terra separando uma área de cerrado no Parque Nacional Grande Sertão Veredas e uma lavoura em pousio. g) Área de pastagem para pecuária extensiva em Minaçú, norte de Goiás. h) Extensa área de agricultura comercial irrigada por sistema de pivô central, Região Oeste da Bahia, entre os munícipios de Correntina e Chapada Gaúcha (Fonte da imagem: Google Earth).

1.10 MUDANÇAS CLIMÁTICAS ASSOCIADAS À ALTERAÇÃO DO USO E COBERTURA DO SOLO

Mesmo com o uso de novas técnicas, como plantio direto, para redução de parte dos impactos ambientais associados à produção de grãos, a expansão da agricultura comercial segue sendo, indubitavelmente, a maior ameaça ao Cerrado, principalmente pelas consequências diretas e indiretas da supressão de vegetação nativa (CARVALHO; DE MARCO; FERREIRA, 2009). Neste cenário, a maior parte dos estudos no Brasil, principalmente na área da ecologia, vêm focando apenas nas consequências diretas da perda de habitat para espécies, assembleias ou comunidades (BATALHA; CIANCIARUSO; MOTTA-JUNIOR, 2010; MUYLAERT; STEVENS; RIBEIRO, 2016). Contudo, os efeitos indiretos resultantes deste processo também representam uma séria ameaça à biodiversidade regional, além de potencialmente gerar grandes impactos socioambientais paras populações humanas residentes nesta e em demais regiões do Brasil. Entre os efeitos indiretos das mudanças no uso e cobertura do solo do Cerrado estão às mudanças climáticas regionais, sendo este é um tema complexo e que pode ser explorado de diferentes maneiras.

A remoção total ou parcial da vegetação de cerrado, especialmente dos elementos arbóreos, altera os padrões locais de evapotranspiração, desencadeando uma série de efeitos de *feedbacks* que podem ser mais facilmente visualizados através de um fluxograma (Figura 6). Embora a maior parte das árvores do cerrado tenha uma parte aérea de pequeno ou médio porte, elas possuem sistemas radiculares densos e profundos que permitem extrair água subterrânea em grandes profundidades (OLIVEIRA *et al.*, 2005; RODRIGUES *et al.*, 2022; SPERA *et al.*, 2016). Esta característica faz com que a vegetação de cerrado seja popularmente chamada de “floresta invertida”, pois a biomassa das raízes muitas vezes supera a da parte aérea. Experimentos de campo mostram que entre junho e setembro, auge do período seco, áreas de campo sujo e cerrado denso mantém taxas de evapotranspiração entre 1,8 e 2,2 mm.dia^{-1}, adicionando, portanto, entre 216-264 mm de vapor d'água na atmosfera durante este período (OLIVEIRA *et al.*, 2005).

A comparação entre a evapotranspiração da vegetação de cerrado e das áreas agrícolas não é uniforme ao longo do ano. No verão, quando as plantações se encontram no seu estágio máximo de desenvolvimento, as taxas de evapotranspiração da lavouras supera aquelas verificadas nas fitofisionomias campestres e savânicas, e se aproximando dos ecossistemas florestais (SPERA *et al.*, 2016; RODRIGUES *et al.*, 2022). No entanto, durante o inverno, a evapotranspiração nas áreas de cerrado é em média 60% superior a das áreas agrícolas, com a diferença chegando a 77% em setembro, no auge do período seco (SPERA *et al.*, 2016). Esta diferença é tão elevada porque, entre maio e setembro, a maior parte das áreas agrícolas se encontra em solo nu ou coberto apenas por palha e/ou vegetação morta no sistema de pousio, enquanto a maior parte das árvores do cerrado mantém o processo de fotossíntese e evapotranspiração. No total, a evapotranspiração média anual no Cerrado chega a 980 mm, o que corresponde a 2/3 da precipitação média anual (RODRIGUES *et al.*, 2022).

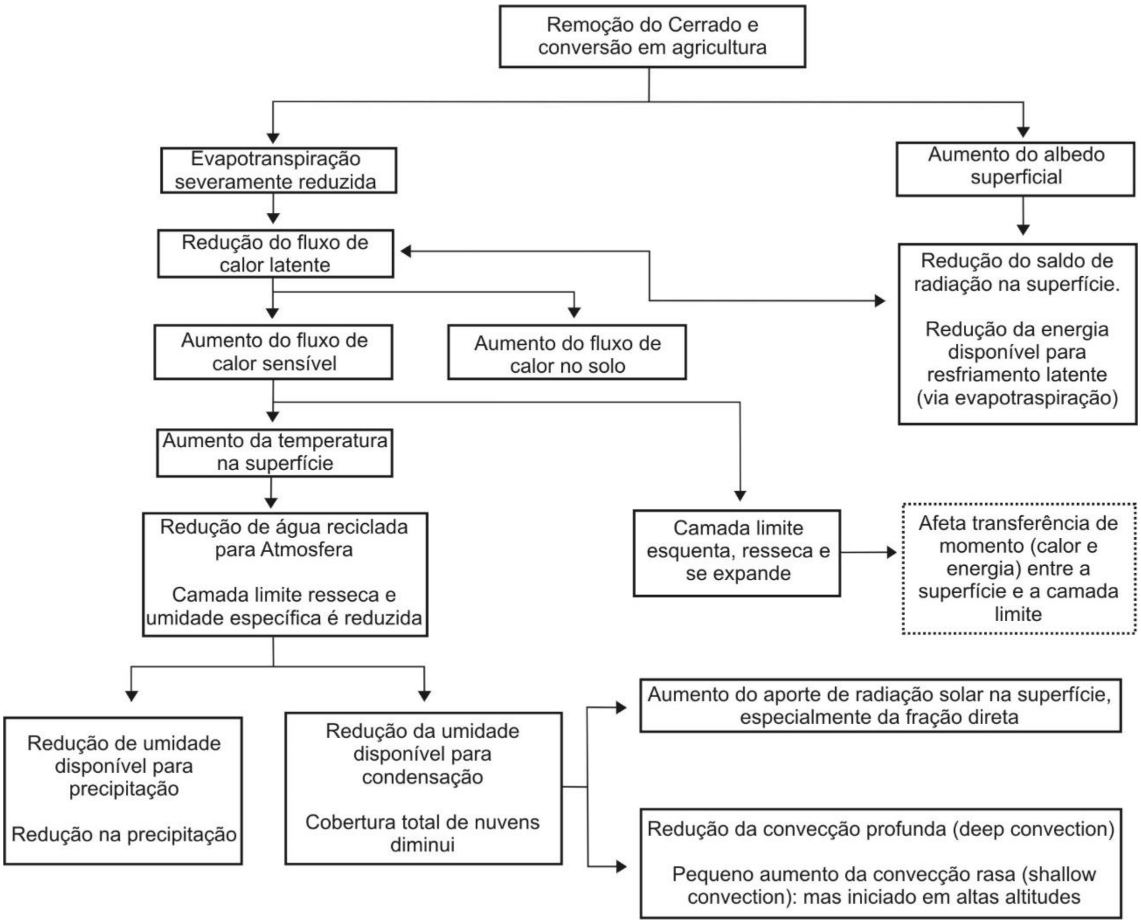

Figura 6. Fluxograma mostrando as principais alterações previstas para os balanços de radiação e energia em um cenário de conversão massiva de cerrado em áreas agrícolas, durante o período de estiagem (junho-outubro), quando os solos das lavouras se encontram expostos ou cobertos apenas pela palha das plantas de cobertura. Adaptado de Snyder et al. (2004).

Em teoria, a supressão massiva de cerrado com posterior conversão em outras formas de uso levaria a um aumento do albedo superficial, aumentando a quantidade de energia refletida pela superfície e provocando assim uma tendência de resfriamento regional (HOFFMANN; JACKSON, 2000; SNYDER; DELIRE; FOLEY, 2004). No entanto, medições mostram que, em um dia de céu claro no Cerrado, a evapotranspiração do cerrado consome cinco vezes mais energia do que o aumento do albedo de uma área agrícola é capaz de refletir (LOARIE *et al.*, 2011). Portanto, a remoção da vegetação parece ser o principal fator que impulsiona as mudanças climáticas no Cerrado brasileiro, afetando diretamente o balanço local de energia pela redução do fluxo de calor latente e aumento dos fluxos de calor sensível e do solo (SNYDER; DELIRE; FOLEY, 2004; COSTA; PIRES, 2010). A partir da queda no fluxo de calor latente, é esperado que todas as principais variáveis meteorológicas sofram forte alteração. Os modelos teóricos que simulam a os efeitos da remoção de savana sugerem um aumento da temperatura anual em torno de 1°C para o Cerrado (HOFFMANN; JACKSON, 2000). Ainda, segundo estes modelos, ao se tornarem mais aquecidas, as camadas de ar junto ao solo tendem a se ressecar, diminuindo a quantidade de água que seria reciclada para atmosfera, tendo assim fortes impactos no ciclo hidrológico (COSTA; PIRES, 2010; SPERA *et al.*, 2016). Nestas condições, a redução da precipitação anual no Cerrado poderia potencialmente atingir entre 150 a 360 mm/ano, o que representaria uma redução próxima a 30% (HOFFMANN; JACKSON, 2000; SNYDER; DELIRE; FOLEY, 2004; COSTA; PIRES, 2010). As reduções ocorreriam em todos os períodos do ano, sendo, provavelmente, mais pronunciadas durante o início do período chuvoso, onde poderiam chegar até 50% do volume (SNYDER; DELIRE; FOLEY, 2004; COSTA; PIRES, 2010). Na medida em que a água é um fator limitante para tanto para produtividade dos ecossistemas quanto para produção agrícola e energética na região do Cerrado, estes cenários teriam impactos socioambientais catastróficos para a Região e para o Brasil.

1.11 OBJETIVO GERAL DA TESE

Esta tese de doutorado tem por objetivo ampliar o conhecimento a respeito das mudanças climáticas que já se encontram em curso no Cerrado brasileiro, a partir da quantificação destas mudanças ao longo das últimas seis décadas e da identificação/quantificação do papel desempenhado pelas áreas agrícolas e de pastagens no aquecimento local/regional, redução da umidade e redução de chuva. Desta forma, os esforços foram concentrados na avaliação das mudanças que já estão causando problemas socioambientais no Cerrado, ao invés de se estabelecer modelos de projeções futuras com base em cenários hipotéticos. Por fim, se pretende demonstrar o possível impacto destas mudanças para a biodiversidade do Cerrado.

1.12 JUSTIFICATIVA

O Cerrado brasileiro possui grande importância ambiental para o Brasil e também para a conservação da biodiversidade na Terra, estando seriamente ameaçado tanto pela ampla redução de áreas naturais para expansão agropecuária quanto pelas mudanças climáticas decorrentes deste processo. Na medida em que oito das 12 principais bacias hidrográficas brasileiras nascem no Cerrado, estas mudanças climáticas também põem em risco o futuro abastecimento de água de grande parte da população, além de ameaçar a produção de alimentos e de energia hidrelétrica em nosso país. Embora estas mudanças climáticas já estejam em curso, suas causas e seus potenciais efeitos ainda não foram completamente compreendidos e quantificados. Portanto, as elucidações da extensão, da magnitude e de todos os mecanismos envolvidos neste processo representam passos fundamentais para a formulação de políticas públicas visando à mitigação das mudanças climáticas e redução dos problemas socioambientais delas decorrentes.

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CAPITULO 2: THE BRAZILIAN CERRADO IS BECOMING HOTTER AND DRIER

Este artigo foi publicado em maio de 2021 na revista Global Change Biology (DOI: 10.1111/gcb.15712). Portanto, o estilo e formatação seguem as normas da revista.

Vereda com alta densidade buritis (*Mauritia flexuosa*) na Reserva Particular do Patrimônio Natural Porto Cajueiro, em Januária, norte de Minas Gerais, Foto: Flávio K. Ubaid

Para quem percorre as enormes extensões recobertas pelo cerrado, o aparecimento de um grupo de buritis constitui como que a visão de um oásis, pelo contraste com a paisagem circundante, contraste esse ainda mais acentuado pelo fato de que acharem os buritis rodeados por um denso tapete verde de gramíneas.

Dora Amarante Roriz

Trecho extraído do livro Aspectos da vegetação do Brasil

THE BRAZILIAN CERRADO IS BECOMING HOTTER AND DRIER

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ABSTRACT

The Brazilian Cerrado is a global biodiversity hotspot with notoriously high rates of native vegetation suppression and wildfires over the past three decades. As a result, climate change can already be detected at both local and regional scales. In this study, we used three different approaches based on independent datasets to investigate possible changes in the daytime and nighttime temperature and air humidity between the peak of the dry season and the beginning of the rainy season in the Brazilian Cerrado. Additionally, we evaluated the tendency of dew point depression, considering it as a proxy to assess impacts on biodiversity. Monthly increases of 2.2−4.0 °C in the maximum temperatures and 2.4−2.8 °C in the minimum temperatures between 1961 and 2019 were recorded, supported by all analyzed datasets which included direct observations, remote sensing, and modeling data. The warming raised the vapor pressure deficit, and although we recorded an upward trend in absolute humidity, relative humidity has reduced by ~15%. If these tendencies are maintained, gradual air warming will make nightly cooling insufficient to reach the dew point in the early hours of the night. Therefore, it will progressively reduce both the amount and duration of nocturnal dewfall, which is the main source of water for numerous plants and animal species of the Brazilian Cerrado during the dry season. Through several examples, we hypothesize that these climate changes can have a high impact on biodiversity and potentially cause ecosystems to collapse. We emphasize that the effects of temperature and humidity on Cerrado ecosystems cannot be neglected and should be further explored from a land use perspective.

Keywords: absolute humidity, climate change, dew, dew point, ecosystem collapse, global biodiversity hotspots, MODIS, Reanalysis II, savanna, temperature

2.1 INTRODUCTION

Climate change represents one of the greatest challenges in recent human history, due to its wide range of socio-economic and environmental impacts (Pecl et al., 2017; Tol, 2009; Wheeler & von Braun, 2013). In 2018, the Special Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that the change in global mean surface temperature is likely to reach 1.5°C above pre-industrial levels between 2030 and 2052 (IPCC, 2018). These changes are mainly attributed to anthropogenic emissions of greenhouse gases, particularly carbon dioxide (CO2), whose concentration increased from 280 ppm during the pre-industrial period to 400 ppm in the first half of the 2010s (NOAA, National Oceanic and Atmospheric Administration, 2019; Ramanathan et al., 2001). Greenhouse gases act as a positive radiative forcing within the Earth's climate system due to the absorption of infrared radiation, which traps thermal energy and re-radiates heat back to the Earth's surface (Farmer & Cook, 2013). Therefore, the nocturnal warming is one of the most noticeable effects of climate change and has been registered worldwide (Vincent et al., 2005; Vose et al., 2005; Zhai et al., 1999; Zhang et al., 2000). However, the influence of human actions on the Earth's climate system is not restricted to the emission of greenhouse gases into the atmosphere. The conversion of natural landscapes to large-scale permanent croplands or pastures alters the regional climate through its effects on energy and water balances (Foley et al., 2005). These processes are linked to complex soil–vegetation–atmosphere interactions and can attenuate or amplify anthropogenic climate change (Alter et al., 2018; Bonan, 2008). Thus, climatic changes caused by massive suppression of native vegetation can vary among biomes.

Over the past few decades, tropical savannas worldwide have been among the most affected biomes due to the suppression of native vegetation. Tropical savannas are typically located between the equatorial rainforests and subtropical semiarid regions, and coincide with the Aw climate type (tropical with dry winter), according to the Köppen classification (Woodward, 2009). Aw is the second most representative climatic type on Earth (covering 11.5% of continental areas), being characterized by high temperatures throughout the year, with wet and dry seasons occurring in summer and in winter, respectively (Peel et al., 2007). The dry season and the deficiency of phosphorus and other nutrient minerals in the very old soils do not favor forest development, giving rise to landscapes consisting mainly of grasslands with sparse or isolated trees (Walter &

Breckle,1986). Fire and other anthropic activities also play an important role both in the structure and composition of the vegetation in savannas (Graeff, 2015b; Walter & Breckle, 1986). In addition to their intrinsic importance in terms of biodiversity, tropical savannas are also essential in the Earth's climate system, accounting for 21% of global evapotranspiration (Miralles et al., 2011). Therefore, environmental changes resulting from human activities in these ecosystems pose threats to both biodiversity and climate.

Historically, the main environmental impacts on savannas are directly or indirectly associated with food production, such as beef cattle production in northern Australia and South America and mixed grazing and permanent cultivation in Africa (Hoffmann & Jackson, 2000). Additionally, tree felling for firewood and charcoal production is a common practice in all savannas around the world (Hoffmann & Jackson, 2000; Oliveira et al., 2005). Furthermore, in recent decades, agricultural production has severely impacted savannas, particularly in South America, where soybean cultivation has become widespread in the Brazilian Cerrado and in the Gran Chaco (an ecoregion formed by parts of the territories of Paraguay, Bolivia, and Argentina; Fehlenberg et al., 2017; Ratter et al., 1997).

The Brazilian Cerrado (also called Neotropical Savanna) is a global biodiversity hotspot that has already lost 46% of its native vegetation cover (Figure 1; Strassburg et al., 2017). Recent studies indicate a conversion rate of 5000 km^2 $year^{-1}$, mainly of grassland and woodland in flat and smooth relief, which have been converted to croplands (Ferreira et al., 2016). However, agricultural production in the region is not performed throughout the year due to the pronounced water deficit between June and September, when the soil is exposed, or covered by summer crop residues (Neto et al., 2010). Except in areas with center-pivot irrigation, most of the cropland areas remain under a fallow system, with large expanses without green vegetation cover throughout the dry season (Figure 1c; Figure S1). In this scenario, theoretical simulations evaluating the climatic effects of savanna suppression have predicted an increase in annual albedo and a consequent reduction of the net radiation incident on the surface (Hoffmann & Jackson, 2000; Snyder et al., 2004). In contrast, they also indicate a latent heat flux decline accompanied by an increase in sensible heat flux, leading to an increase in air temperature and a large reduction in near-surface humidity and precipitation. Indeed, empirical studies conducted in small portions of the Brazilian Cerrado have corroborated the climate projections made by theoretical simulations due to land cover changes (Loarie et al., 2011; Oliveira et al., 2005; Spera et al., 2016).

A second anthropic factor affecting the climate system in the Brazilian Cerrado is the high concentration of aerosol particles in the atmosphere caused by biomass burning in wildfires. Burning is an ancient and widespread practice throughout the Brazilian Cerrado and is used by both traditional communities and ranchers (Eloy et al., 2018; Mistry, 1998). Additionally, fire is used to remove crop residues from some commercial cultures, such as sugarcane (Pivello, 2011; Ratter et al., 1997). In total, more than 68,000 fires are annually detected by satellites throughout the Brazilian Cerrado, of which over 80% occur between July and October (INPE, 2020). Aerosols and particulates from wildfires during the dry season have an average atmospheric residence time of 1 week and, eventually, form a thick smoke layer over large extents of the North and Midwest regions of Brazil (Freitas et al., 2005). The smoke particles from biomass burning can change the local and regional energy budgets through scattering and absorption of solar radiation and, therefore, lead to atmospheric heating and surface cooling (Yamasoe et al., 2006). Consequently, there is a tendency to stabilize the atmosphere due to the inhibition of the turbulent fluxes near the ground (Jacobson, 2002; Liu, 2005). Therefore, given the extent of the Brazilian Cerrado which is already suppressed, and the high concentration of aerosols from wildfires, it is likely that climate change can be detected at both local and regional scales in the biome.

In this study, we used three different approaches based on independent datasets to investigate possible changes in the daytime and nighttime temperatures and air humidity between the peak of the dry season and the beginning of the wet season in the Brazilian Cerrado (July–October). Additionally, as dew can be the only liquid water source for sessile organisms and species with low vagility during the dry season, we also evaluated the trend of dew point depression, considering it as a proxy to access possible impacts on biodiversity (see details in the Discussion Section). To quantify the magnitude of climate change, we used the climate dataset with the longest available time series (1961–2019). This series spans the period prior to the expansion of agribusiness in the Cerrado, extending to the present. Finally, we projected climate trends for the next 31 years, which permits direct comparison with projections by Strassburg et al. (2017) who suggested that 31%–34% of the remaining Cerrado is likely to be cleared by 2050.

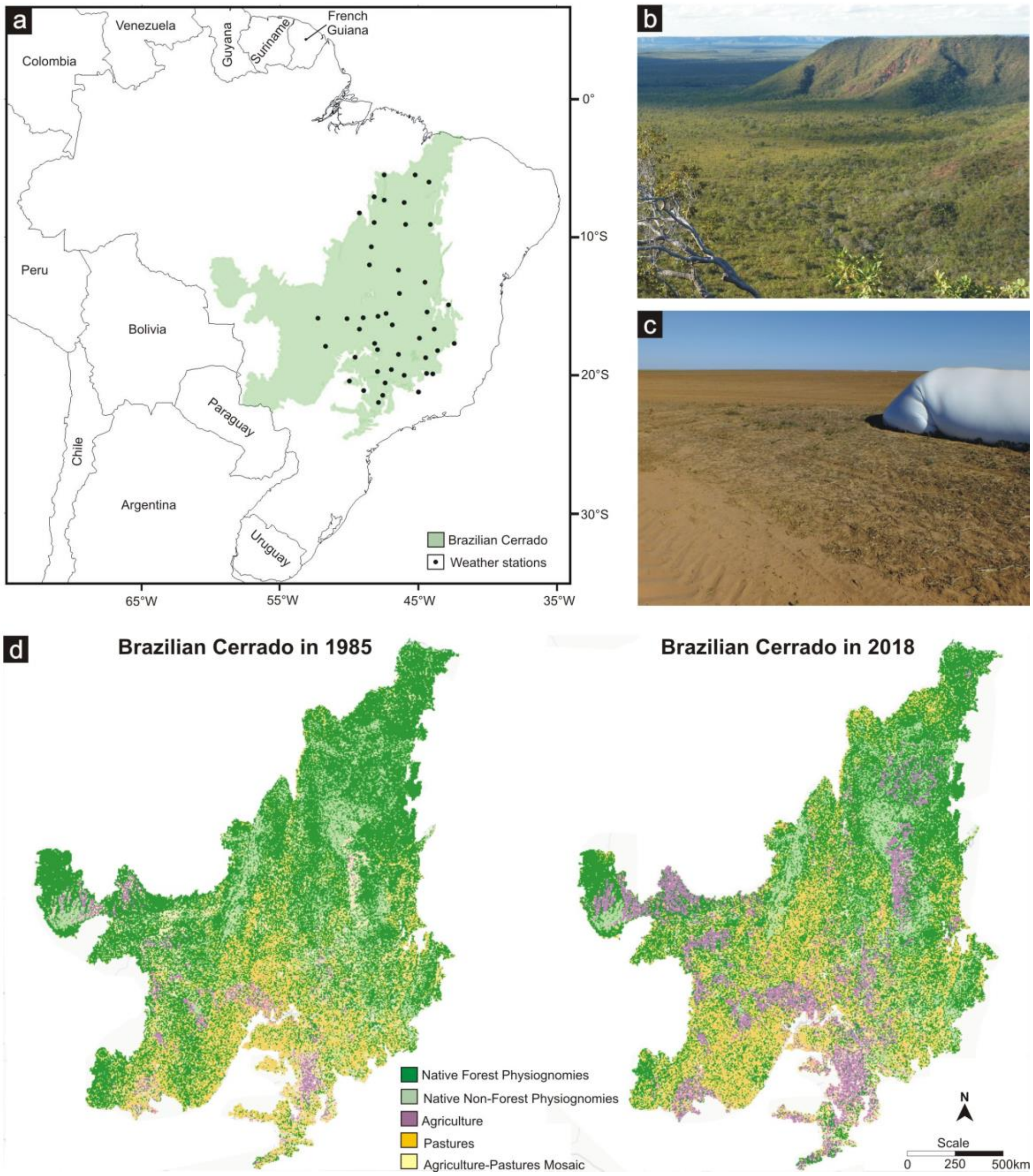

Figure 1: Location of the Brazilian Cerrado and its land use/land cover changes in recent decades. (a) Official limits of the Brazilian Cerrado ecoregion (green) and location of the weather stations used in this study (black dots). (b) Intact Cerrado area with Borá peak, a sandstone hill near Mambaí municipality, in the state of Goiás. (c) Extensive cropland area (in fallow stage) and a bag silo for harvest storage in the west of the State of Bahia. (d) Land use/land cover maps of the Brazilian Cerrado in the years of 1985 and 2018 (data source: MapBiomas—Collection 4.1 of Brazilian Land Use Land Cover Map Series, accessed on 28/12/2019 through the link: http://mapbi omas.org/).

2.2 METHODS

2.2.1 Study Area

The Cerrado is an ecoregion that extends over 2 million km² (i.e., equivalent to the area of Mexico), from the equatorial region to 25°S at its southern limit (in the state of Paraná), and occurring in 10 of the 26 Brazilian states (Figure 1). The altitudinal gradient varies from sea level to 1800 m (Ratter et al., 1997). Based on the Köppen climate classification, the Aw type predominates in the region, except at higher altitudes, with Cwa (subtropical with dry winter and hot summer) and Cwb (subtropical with dry winter and temperate summer), and Am (tropical with monsoon) in the transition zones to the Amazon Rainforest biome (Alvares et al., 2014). The Cerrado vegetation is a mosaic of different phytophysiognomies (Figure S1), in a gradient of grasslands (*campos rupestres* and *campos sujos*), savannas (*cerrado stricto sensu* and *veredas*), and forest formations (*cerradão*, riparian forests, and dry forests; Graeff, 2015a). All these vegetation formations are closely related to edaphic characteristics, although they are also strongly influenced by other factors such as fire (including natural fire) and cattle grazing (Graeff, 2015a; Walter & Breckle, 1986).

The Brazilian Cerrado is under a process of land cover and land use change which remounts to more than a half-century and can be split into three main phases. Until the 1960s, the native vegetation suppression was restricted to small plots, especially by the logging of trees for coal production and the use of fire for the creation of pasture areas for livestock (Ratter et al., 1997). Between the 1960s and the 1980s, the process was enhanced by the growth of the new capital Brasilia and by concessions of Brazilian Military Dictatorship to private companies to implement new agricultural projects on the western Brazilian border (Ratter et al., 1997; Silva, 2010). Finally, from the 1990s, native vegetation loss has intensified due to the expansion of soybean plantations over new agricultural frontiers in the states of Maranhão, Tocantins, Piauí, and Bahia (Lahsen et al., 2016; Spera et al., 2016).

2.2.2 Local and regional climate changes and projections for 2050

First, we analyzed the trend of four climatic variables: maximum and minimum temperature, absolute humidity, and dew point depression (considered a proxy for dewfall) during the 4 months of the dry season. In this step, our analyses were restricted to data recorded by conventional weather stations (i.e., those in which records are taken by a meteorological observer) because the first automatic weather stations in Brazil were only installed from 2000 onward. We accessed the historical database of the Brazilian National Meteorology Institute (Instituto Nacional de Meteorologia—INMET) from its website at https://tempo.inmet.gov.br/TabelaEstacoes. Climate records of all conventional weather stations in the Brazilian Cerrado biome (1961–2019) were compiled. No weather station with more than 30% of missing values for a given variable was considered for the models shown in Tables S1 and S2. However, in case a weather station contained a good dataset for one or more variables but also many missing values for others, we used all the suitable variables and discarded only the problematic ones (i.e., the NA cases in Tables S1 and S2). A total of 45 weather stations remained suitable for our analysis and their spatial distribution is shown in Figure1 (note that at the western boundary of the Cerrado, no weather station was selected). From Brazilian conventional weather stations, data on the main meteorological variables are available for 00, 12, and 18 h Coordinated Universal Time (UTC), and also the daily maximum and minimum records. Therefore, the only nocturnal meteorological record to evaluate a possible increase in dew point depression was at 00 h UTC (09 PM local time).

Daily values of absolute humidity and dew point depression (at 00 h UTC) used in our models were obtained from the following equations:

$$es_u = 4.58 * 10^{\frac{(7.5 * Tu)}{(287.5 + Tu)}}$$

where, es_u is the saturation pressure for the wet-bulb temperature (as defined by the Tetens equation, here presented in a form adapted to atmospheric pressure in mmHg and exponentiation with base 10), and Tu is the wet-bulb temperature (ºC).

$$e = es_u - (A * P * (T - Tu))$$

where, e is the vapor pressure (mmHg) (according to Dalton's law), A is the psychrometer coefficient (i.e., $0.0008°C^{-1}$), P is the atmospheric pressure (mmHg), and T and Tu are the temperatures of the dry-bulb and wet-bulb (°C), respectively.

$$AH = 289 * \left(\frac{e}{T + 273.16}\right)$$

where, AH is the absolute humidity (g/m^3), e is the vapor pressure (mmHg), and T is the temperature of dry-bulb (°C).

$$Tdp = 237.5 * 10^{\frac{\left(\frac{e}{4.58}\right)}{\left(7.5 - 10^{\left(\frac{e}{4.58}\right)}\right)}}$$

where, *Tdp* is the dew point temperature (°C), and *e* is the vapor pressure (mm Hg).

$$Dpd = T - Tdp$$

where, *Dpd* is the dew point depression (°C), *Tdp* is the dew point temperature (°C), and T is the temperature of the dry-bulb (°C).

Then, we calculated the monthly values of the four variables from the arithmetic mean of the daily values used for two purposes. First, we used the arithmetic mean of monthly values of all 45 weather stations to obtain measures of the four variables that were representative of the entire Cerrado ecoregion (hereinafter referred to as entire Cerrado). For this calculation, we chose not to use the estimated data. Therefore, stations lacking data in a specific month were not considered when computing the monthly average for that year. Thus, the monthly values of the entire Cerrado (used in the 16 forecasts from linear regression models shown in Figure 2) were formed only by measured values, so some years did not include data from some weather stations. To evaluate regional climate changes, the forecasts from linear regression time series models were used because of the easy interpretation of trends and because this method also enables data projection for future prediction intervals (for details about this method, see Hyndman & Athanasopoulos, 2018).

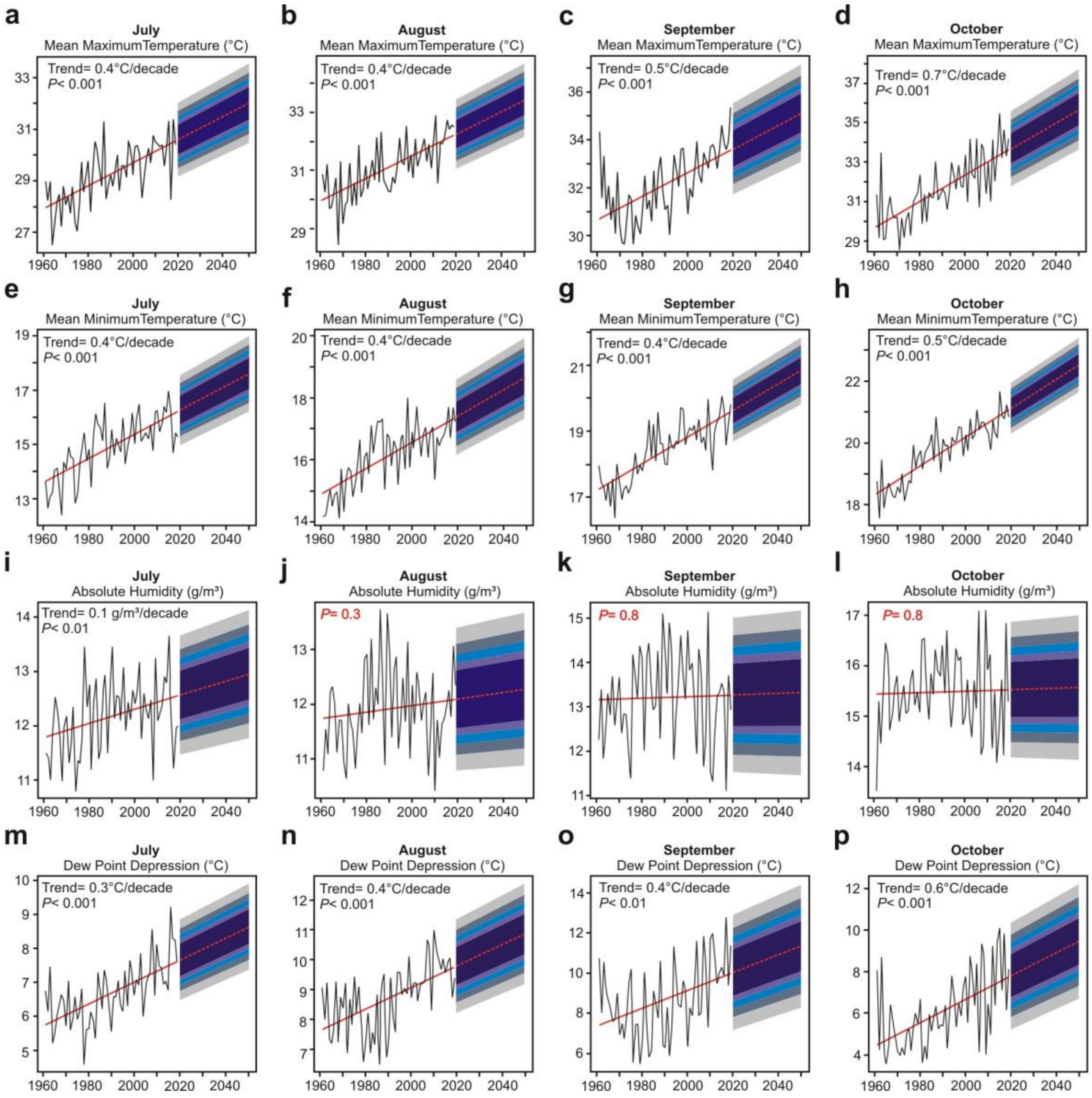

Figure 2. Linear regression models between 1961 and 2019 and forecasts until the year 2050 for the entire Cerrado. (a–d) Models considering the mean maximum temperature as the dependent variable for the months of July, August, September, and October, respectively. (e–h) Models considering the mean minimum temperature as the dependent variable. (i–l) Models considering the absolute humidity (estimated at 00 h UTC) as the dependent variable. (m–p) Models considering the dew point depression (estimated at 00 h UTC) as the dependent variable. In all linear models, the time (1961–2019) was considered the independent variable. The black solid lines describe the annual mean of four variables. The red solid lines represent the best-fitting line of each model between 1961 and 2019. The red dashed lines describe projected values until 2050, and the 50%, 60%, 70%, 80%, 90% prediction intervals are represented by the dark-blue to light-gray bands, respectively. UTC, Coordinated Universal Time.

Second, to assess the heterogeneity of regional climate change, we also ran a total of 16 forecasts from linear regression models for each weather station (see Table S1). However, contrary to the data of the entire Cerrado, for the models of each weather station, it was necessary to fill the missing values for all months in which the records were not available in the INMET database. Thus, using the entire dataset available, we calculated the monthly deviations of each weather station in relation to the regional mean (entire Cerrado values) for all four variables. The missing values were filled by the difference between the regional mean for that month (the entire Cerrado value) and the weather station monthly deviation value. All linear models were performed using the fpp package for R (Hyndman & Athanasopoulos, 2018).

2.2.3 Evaluation of the consistency of the entire Cerrado analysis using MODIS data

In the second step, we evaluated the consistency of the means calculated for the entire Cerrado analysis based on data from remote sensing. Given that most of the weather stations were initially installed in rural areas but eventually became closer to or have been engulfed by towns or villages due to urban expansion, we aimed to evaluate whether the land use and land cover changes around the weather stations could have influenced the measurements, for example, through urban heat-island effects (Gallo et al., 1996; Sati & Mohan, 2018). For that, we compared the monthly values of minimum and maximum temperatures with data detected with the Moderate Resolution Imaging Spectroradiometer (MODIS).

Moderate Resolution Imaging Spectroradiometer land surface temperature data were obtained from the MOD11A2 version 6 product (Wan et al., 2015), provided by the Land Processes Distributed Active Archive Center, managed by the NASA Earth Science Data and Information System project (https://lpdaac.usgs.gov). This product is based on MODIS imagery, onboard Terra (data collected between 00 and 03 h UTC), and Aqua (data collected between 15 and 18 h UTC) platforms, providing an average 8-day land surface temperature globally at 1 km spatial resolution.

From the entire series, we selected the months of July to October, from 2000 to 2019, filtered by a high-quality control flag, covering the official limits of Brazilian Cerrado as defined by the Brazilian Institute for Geography and Statistics (Instituto Brasileiro de Geografia e Estatística). The land surface temperature values (originally supplied in Kelvin) were converted to Celsius for comparison with weather station data. Using all the available records, we generated a monthly value of land surface temperature for all years of the MODIS data collection (2000–2019 for MODIS/Terra and 2002–2019 for MODIS/Aqua) through the arithmetic mean values of all pixels included in the Cerrado area. Then, the monthly values of land surface temperature from MODIS data were compared to the entire Cerrado mean temperatures recorded by weather stations using Pearson's correlation test. Additionally, we examined the homogeneity of the regression slopes of the two datasets through ANCOVA. Both correlations and ANCOVA tests were performed using PAST.4.03.

2.2.4 Evaluation of large-scale regional trends with the NCEP/DOE Reanalysis II dataset

Third, we evaluated large-scale regional trends in surface temperature and relative humidity, based on the National Center for Atmospheric Research/Department of Energy (NCEP/DOE) Reanalysis II dataset (Kanamitsu et al., 2002). The product reports global data 4-times daily (00 h to 18 h UTC) at 2.5° lat/lon spatial resolution, and it is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website (https://www.esrl.noaa.gov/psd/). The NCEP Reanalysis II is based on an analysis/forecast system to perform data assimilation by combining observations from satellites and conventional ground-based stations. Data were selected covering all of Brazil territory from July to October, at 06 h UTC and 18 h UTC, starting in 1990, when agricultural processes currently observed in the region started to intensify (Lahsen et al., 2016). We analyzed the large-scale regional trends comparing the surface temperature and relative humidity averages for the years 2014–2019 and 1990–1995, at both nighttime and daytime periods.

2.3 RESULTS

Our regression models for the entire Cerrado show maximum temperatures increase, predominantly in October (Figure 2a–d). In this month, the mean maximum temperature increased by 4.0°C between 1961 and 2019 and, if this tendency persists, the temperature will be 6.0°C higher in 2050 than in 1961 (Table 1). The same pattern was also observed in most weather stations, with some localities showing trend values higher than 1°C per decade (Table S1). Minimum temperature values also showed an increasing tendency for both the entire Cerrado and most of the localities (Figure 2e–h), with forecasts for 2050 displaying less uncertainty than the projections for the other variables analyzed (as shown by relatively narrower ranges of 50%, 60%, 70%, 80%, and 90% prediction intervals). For absolute humidity, the trends for entire Cerrado considering a linear fit displayed a slight (and less conclusive) increase in most cases (Figure 2j–l, $p \geq 0.3$), except for July (Figure 2i, $p < 0.01$). Considering the values from 1990, the tendency of absolute humidity records indicates a decline, and suggest an inverted U-shaped pattern (more clearly evidenced in September; Figure 2k). The analysis for dew point depression (Figure 2m–p) showed a pattern similar to that of the maximum temperature, increasing with the succession of the dry months.

Table 1. Regional climate changes and projections for 2050 in the Brazilian Cerrado. Results of linear regressions between 1961 and 2019 and forecasts until the year 2050 for entire Cerrado, where the variables trend values were calculated by multiplying between slope β and the number of years in each period (i.e., 59 years for 1961–2019 and 90 years for 1961–2050). NA (not available) indicates models whose results were not statistically significant (p > 0.05).

Month	Maximum Temperature (°C)		Minimum Temperature (°C)		Absolute Humidity (g/m³)		Dew Point Depression (°C)	
	1961-2019	2050 forecast	1961-2019	2050 forecast	1961-2019	2050 forecast	1961-2019	2050 forecast
July	2.6	4.0	2.6	4.0	0.8	1.2	1.9	2.9
August	2.2	3.4	2.5	3.8	NA	NA	2.1	3.2
September	2.9	4.4	2.4	3.6	NA	NA	2.6	4.0
October	4.0	6.0	2.8	4.2	NA	NA	3.3	5.0

The comparisons between monthly values of land surface temperature from MODIS and maximum and minimum temperatures recorded by weather stations for the entire Cerrado are displayed in Figure 3. Pearson's correlation coefficients between the monthly values of MODIS and the entire Cerrado ranged from 0.47 to 0.89, and were significant ($p < 0.05$) for all cases analyzed. As shown, the trend values are positive in all cases and, for each month, changes in daytime temperature were always higher than nighttime changes. All ANCOVA tests were not significant ($p > 0.05$); therefore, there was no difference between the slopes of MODIS and those of the entire Cerrado.

Based on the information from the NCEP/DOE Reanalysis II, the average surface temperatures in the months from July to October were higher for 2014–2019 than for 1990–1995, during both nighttime and daytime periods (Figure 4a,b, respectively). In this dataset, the increase in temperature was the highest in the afternoon. The difference between the earlier and later years was approximately 1–2.5°C for the daytime period (18 h UTC) and 0.5–1°C for the nighttime period (06 h UTC) in most of the Cerrado. In parallel, relative humidity showed a downward tendency for most of the biome, between 1990–1995 and 2014–2019 decreasing by ~15% for both 06 and 18 h UTC (Figure 4c,d).

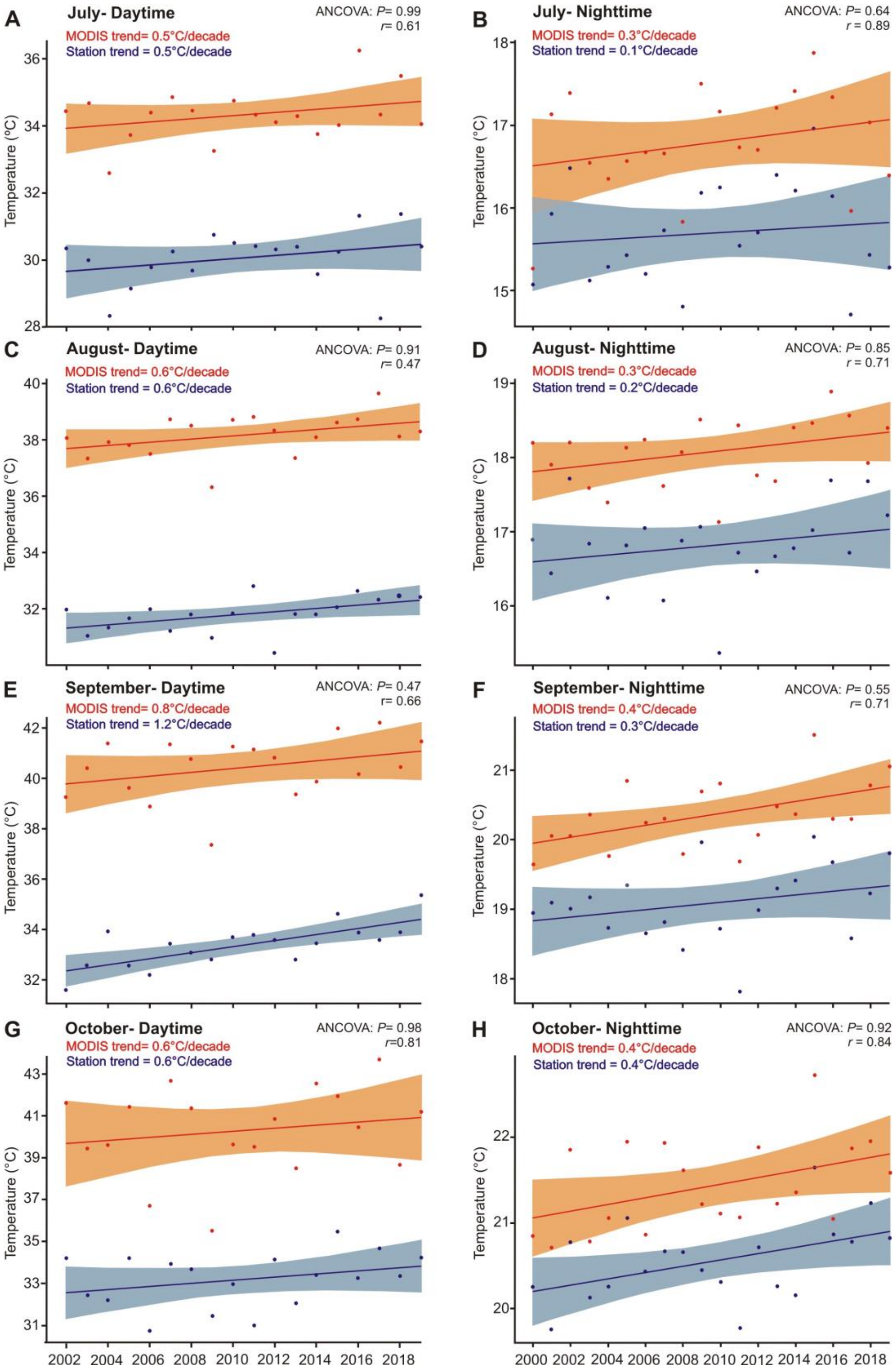

Figure 3. Comparison between the temperatures calculated for the entire Cerrado (weather stations data) and land surface temperatures for all pixels of Cerrado recorded by satellites Aqua and Terra (MODIS data) for the same period. (a, c, e, and g). Comparison between mean maximum temperatures for the entire Cerrado (blue dots) and land surface temperature product of MODIS/Aqua satellite between 15 and 18 h UTC (red dots) for the months of July, August, September, and October, respectively. (b, d, f, and h). Comparison between mean minimum temperatures for the entire Cerrado (blue dots) and land surface temperature product of

MODIS/Terra satellite between 00 and 03 h UTC (red dots). In all linear models, the time was considered the independent variable (2000–2019 for minimum temperature and MODIS/Terra comparison, and 2002–2019 for minimum temperature and MODIS/Aqua comparison). Solid lines represent the best-fitting line of each model (red lines for satellite data and blue lines for entire Cerrado means) and trend values are showed at each graph (red values for satellite data and blue values for entire Cerrado means). Red and blue bands represent the 95% prediction intervals for satellite and entire Cerrado models, respectively. The Pearson correlation coefficient between both datasets and the ANCOVA results is shown at the top of each graph. UTC, Coordinated Universal Time.

2.4 DISCUSSION

Here, we present analyses of atmospheric conditions near the surface for the past decades in the Brazilian Cerrado, including data from weather stations, remote sensing, and modeling. When compared to past decades, hotter and dryer conditions have been verified in the study region, both locally and at a regional scale. This overall pattern in the results is supported by all analyzed datasets, which include direct observations from ground station reporting data from approximately 60 years ago. As presented, weather stations showed increases in maximum and minimum temperatures, increases in dew point depression, and decreases in absolute humidity in recent years (except for the July month). There was an important agreement between the ground measurements and remote sensing data revealing a rise in temperature for the entire series of MODIS data. In addition, broad-scale information from NCEP-DOE Reanalysis II was in agreement with these datasets, showing substantially higher temperatures and lower relative humidity near the ground in recent years (2014–2019 compared to 1990–1995) in the study region. These results also corroborated the heterogeneity observed in trends of weather stations, showing variation in changes within the Brazilian Cerrado, where the eastern and central sectors seem to have become warmer and drier than the western one. However, even though this difference may be real, it must be interpreted with caution due to the reduced number of stations in the latter.

In addition to the consistency between the analyzed data, the results we present are also in agreement with those of other studies. First, they are consistent with the observed global warming, which is linked to the increasing concentration of atmospheric greenhouse gases (IPCC, 2018). Second, they corroborate the results of other studies that simulate land use changes in savannas. For instance, the pronounced increase in temperatures during the dry season is consistent with the forecasts from all three theoretical studies that simulated climate change due to savanna removal (Bounoua et al., 2002; Hoffmann & Jackson, 2000; Snyder et al., 2004). However, in terms of intensity, the increase in the maximum and minimum temperatures detected in this study was higher than those projected by previous theoretical studies. Our temperature trends were also considerably higher than that of the global warming of 0.2°C/decade estimated by the IPCC (IPCC, 2018) and by Vose et al. (2005) for the Southern Hemisphere (i.e., maximum and minimum temperature trends between 0.086–0.126 and 0.125–0.14°C/decade, respectively.

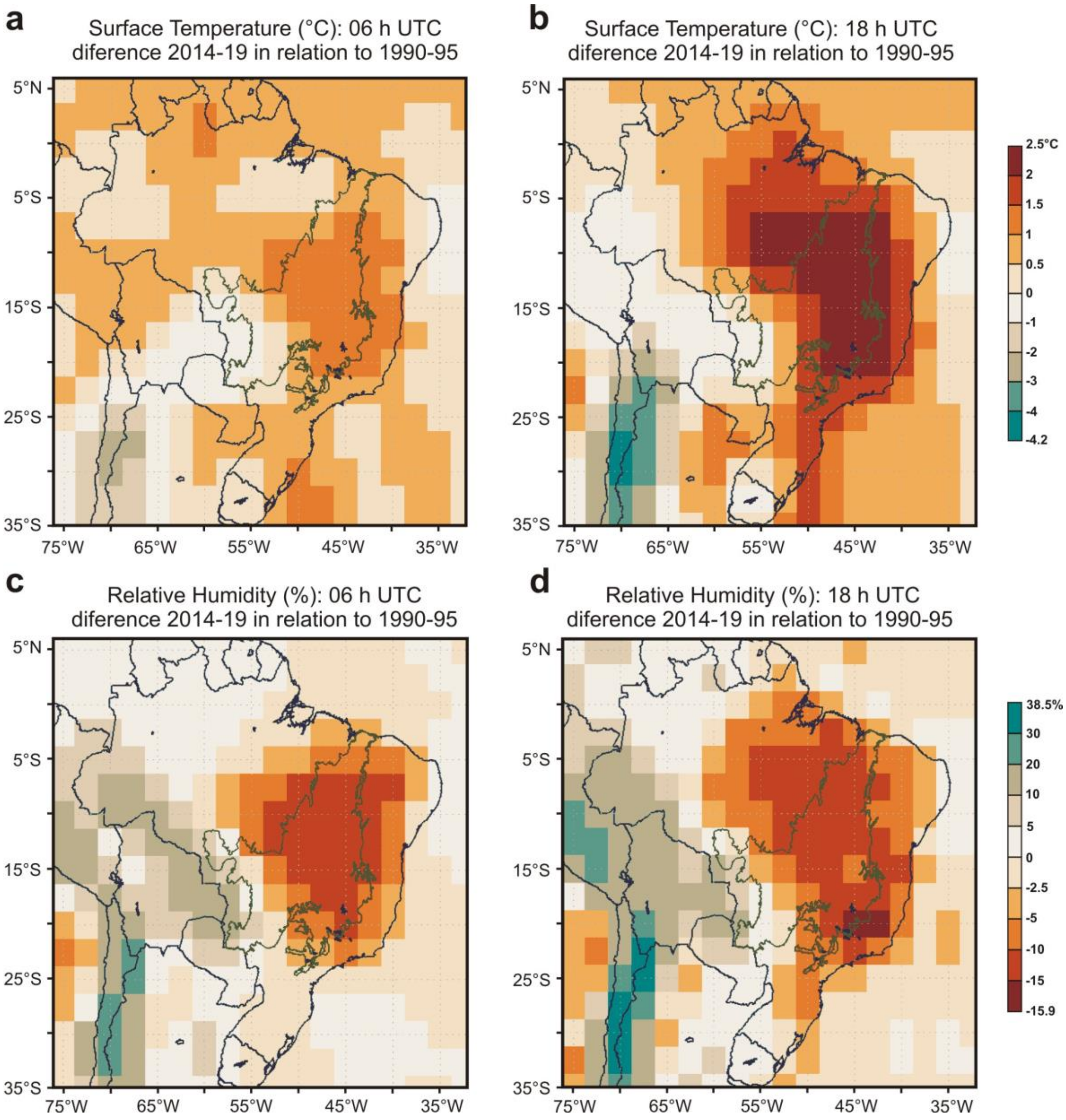

Figure 4. Large-scale regional trends for both daytime and nighttime surface temperature and relative humidity in Brazilian Cerrado between 2014–2019 and 1990–1995. (a, b). Difference in mean surface temperature (°C) between 2014–2019 and 1990–1995 at 06 and 18 h UTC. (c, d). Difference in mean relative humidity (%) between 2014–2019 and 1990–1995 at 06 and 18 h UTC. The green solid line represents the official limits of the Brazilian Cerrado. Analyzes generated from the dataset of National Center for Atmospheric Research/Department of Energy Reanalysis II dataset. UTC, Coordinated Universal Time.

Thus, it may seem that our temperature means of the entire Cerrado could be biased by the effect of urban heat islands. However, the comparison of data from weather stations with that of surface temperatures from MODIS was essential to discard this concern. Hence, we considered two possible reasons to explain the difference between the magnitude of our trends and that of the former studies, associated with land use and land cover changes that occurred in the Brazilian Cerrado since the beginning of the records in the datasets that we analyzed.

First, both IPCC projections and the three theoretical models consulted do not consider the synergy between the global increase in greenhouse gases concentration, land use and land cover changes on the local and regional scales. In fact, diurnal local/regional warming increases the vapor-pressure deficit, inducing higher release of water vapor into the atmosphere through evapotranspiration (e.g., explaining the absolute humidity trends recorded here in the period between the 1960s and 1990s, when the magnitude native vegetation suppression was still lower). Furthermore, the water vapor added to the other greenhouse gases amplifies regional warming. Therefore, the coupling of the two different radiative forcings and their feedback effects may explain the high warming tendencies in the Brazilian Cerrado.

Second, it was assumed complete savanna vegetation conversion into barren soil (Snyder et al., 2004), grasslands (Hoffmann & Jackson, 2000), and crops (Bounoua et al., 2002), is not the current reality in the Cerrado. Specifically, in the scenario described by Snyder et al. (2004), the removal of the Cerrado could increase the regional albedo, resulting in a reduction of net radiation absorbed and, therefore, attenuating the rise in temperature. However, the albedo increase due to savanna vegetation removal seems to be secondary in regional climate change in the Cerrado. A previous study showed that evapotranspiration reduction is the main factor driving the climatic changes associated with the Cerrado destruction because it potentially consumes almost five times as much energy as the albedo increase reflects under clear sky daytime conditions (Loarie et al., 2011). Field experiments show that, because of a deep root system, even during the dry season, part of the Cerrado vegetation maintains evapotranspiration rates between 1.8 and 2.2 mm day^{-1} (i.e., 216–264 mm of water vapor are potentially added to the atmosphere between July and October; Oliveira et al., 2005). Continuous monitoring exposes the impact of the savanna vegetation removal on local climate. In the first year after a 45 km^2 Cerrado vegetation suppression, Oliveira et al. (2014) reported a decrease of 36% (429 mm) in annual evapotranspiration. Therefore, the Cerrado vegetation conversion is expected to significantly alter the local energy balance, with a reduction in latent heat flux and a consequent augmented sensible heat flux, which leads to a strong increase in air temperature.

Although a reduction in evapotranspiration rates is expected due to the widespread removal of original vegetation in recent decades, Oliveira et al. (2014) found diverging annual tendencies between different portions of the Cerrado. An increasing tendency was observed in the western portion, whereas in the south it tended to decrease, and the east and north presented no tendency (associated with higher errors in evapotranspiration estimates). Yet, the western upward tendency is associated with lower portions of the relief and is possibly a consequence of higher evapotranspiration rates during the wet season, both due to larger and longer water availability. This pattern is consistent with the daytime temperature patterns recorded in this study (Figure 4b), where the western portion has a less pronounced heating than the southern, eastern, and northern sectors of the Brazilian Cerrado. Specifically related to the dry season, our results corroborate those of Spera et al. (2016), who detected pronounced evapotranspiration reduction in croplands when compared with native Cerrado vegetation.

Further evidence reinforces the possibility that the shifts in land use and land cover can be the main radiative force driving climate change in the Brazilian Cerrado. For example, the construction of large hydroelectric dams in the Tocantins and Araguaia river basins over the last decades has significantly altered the extent of water bodies in many localities, affecting radiation and energy balance. This is the case of the Carolina municipality located near the Tocantins River, where the weather station recorded one of the steepest trend values of absolute humidity, probably a consequence of the nearby large water body from a dam constructed in the 2000s (Figure S2; Table S2). Similarly, the expansion of other types of anthropic projects may result in local changes, differing from most of our estimates (e.g., conversion of existing crops into sugarcane crops; Loarie et al., 2011).

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municipality located near the Tocantins River, where the weather station recorded one of the steepest trend values of absolute humidity, probably a consequence of the nearby large water body from a dam constructed in the 2000s (Figure S2; Table S2). Similarly, the expansion of other types of anthropic projects may result in local changes, differing from most of our estimates (e.g., conversion of existing crops into sugarcane crops; Loarie et al., 2011). the dry season. As a consequence, evapotranspiration is widely reduced in extensive areas without green vegetation cover, leading to a sharp increase in diurnal temperatures due to the sensible heat flow enlargement at the expense of the latent heat flux reduction. Furthermore, if the main radioactive forcings behind regional climate change were the increase in the concentration of greenhouse gases or smoke from wildfires, nighttime warming should have been more intense than diurnal and with less variation than of local models (Tables S1 and S2). Yet, we emphasize that the smoke from wildfires probably plays a secondary role in the climate changes observed here (mainly on the local scale and in years with a high number of wildfires).

The daytime and nighttime warming in the Cerrado and the related increase in both absolute humidity and dew point depression can be explained by the Tetens equation (Tetens, 1930), which shows that a linear increase in air temperature raises the vapor pressure deficit exponentially. Although there is an upward tendency of absolute humidity (i.e., water vapor addition in the atmosphere), relative humidity was decreased by a larger proportion, therefore, as a paradox, the air became drier (as shown in the relative humidity trends in Figure 4c,d). In other words, the rising temperature allows the local atmosphere to retain more water vapor than evapotranspiration can supply. Thus, the succession of dry months in the Cerrado progressively reduces the amount of water available for evapotranspiration, which could explain the smaller slope of the absolute humidity trend in the models of September and October compared to July and August (Figure 2i–l). However, the reduction in the rise of absolute humidity for all months analyzed is mainly due to the sudden drop from the 1990s (generating an inverted U-shaped pattern). It is likely that decreases in absolute humidity beginning in the 1990s are associated with native vegetation suppression, which has intensified throughout the Cerrado. However, this humidity reduction may be partly a consequence of the abrupt decrease in global evapotranspiration due to the terrestrial moisture-supply limitation that occurred between 1998 and 2008 and mainly affected the Southern Hemisphere, including a region in the middle of South America that overlaps with the Cerrado (Jung et al., 2010).

Whatever the reason, many weather stations have recently displayed negative trends of absolute humidity, which leads us to project an intensification of regional atmospheric dryness for the next decades. Lastly, our results show that the dew point depression in Brazilian Cerrado nights progressively moves away from vapor pressure saturation. The gradual air warming will cause the night cooling to take longer to reach the dew point temperature and, therefore, will progressively reduce both the amount and duration of dewfall in Brazilian Cerrado nights during the dry season.

2.4.1 Implications of rising dew point depression for Cerrado biodiversity

Dew is water vapor condensation on a substrate resulting from radiative deficit between the atmosphere and surfaces (Beysens et al., 2016). Dew formation, normally at night, is favored by windless and clear sky conditions when the temperature of the surface on which condensation occurs reaches the dew point temperature (Agam & Berliner, 2006). Although dewfall represents small amounts of liquid water compared to rainfall, in some regions, it may reach a maximum potential of 0.6 mm (0.6 L/m² or 6000 L/ha) per night (Sharan et al., 2017). In dry environments (or in dry seasons as analyzed), dew can be the only liquid water source for sessile organisms and for species with low vagility, thus having a significant ecological importance for biodiversity. Although dew is historically recognized as a fundamental resource for many organisms, its importance as a water source is still undervalued in biology (Tomaszkiewicz et al., 2015).

While dew can potentially form every night in the Cerrado, rain is a rare event during the winter; therefore, several plants and small animals cannot depend on rain as a stable source of water. For instance, epiphytic plants account for 10% of all vascular plant species (Benzing, 1987) and are highly dependent on dew (Schimper, 1888). The number of vascular epiphyte species in the Cerrado is unknown, but it is known that they are abundant in the vegetation of mountains with rupestrian grasslands (campo rupestre), where they are pulse supplied. Thus, the reduction in dew availability during the dry season could result in the extinction of the most sensitive species. The climatic changes detected can also cause other impacts to plant species. For example, many plant species usually have their pollen viability reduced due to dehydration when exposed to very low air humidity conditions (Corbet, 1990). As many woody species in the Cerrado flowering during September and October (Batalha & Martins, 2004), the period that we recorded the more pronounced regional climate changes, great uncertainty emerges about the maintenance of the reproductive success of these species in the future. In the Cerrado, the climate patterns also drive the establishment and frequency of mutualistic interactions, such as ant–plant–herbivore interactions through the production and secretion of extrafloral nectar by plants during the beginning of the rainy season (Calixto et al., 2021). Therefore, the impacts of regional climate changes on plant species will probably not be restricted to the organism or population levels (e.g., fitness reduction or local extinction), and their effects may extend to the community level through changes in interspecific interactions. So far, few studies have been able to demonstrate these possible impacts. One exception was a recent work that monitored four Malpighiaceae species in the Brazilian Cerrado for 10 years and showed that variations in temperature and precipitation resulted in shifts in the onsets of flowering and increased the degree of plant phenological overlap, which influenced the herbivory and fruit set of species (Vilela et al., 2017).

Dew is also an important direct water source for insects, such as honeybees, which use dew and raindrops more than other sources (Joachimsmeier et al., 2012). The insects, particularly bees, are the main pollinators of woody and herbaceous Cerrado flora (Oliveira & Gibbs, 2002). Therefore, the reduction in dew represents a serious additional threat to both the pollinator assemblage and the pollination process itself (i.e., another potential impact on a community level). Another example of the potential effect of dew reduction in animals can be seen in the Bolivian savanna, where it is suggested as the main cause of the decline and local species extinctions of rodent populations (Emmons, 2009). In this regard, there are few comparative studies or data available on body water conservation and regulation in South American small mammals (Tirado et al., 2008), particularly regarding the Cerrado fauna, which is one of the most diverse regions in South America (Carmignotto et al., 2012). Seasonal and annual variations in urine concentration and renal expression levels of aquaporins in response to environmental changes associated with El Niño events have been detected in rodents in xeric biomes of South America (Bozinovic et al., 2007; Gallardo et al., 2005), but have not been extensively studied in regions with pronounced climatic seasonality, such as the Cerrado.

To conclude, we emphasize that the effects of temperature and humidity on the properties of the Cerrado ecosystems cannot be neglected and should be further explored from a land use perspective. Due to the massive habitat loss and the resulting deep regional climate changes, ecological studies must begin to assess the synergistic effects of both impacts. We believe that the regional climate changes described in this paper will impact directly or indirectly the biodiversity on different ecological levels (i.e., organism, population, and community), eventually resulting in cascade effects and causing ecosystems to collapse. Therefore, our results reinforce the alert issued by Strassburg et al. (2017) and highlight the need for urgent measures to avoid the collapse of the Cerrado hotspot.

2.5 ACKNOWLEDGMENTS

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2.6 DATA AVAILABILITY STATEMENT

The authors are committed to providing any information or data related to this study that may be requested in the future.

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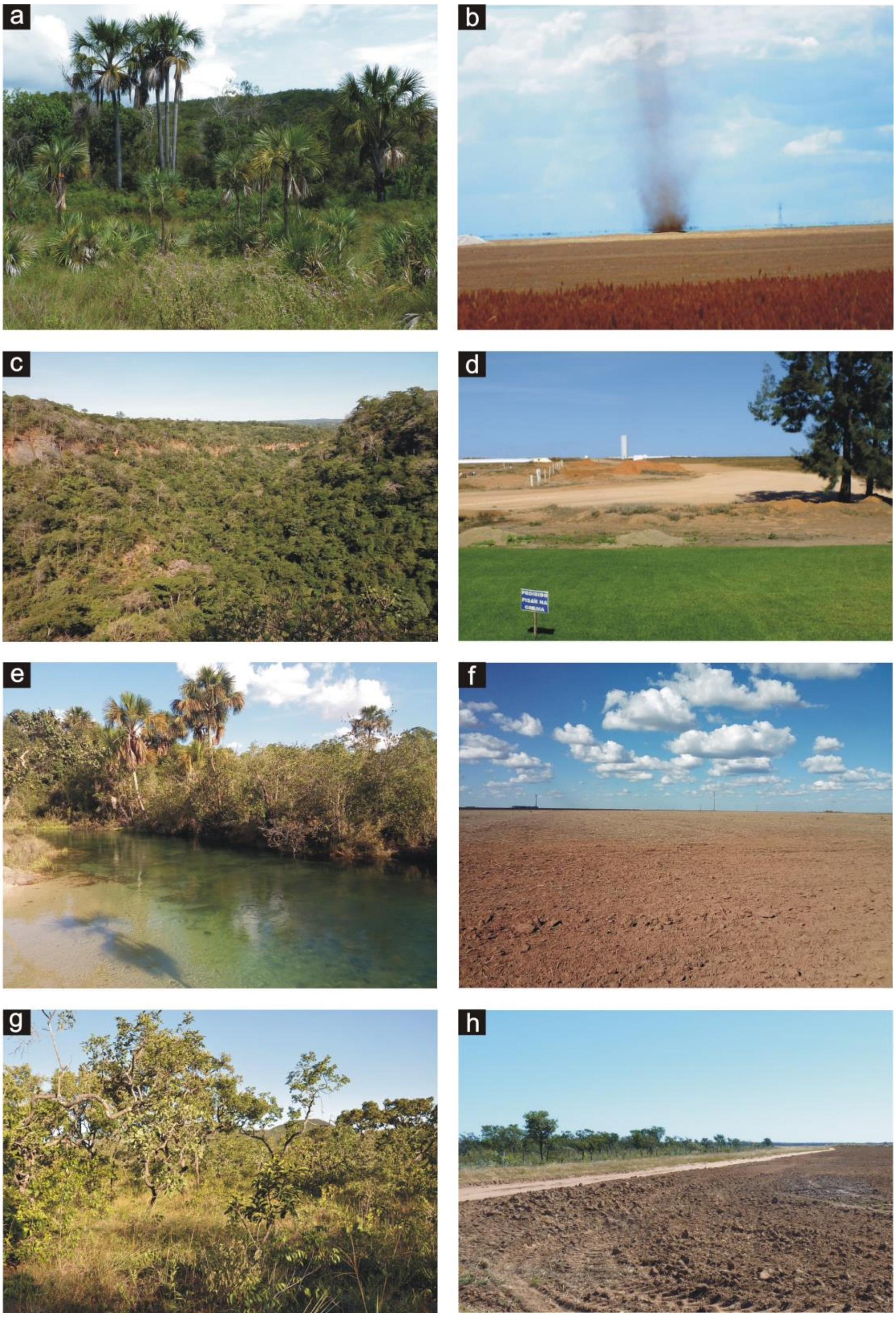
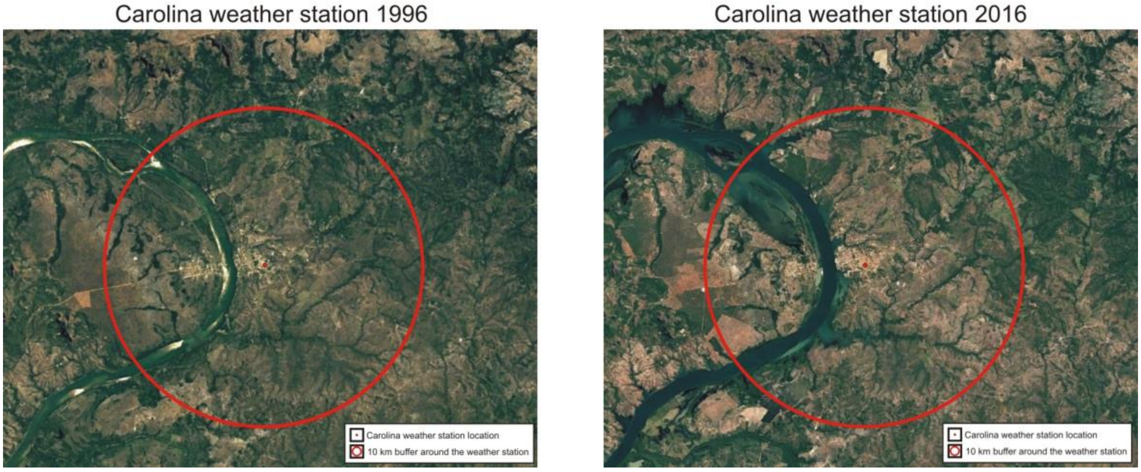
2.8 SUPPLEMENTARY MATERIAL



Supplementary Figure 1. Native Cerrado physiognomies and Cerrado cropland areas. a, *Mauritia flexuosa* palm swamps (*Veredas*) in Goiás state. b, Dust devil recorded in a fallow area, where the soil remains without vegetation cover during dry season. c, Deciduous forest established on limestone outcrops of Bambuí Group in Mambaí, Goiás state. d, Warning plate for the prohibition of stepping on the grass at the entrance of a large rural property on the border between Goiás and Bahia states. e, Riparian vegetation of Pratudão River on Veredas do Oeste Baiano Wildlife Refuge. f, Extensive fallow area on property adjacent to Veredas do Oeste Baiano Wildlife Refuge. g, Area of Cerrado *stricto sensu*, in Goiás state. h, The border of a large rural property and the Grande Sertão Veredas National Park, in Minas Gerais state.



Supplementary Figure 2. Land use/land cover changes around the Carolina weather station (World Meteorological Organization code: 82765) between 1996 and 2016. Local increase in the area covered by water is due to the construction of a dam in the Tocantins River for electricity generation. Red dots represent the Carolina weather station locations and red circles show a 10 km buffer around the weather station.

Supplementary Tables 1 and 2. Local climate changes in the Brazilian Cerrado. Results of linear regressions between 1961 to 2019 and forecasts until the year 2050 for all 45 weather stations, where the proxies trend values were calculated by multiplying the slope β by the number of years in each period (i.e., 59 years for 1961–2019 and 31 years for 2020–2050). Asterisks above the trend values indicate significant models (P <0.05). NA indicates cases where the dataset was not available.

Local	WMO Code	Altitude (m)	Latitude	Longitude	Max. Temperature (°C)				Min. Temperature (°C)			
					Jul	Aug	Sep	Oct	Jul	Aug	Sep	Oct
Brasília	83377	1161	-15.76	-47.93	0.1	0.1	0.2	0.5*	0.4*	0.3*	0.4*	0.4*
Aragarças	83368	327	-15.90	-52.25	0.5*	0.5*	1*	0.9*	0.1	0.2	0	0.2*
Catanduva	83676	570	-21.12	-48.95	-0.1	-0.2	-0.1*	0.2	0.6*	0.5*	0.3*	0.3*
Catalão	83526	858	-18.17	-47.96	NA	NA	NA	NA	NA	NA	NA	NA
Diamantina	83538	1318	-18.24	-43.62	0.3*	0.2	0.8*	0.6*	0.1	0	0.3*	0.3*
Araxá	83579	1018	-19.61	-46.95	0.3*	0.3*	0.8*	0.7*	0.6*	0.5*	0.7*	0.6*
Belo Horizonte	83587	915	-19.93	-43.95	0.1	0	0.2	0.4*	0.5*	0.4*	0.3*	0.4*
Capinópolis	83514	608	-18.72	-49.56	0.3*	0.2	0.7*	0.7*	0.5*	0.3*	0.4*	0.5*
Ipameri	83522	778	-17.72	-48.17	0.3*	0.4*	0.8*	0.6*	0.4*	0.4*	0.5*	0.5*
Jatai	83464	491	-17.92	-51.72	0.4*	0.5*	1*	0.5*	0.3*	0.2	0.4*	0.4*
João Pinheiro	83481	760	-18.73	-49.56	0.4*	0.3*	0.5*	0.6*	0.9*	0.8*	0.9*	0.8*
Formosa	83379	938	-15.55	-47.34	0.3*	0.2*	0.4*	0.6*	0.5*	0.6*	0.6*	0.7*
Pedro Afonso	82863	189	-8.97	-48.18	0.4*	0.6*	1*	1*	0.3*	0.2	0.3*	0.4*
Peixe	83228	252	-12.02	-48.54	0.3*	0.3*	0.7*	0.8*	0.2	0.2*	0.2	0.4*
Pirenópolis	83376	767	-15.85	-48.97	0.5*	0.6*	1.1*	0.9*	0	0.1	0.1	0.2*
Franca	83630	1004	-20.58	-47.38	0.3*	0.2	0.3*	0.6*	0.6*	0.5*	0.5*	0.6*
Goiânia	83423	748	-16.67	-49.26	0.5*	0.5*	0.6*	0.7*	0.6*	0.6*	0.5*	0.3*
Goiás	83374	512	-15.94	-50.14	0.3*	0.3*	0.5*	0.7*	0.4*	0.4*	0.4*	0.4*
Lavras	83687	916	-21.23	-44.98	0.3*	0.1	0.2	0.4*	0.3*	0.3*	0.3*	0.3*
Patos de Minas	83531	947	-18.52	-46.44	0.3*	0.2*	0.4*	0.6*	0.2*	0.1	0.1	0.8*
Montes Claros	83437	645	-16.69	-43.84	0.3*	0.2*	0.4*	0.6*	0.3*	0.6*	0.5*	0.5*
Pirapora	83483	509	-17.35	-44.92	0.4*	0.3*	0.5*	0. 7*	0.6*	0.6*	0.6*	0.5*
São Carlos	83726	860	-21.98	-47.88	0.3*	0.2	0.2	0.5*	0.2*	0.2	0.3*	0.5*
São Simão	83669	620	-21.46	-47.58	0.3*	0.2*	0.3*	0.6*	-0.1	-0.2	-0.1	0.1
Taguatinga	83235	604	-12.40	-46.44	0.3*	0.3*	0.4*	0.7*	0.6*	0.5*	0.4*	0.6*
Posse	83332	830	-14.09	-46.37	0.2*	0.4*	0.8*	0.9*	0.3*	0.2	0.3*	0.4*
Curvelo	83536	670	-18.75	-44.45	0.4*	0.2*	0.5*	0.7*	0.1	0	0.2*	0.1
Alto Parnaíba	82970	284	-9.11	-45.93	0.4*	0.5*	0.7*	0.9*	0.2	0.2	0.3*	0.4*
Araguaína	82659	231	-7.10	-48.20	0.2	0.3*	0.5*	0.6*	0.5*	0.4*	0.3*	0.3*
Unaí	83428	595	-16.37	-46.89	0.5*	0.6*	0.8*	0.9*	0.6*	0.5*	0.4*	0.4*
Carolina	82765	183	-7.34	-47.46	0.6*	0.8*	0.9*	0.8*	0.6*	0.7*	0.7*	0.6*
Imperatriz	82564	123	-5.53	-47.48	0.4*	0.5*	0.6*	0.6*	0.5*	0.5*	0.5*	0.3*
Balsas	82768	259	-7.53	-46.03	0.5*	0.6*	0.9*	1*	0.1	0.1	0.6*	0.4*
Votuporanga	83623	510	-20.44	-49.98	0.7*	0.6*	1*	0.8*	-0.2	-0.3	-0.1	-0.2
Bom Jesus do Piauí	82975	331	-9.10	-44.11	0.4*	0.2*	0.3*	0.5*	0.3*	0	-0.2	-0.2
Conceição do Araguaia	82861	156	-8.26	-49.26	0.5*	0.6*	0.7*	0.5*	1.4*	1.4*	1.1*	0.9*
Uberaba	83577	753	-19.74	-47.95	0.3*	0.2*	0.3*	0.6*	0.2*	0.1	0.1	0.3*
Barra do Corda	82571	155	-5.51	-45.24	0.4*	0.5*	0.5*	0.5*	0.8*	0.8*	0.8*	0.6*
Bambuí	83582	684	-20.03	-46.01	0.2	0.1	0.6*	0.5*	0.2	0	0.1	0.7
Januária	83386	480	-15.45	-44.37	0.4*	0.3*	0.4*	0.6*	0.1	0.1	0.2*	0.3*
Espinosa	83338	565	-14.91	-42.81	0.3*	0.2*	0.5*	0.7*	0.5*	0.5*	0.3*	0.5*

Colinas	82676	176	-6.03	-44.23	0.5*	0.6*	0.7*	0.9*	0.4*	0.3*	0.3*	0.4*
Florestal	83581	753	-19.89	-44.42	0.4*	0.3*	0.5*	0.7*	NA	NA	NA	NA
Porto Nacional	83064	243	-10.71	-48.41	0.5*	0.4*	0.5*	0.6*	0.7*	0.7*	0.6*	0.5*
Correntina	83286	551	-13.33	-44.61	0.4*	0.5*	0.7*	1*	0	-0.2	-0.4	0.1

Supplementary Tables 1 and 2. Local climate changes in the Brazilian Cerrado. Results of linear regressions between 1961 to 2019 and forecasts until the year 2050 for all 45 weather stations, where the proxies trend values were calculated by multiplying the slope *β* by the number of years in each period (i.e., 59 years for 1961–2019 and 31 years for 2020–2050). Asterisks above the trend values indicate significant models (*P* <0.05). NA indicates cases where the dataset was not available.

Local	WMO Code	Altitude (m)	Latitude	Longitude	Absolute Humidity (g/m^3)				Dew Point Depression (°C)			
					Jul	Aug	Sep	Oct	Jul	Aug	Sep	Oct
Brasília	83377	1161	-15.76	-47.93	-0.1	-0.1*	-0.2*	-0.4*	0.5*	0.6*	0.8*	1*
Aragarças	83368	327	-15.90	-52.25	-0.1	-0.4*	-0.3	-0.2	0.7*	1*	1.1*	0.9*
Catanduva	83676	570	-21.12	-48.95	0	0	0.	-0.1	0.7*	0.7*	0.6*	0.5*
Catalão	83526	858	-18.17	-47.96	0.2*	0	0	-0.1	0.2*	0.3*	0.4*	0.7*
Diamantina	83538	1318	-18.24	-43.62	0.1	0.1	0	0	0	-0.1	0.4*	0.5*
Araxá	83579	1018	-19.61	-46.95	-0.2	-0.4*	-0.3	0	0.6*	0.8*	1*	0.9*
Belo Horizonte	83587	915	-19.93	-43.95	-0.1	-0.2*	-0.2	-0.2*	0.6*	0.6*	0.6*	0.7*
Capinópolis	83514	608	-18.72	-49.56	-0.2	-0.6*	-0.5*	-0.4*	0.5*	0.8*	0.9*	0.8*
Ipameri	83522	778	-17.72	-48.17	-0.1	-0.4*	-0.6*	-0.4*	0.7*	1.2*	1.4*	0.8*
Jatai	83464	491	-17.92	-51.72	-0.1	-0.5*	-0.6*	-0.2	0.8*	1.1*	1.4*	0.5*
João Pinheiro	83481	760	-18.73	-49.56	0	0	0	0.1	0.5*	0.5*	0.6*	0.6*
Formosa	83379	938	-15.55	-47.34	0	-0.1	-0.1	-0.2*	0.5*	0.5*	0.6*	0.8*
Pedro Afonso	82863	189	-8.97	-48.18	-0.2*	-0.6*	-0.8*	-0.4*	0.3*	0.6*	1.1*	0.7*
Peixe	83228	252	-12.02	-48.54	-0.3*	-0.6*	-0.7*	-0.4*	0.3*	0.7*	1.1*	0.9*
Pirenópolis	83376	767	-15.85	-48.97	0	-0.2	-0.5*	-0.2	0.2	0.5*	1.2*	0.6*
Franca	83630	1004	-20.58	-47.38	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.4*
Goiânia	83423	748	-16.67	-49.26	0	-0.1	-0.2	-0.2*	0.6*	0.6*	0.9*	0.8*
Goiás	83374	512	-15.94	-50.14	-0.1	-0.5*	-0.5*	-0.1	0.6*	1*	1.1*	0.5*
Lavras	83687	916	-21.23	-44.98	0	-0.1	-0.1	-0.1	0.4*	0.4*	0.4*	0.5*
Patos de Minas	83531	947	-18.52	-46.44	0.1	0.1	0.1	-0.1	0.1	0	0.1	0.5*
Montes Claros	83437	645	-16.69	-43.84	0.3*	0.1	0.1	-0.1	0.5*	0.2	0.4*	0.7*
Pirapora	83483	509	-17.35	-44.92	0.2	0	-0.2	-0.3*	0.4*	0.6*	0.8*	0.9 *
São Carlos	83726	860	-21.98	-47.88	0.2*	0.1	0.2*	0.2*	-0.4*	-0.4*	-0.3	0.1
São Simão	83669	620	-21.46	-47.58	0.2*	0.2	0.2	0.2*	-0.2	-0.2	-0.4	0.2
Taguatinga	83235	604	-12.40	-46.44	-0.1	-0.1	-0.2*	-0.3*	0.7*	0.7*	0.9*	1*
Posse	83332	830	-14.09	-46.37	-0.1	-0.1	-0.3*	-0.3	0.5*	0.5*	1*	1.1*
Curvelo	83536	670	-18.75	-44.45	0	0	0	0	0.1	0.2	0.4	0.6*
Alto Parnaíba	82970	284	-9.11	-45.93	-0.3	-0.3	-0.4	-0.5	0.8*	0.8*	1*	1.2*
Araguaína	82659	231	-7.10	-48.20	0.2	0.1	-0.1	0	0.5*	0.7*	0.8*	0.8*
Unaí	83428	595	-16.37	-46.89	-0.6*	-1*	-1.1*	-0.9*	1.5*	1.8*	2*	1.7*
Carolina	82765	183	-7.34	-47.46	0.6*	0.6*	0.5*	0.3*	-0.2	-0.2	0.1	0.2*
Imperatriz	82564	123	-5.53	-47.48	0.1	0.3*	0.4*	0.3*	0.5*	0.4*	0.5*	0.4*
Balsas	82768	259	-7.53	-46.03	0.9*	1*	0.8*	0.4*	0	0	0.3	0.8*
Votuporanga	83623	510	-20.44	-49.98	0.4*	0.4	0.2	0.3	-0.2	-0.3	0.3	0.2
Bom Jesus do Piauí	82975	331	-9.10	-44.11	-0.1	0.3	0.3	-0.3	1.5*	0.9*	0.8*	1.9*
Conceição do Araguaia	82861	156	-8.26	-49.26	0.3	0.2	0	0.2	1*	1 *	1*	0.5*
Uberaba	83577	753	-19.74	-47.95	0	-0.1	-0.1	-0.2	0.1	0.1	0.2	0.5*
Barra do Corda	82571	155	-5.51	-45.24	0.20	0.1	0	0	0.6*	0.7*	0.8*	0.7*
Bambuí	83582	684	-20.03	-46.01	0.2	0	0	0.1	-0.1	-0.1	0	0
Januária	83386	480	-15.45	-44.37		-0.1	-0.2	-0.3*	0.2	0.1	0.2	0.7*
Espinosa	83338	565	-14.91	-42.81	NA	NA	NA	NA	NA	NA	NA	NA
Colinas	82676	176	-6.03	-44.23	NA	NA	NA	NA	NA	NA	NA	NA
Florestal	83581	753	-19.89	-44.42	NA	NA	NA	NA	NA	NA	NA	NA
Porto Nacional	83064	243	-10.71	-48.41	0	-0.2	-0.2	-0.2*	0.3*	0.4*	0.5*	0.5*

Correntina	83286	551	-13.33	-44.61	-0.2	-0.3	-0.2	0.1	0.4	0.5*	0.4	0.4

CAPITULO 3: CHANGES IN ATMOSPHERIC CIRCULATION AND EVAPOTRANSPIRATION ARE REDUCING RAINFALL IN THE BRAZILIAN CERRADO

Este artigo foi publicado em julho de 2023 na revista *Scientific Reports* (https://doi.org/10.1038/s41598-023-38174-x). Portanto, o estilo e formatação do seguem as normas da revista.

Paisagem do Cerrado no município de São Domingos, Goiás, nas imediações do Parque Estadual de Terra Ronca.

Foto: Luís Flamarion B. Oliveira

Os chapadões do Brasil Central são áreas bastante antigas, remontando em grande parte ao Pré-Cambreano ou chegando ao Cretáceo. Jazem ali alguns dos perfis de solo mais profundos e evoluídos do Planeta...

Orlando Graeff

Trecho extraído do livro Fitogeografia do Brasil: uma atualização de bases e conceitos.

Changes in atmospheric circulation and evapotranspiration are reducing rainfall in the Brazilian Cerrado

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ABSTRACT

Here we analyze the trends of rainfall and the frequency of rainy days over the Brazilian Cerrado between 1960 and 2021 in four distinct periods according to the seasonal patterns over the region. We also evaluated trends in evapotranspiration, atmospheric pressure, winds, and atmospheric humidity over the Cerrado to elucidate the possible reasons for the detected trends. We recorded a significant reduction in rainfall and frequency of rainy days in the northern and central Cerrado regions for all periods except at the beginning of the dry season. The most pronounced negative trends were recorded during the dry season and the beginning of the wet season, where we recorded reductions of up to 50% in total rainfall and the number of rainy days. These findings are associated with the intensification of the South Atlantic Subtropical Anticyclone, which has been shifting atmospheric circulation and raising regional subsidence. Moreover, during the dry season and the beginning of the wet season, there was a reduction in regional evapotranspiration, which also potentially contributed to the rainfall reduction. Our results suggest an expansion and intensification of the dry season in the region, potentially bringing broad environmental and social impacts that transcend the Cerrado boundaries.

3.1 INTRODUCTION

Brazil has been a main international focus point concerning biological conservation and global climate change, primarily due to the size and high diversity of its forests. However, while most of the attention of scientists and decision-makers remains focused on the Amazon and the Atlantic Forest, the other non-forest ecoregions in Brazil are undergoing an accelerated destruction process due to the expansion of the agricultural frontier[1]. This is the case of the Brazilian Cerrado (also called Neotropical Savanna, and hereinafter referred to as Cerrado), a global biodiversity hotspot that extends over 2 million km^2 and has already lost 50% of its native vegetation cover[2,3] (Fig. 1a). The Cerrado vegetation is a mosaic of native grasslands, savannas, and forests, and their conversion into pasture or cropland can be associated with a pronounced climate change at local and regional scales[4]. These land use and cover changes are linked to shifts in the local energy budget, especially in the latent heat flux due to the significant reduction in evapotranspiration[5,6], resulting in higher temperatures and lower relative humidity near the ground4. In addition to air temperature and humidity shifts, theoretical simulations evaluating the climatic effects of savanna suppression have predicted a large reduction in precipitation due to both the reduced moisture flux from the land surface as well as weakened moisture convergence into the savanna's core areas[7,8]. According to these projections, the reduction in rainfall could exceed 300 mm/year, representing more than 20% of the annual amount.

Recently, other studies already found trends of reduced rainfall for the Cerrado regions corroborating these theoretical forecasts[9–11]. This reduction in rainfall over the Cerrado is probably not only associated with land use and land cover changes. Since the late 1950s, several studies have found significant changes in atmospheric circulation over the tropical region, especially by an intensification in the Hadley and Walker cells[12–15]. There is consistent evidence of a widening of the Hadley cell's poleward edge during the austral summer on the South Atlantic Ocean due to increasing greenhouse gases and decreasing stratospheric ozone concentrations in the Southern Hemisphere[16]. The South Atlantic Subtropical Anticyclone (SASA) is one of three anticyclones that form in Hadley cell's poleward edge in the oceans of the Southern Hemisphere and controls the climatic seasonality in all Brazilian tropical regions. Variations in the location and intensity of SASA deeply affect the Brazilian weather through changes in atmospheric pressure, air subsidence intensity, winds, and humidity flux that reach the continental areas[17].

Therefore, these alterations in the Hadley cell can lead to deep impacts on the hydrological cycle and regional energy budget in the continental areas of South America. For instance, the increasing tropospheric and surface dryness over the Brazilian tropical region is projected by models considering Hadley cells circulation in different CO_2 warming scenarios[18]. So far, the consequences of strengthening the SASA next to the Brazilian coast have yet to be fully known, as well as the likely changes in atmospheric circulation and hydrological cycle over the adjacent tropical continental areas[17,19].

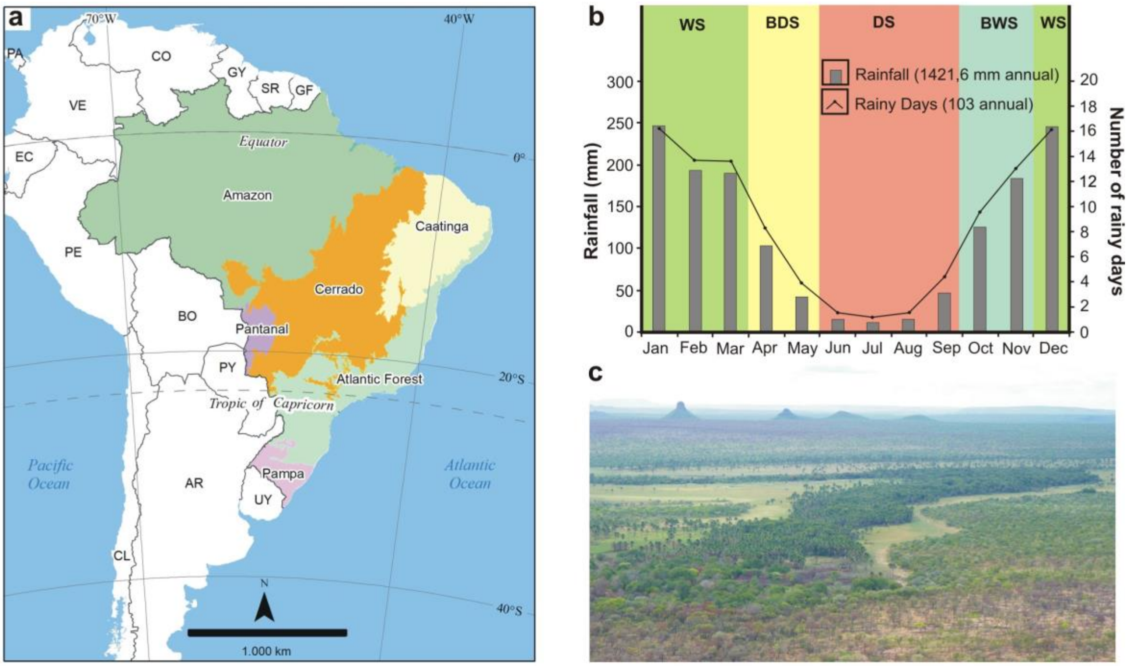


Fig. 1. Location of the Brazilian Cerrado and its annual rainfall cycle. (a) Official limits of the Cerrado and other Brazilian ecoregions. **(b)** Monthly means of total rainfall (gray bars) and the frequency of rainy days (black line) in Cerrado between 1960 and 1990 (here considered as period reference), where the values were calculated by the average of all 70 pluviometric stations used in this study. The acronyms WS, BDS, DS, and BWS represent the Wet Season, Beginning of Dry Season, Dry Season, and Beginning of Wet Season, respectively. **(c)** Panoramic view of the Cerrado vegetation during the dry season, near Terra Ronca State Park (state of Goiás). The map in the upper level was produced using ArcGIS (https:// www. arcgis. com).

Like other areas of tropical savannas, the climate in the Cerrado is characterized by high temperatures throughout the year, with wet and dry seasons occurring in the austral summer and winter, respectively[20]. The annual rainfall ranges from 1800 mm in the transition zones with the Amazon rainforest to 1000 mm in the areas bordering the Caatinga (a semi-arid ecoregion in northeastern Brazil)[21,22]. The weather stability of the dry season in the Cerrado is a consequence of the subsidence generated by the SASA that inhibits the moisture convection and the vertical development of clouds[23]. During this period, the prevailing winds blow from east to west, and the humidity transport from the

Atlantic Ocean and Amazon forest is minimal compared to the summer[24]. The summer wet season is associated with the South American Monsoon System (SAMS), a period in which both the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ) occur in the region[25]. The wet season begins between late September and the beginning of November, when the Southern Hemisphere becomes progressively warmer due to the greater incidence of solar radiation, weakening and moving away the SASA from the South American continent17. The progressive heating of the continent reverses the direction of 850-hPa zonal winds, reduces the atmospheric pressure over South America, and intensifies the moisture flow from the Atlantic Ocean and the Amazon forest into the Cerrado[26]. So, the low atmospheric pressure and high humidity over the Cerrado favored the deep convection and occurrence of intense rainfall events. From the end of March, convection gradually migrates to the equatorial region, and moisture transport from the Amazon weakens, ending the wet season in the Cerrado[24].

In this study, our main objective is to further investigate trends in the amount and frequency of rainfall over the Cerrado between 1960 and 2021, and relate them to other environmental variables. For that, we also evaluated changes in evapotranspiration, atmospheric pressure, winds, and atmospheric humidity over the Cerrado to elucidate possible shifts in atmospheric circulation and the SAMS in the same period. Therefore, our analyses cover the period from the first years of Hadley cell intensification/expansion records to the present, and date back to the period before agricultural expansion in the region. We performed all data analyses in four distinct periods according to the rainfall distribution patterns over Brazilian tropical areas throughout the year[23,24]. These periods are the wet season (WS; formed by December, January, February, and March), the beginning of the dry season (BDS; April and May), the dry season (DS; June, July, August, and September), and the beginning of the wet season (BWS; October and November) (Fig. 1b)

3.2 RESULTS

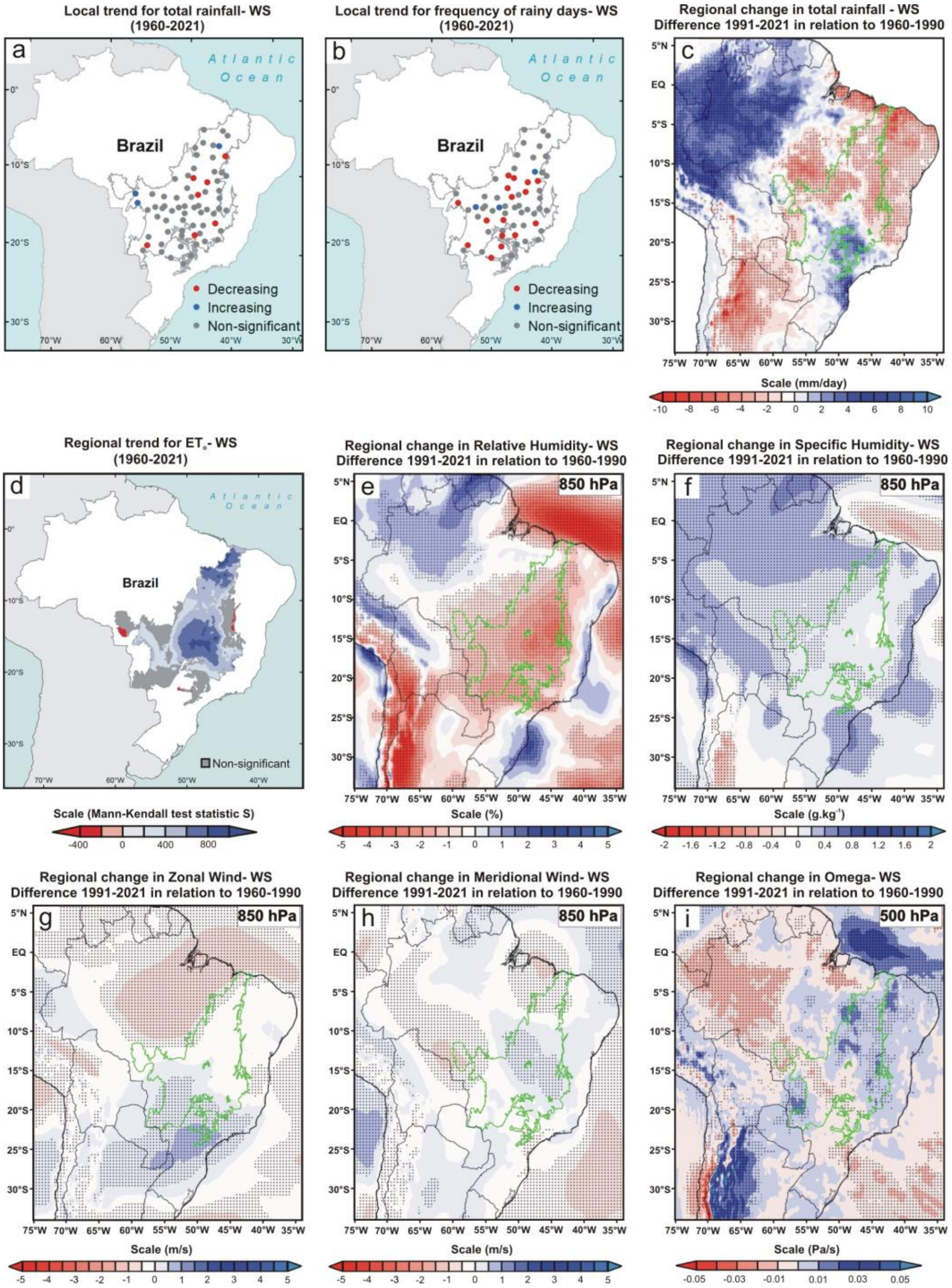
3.2.1 Rainfall reduction over Cerrado

As a starting point, we define the 1960–1990 climate normal as a reference value to estimate the changes in rainfall in the Cerrado. Our analyses were based on data from direct observation in 70 pluviometric stations spread across all Cerrado sub-regions (i.e., local scale) and from a combination of model data with observations generated by the ERA5 global reanalysis (regional scale) (Methods). At the local scale, the Mann–Kendall test showed that most localities have a downward trend for both total rainfall and the frequency of rainy days (Figs. 2, 3, 4, 5, 6a, and b). In all analyzed periods, we found more significant cases in the frequency of rainy days than total rainfall. A similar result has already been observed in a study limited to northern Cerrado and considering a shorter sample period[10]. However, this difference may also be partially associated with the high variance of rainfall data in Cerrado, impairing model fitting, even non-parametric ones, such as the Mann–Kendall test. The high variance of precipitation data is a characteristic that can also be observed in the other tropical ecoregions of Brazil[23,27,28]. In our study, for example, the last two years of the series (2020 and 2021) were exceptionally wet due to high-intensity precipitation events (above 100 mm/day).

Results from reanalysis data corroborated the local trends showing a significant reduction of total rainfall in the central portion and no significant changes in the southern Cerrado (Fig. 2, 3, 4, 5, 6c). However, only the reanalysis showed a significant reduction in the northern portion. Again, we attribute this disagreement to the difficulty of fitting the models to the high variance in the observed total rainfall because the negative trends far outweigh the positive ones in the northern Cerrado, even if the fitting are not statistically significant. These nonsignificant reduction trends of total rainfall can be seen by comparing the mean of the last 31 years (1991–2021) to that of the first 31 years (1960–1990) because 54 of the 70 pluviometric stations have a reduction in annual rainfall (Fig. 6d; Supplementary Table S1). From this comparison, considering the mean of the 70 monitoring sites, we calculated that the annual reduction was 64.8 mm in precipitation and of 5.2 days in the number of rainy days, a reduction similar to that found in previous studies[11]. Nonetheless, both values represent overall estimates for the entire Cerrado and, in many sites, these reductions are greater than twice these means (Fig. 6d–e; Supplementary Tables S1 and S2). The DS is when the trend towards reduced precipitation and frequency of rainy days is more consistent, occurring practically in the entire Cerrado (i.e., 67 of the 70 monitoring sites; Fig. 4a–c; Supplementary Fig. S1c). This period was also the one in which the reductions in rainfall amount and frequency of rainy days were proportionally higher compared to the 1960–1990 climate normal, with dozens of monitoring sites having reductions greater than 30% in both variables (Supplementary Tables S1 and S2). As shown in Fig. 4c, the significant reduction in precipitation during the DS goes beyond the Cerrado boundaries, extending to neighboring ecoregions such as the Pantanal (west edge), south and east of the Amazon (northwest edge), part of the Atlantic Forest (southeast edge) and a narrow portion of Caatinga (northeast edge). Other studies conducted in some of these ecoregions have confirmed this outcome[10,27,29,30]. We also detected a significant reduction in rainfall during the BWS in the central Cerrado, extending to the southern Amazon and the center of the Atlantic Forest (Fig. 5a–c). This change is important because the expansion of the DS is one of the main predictions of theoretical simulations evaluating the climatic effects of savanna supression[7] and has also been observed by other studies in the south and east of the Amazon[10,14]. During the WS, rainfall was significantly reduced in central and northern Cerrado (Fig. 2a–c), encompassing the southeastern Amazon, Pantanal, and the entire northeastern region of Brazil. The BDS is the period when the changes were less noticeable, with significant reduction trends of the total rainfall occurring only in the western edge of the Cerrado (Fig. 3a–c), extending to the south and east of the Amazon[30]. In summary, we found a broad tendency toward an annual reduction in total rainfall and in the frequency of rainy days in almost all Cerrado (Fig. 6a–c). Moreover, we observed this same pattern for large areas of other Brazilian tropical ecoregions such as Pantanal, Caatinga, Atlantic Forest, and southern Amazon (Fig. 6c).

3.2.2 Changes in evapotranspiration, air humidity, and atmospheric circulation

From the TerraClimate dataset, we again used the Mann-Kendell test to analyze the trend in reference evapotranspiration (ETo; based on the Penman-Montieth method) for the entire Cerrado between 1960 and 2021 (Methods). We recorded positive ETo trends in large areas in the Cerrado during the WS and at the BDS (Figs. 2, 3d). This trend is directly associated with the recent warming of the Cerrado, which has been raising the regional evaporative demand, consequently increasing the evapotranspiration rates in periods of high water availability[31,32]. We believe that ETo is a good approximation to evaluate evapotranspiration in our case, give the predominance of grassland and savanna ecosystems and the high availability of water during the summer months in Cerrado, which are factors that support the trends found at the WS and BDS[33]. Additionally, the extensive conversion of native vegetation into agriculture and pasture does not seem to be a factor that can shift the trends in these two periods because some cropping systems in the Cerrado have evapotranspiration rates similar to or greater than natural vegetation between December and May when cultures are at an advanced stage of growth[34].



Local trend for total rainfall- WS (1960-2021)

Local trend for frequency of rainy days- WS (1960-2021)

Regional change in total rainfall - WS Difference 1991-2021 in relation to 1960-1990

Regional trend for ET$_o$- WS (1960-2021)

Regional change in Relative Humidity- WS Difference 1991-2021 in relation to 1960-1990

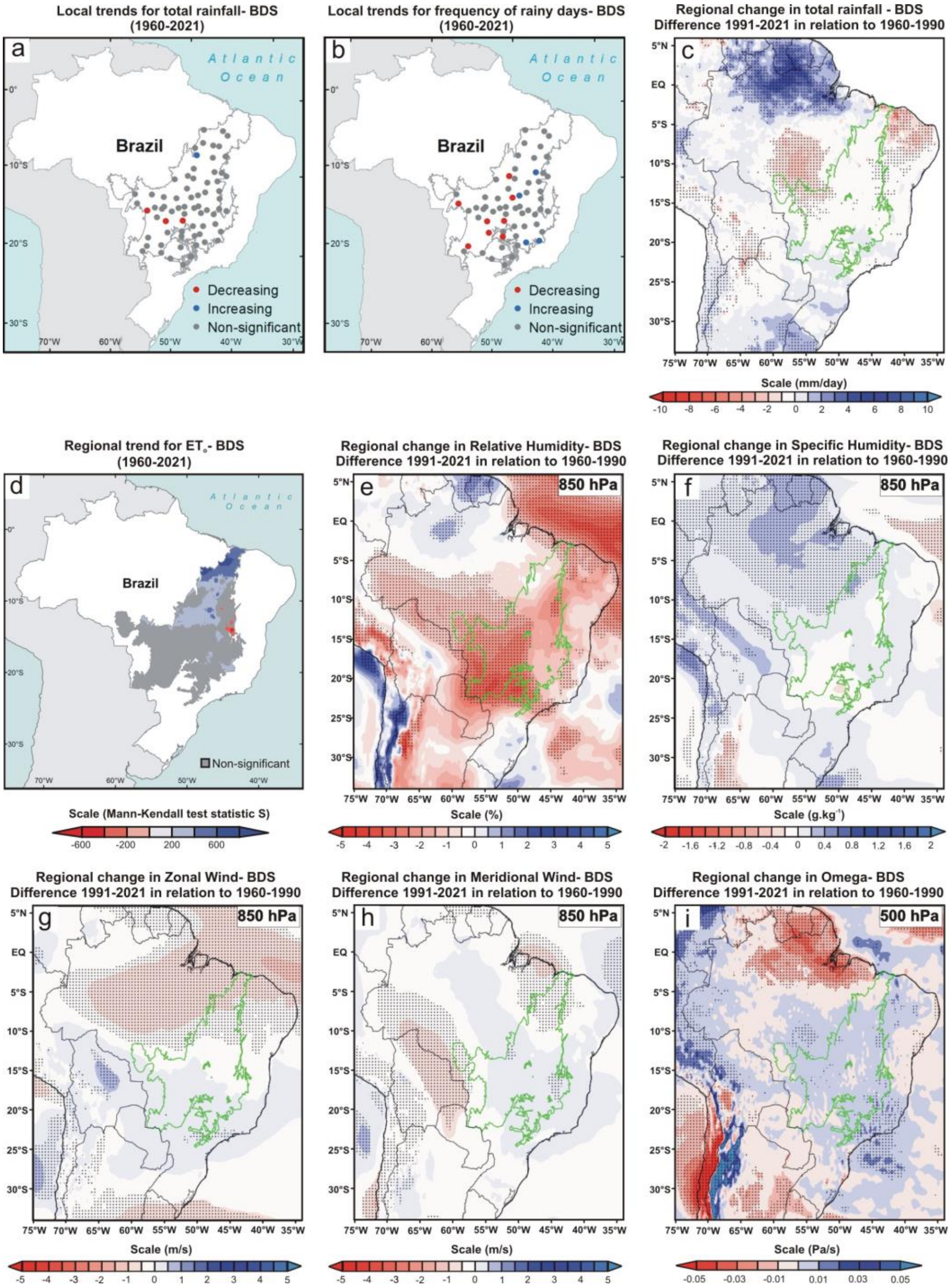
Regional change in Specific Humidity- WS Difference 1991-2021 in relation to 1960-1990

Regional change in Zonal Wind- WS Difference 1991-2021 in relation to 1960-1990

Regional change in Meridional Wind- WS Difference 1991-2021 in relation to 1960-1990

Regional change in Omega- WS Difference 1991-2021 in relation to 1960-1990

Fig. 2. Climate changes over the last six decades during the wet season (WS; December, January, February, and March) of the Brazilian Cerrado. (a, b, and d) Mann-Kendall test over 1960─2021 for total rainfall (mm), frequency of rainy days, and reference evapotranspiration (ET$_o$; mm), respectively. The blue, red, and gray colors represent the areas with a significant increasing trend ($p< 0.05$), significant decreasing trend ($p< 0.05$), and non-significant trend, respectively. The blue and red color gradient for reference evapotranspiration analyses represents Mann-Kendall's S-statistics results for all pixels with a significant trend. **(c, e─i)** Regional changes detected by ERA5 reanalysis for total rainfall (mm/day), relative humidity (%) at 850-hPa, specific humidity (g.kg^{-1}) at 850-hPa, horizontal speed of zonal wind (m/s), horizontal speed of meridional wind (m/s) at 850-hPa, and vertical velocity (omega) (Pa/s) at 500-hPa, respectively. In all reanalysis, the dotted areas demonstrated a significant difference ($p< 0.05$) between the climate normals 1991─2021 and 1960─1990. The gray and green polygons show the official limits of the Brazilian Cerrado in the Mann-Kendall tests and reanalysis, respectively. Maps showing local scale trends were generated using ArcGIS (https://www.arcgis.com). The ET$_o$ results map was generated using Google Earth Engine (https://earthengine.google.com/). The ERA5 reanalysis maps were generated using GrADS-Grid Analysis and Display System (http://opengrads.org).



Local trends for total rainfall- BDS (1960-2021)

Local trends for frequency of rainy days- BDS (1960-2021)

Regional change in total rainfall - BDS Difference 1991-2021 in relation to 1960-1990

Regional trend for ET_o- BDS (1960-2021)

Regional change in Relative Humidity- BDS Difference 1991-2021 in relation to 1960-1990

Regional change in Specific Humidity- BDS Difference 1991-2021 in relation to 1960-1990

Regional change in Zonal Wind- BDS Difference 1991-2021 in relation to 1960-1990

Regional change in Meridional Wind- BDS Difference 1991-2021 in relation to 1960-1990

Regional change in Omega- BDS Difference 1991-2021 in relation to 1960-1990

Fig. 3. Climate changes over the last six decades during the beginning of the dry season (BDS; April and May) of the Brazilian Cerrado. (a, b, and d) Mann-Kendall test over 1960─2021 for total rainfall (mm), frequency of rainy days, and reference evapotranspiration (ET_o; mm), respectively. The blue, red, and gray colors represent the areas with a significant increasing trend ($p < 0.05$), significant decreasing trend ($p < 0.05$), and non-significant trend, respectively. The blue and red color gradient for reference evapotranspiration analyses represents Mann-Kendall's S-statistics results for all pixels with a significant trend. (**c, e─i**) Regional changes detected by ERA5 reanalysis for total rainfall (mm/day), relative humidity (%) at 850-hPa, specific humidity ($g.kg^{-1}$) at 850-hPa, horizontal speed of zonal wind (m/s), horizontal speed of meridional wind (m/s) at 850-hPa, and vertical velocity (omega) (Pa/s) at 500-hPa, respectively. In all reanalysis, the dotted areas demonstrated a significant difference ($p < 0.05$) between the climate normals 1991─2021 and 1960─1990. The gray and green polygons show the official limits of the Brazilian Cerrado in the Mann-Kendall tests and reanalysis, respectively. Maps showing local scale trends were generated using ArcGIS (https://www.arcgis.com). The ET_o results map was generated using Google Earth Engine (https://earthengine.google.com/). The ERA5 reanalysis maps were generated using GrADS-Grid Analysis and Display System (http://opengrads.org).

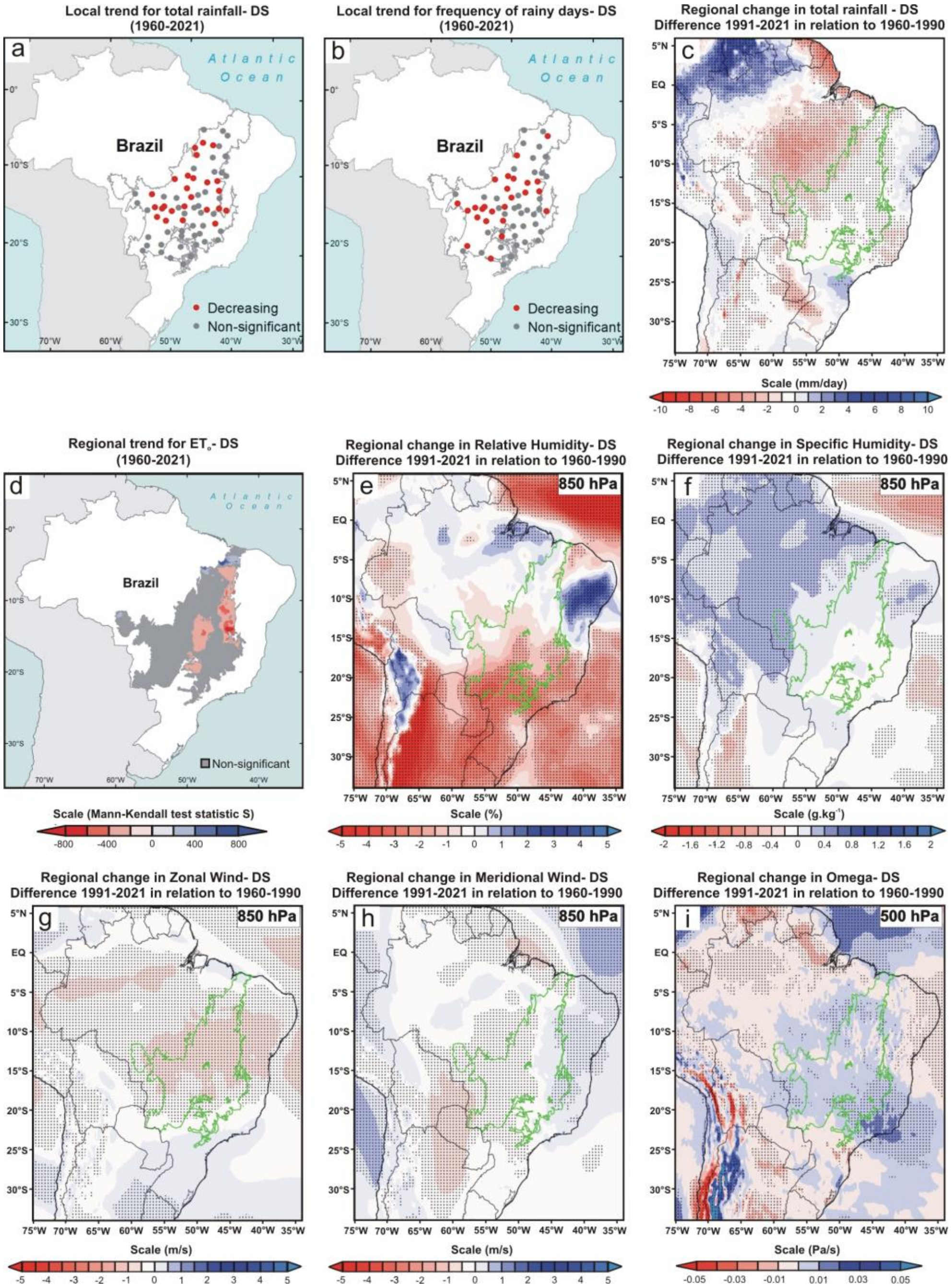


Fig. 4. Climate changes over the last six decades during the dry season (DS; June, July, August and September) of the Brazilian Cerrado. (a, b, and d) Mann-Kendall test over 1960─2021 for total rainfall (mm), frequency of rainy days, and reference evapotranspiration (ET$_o$; mm), respectively. The blue, red, and gray colors represent the areas with a significant increasing trend ($p< 0.05$), significant decreasing trend ($p< 0.05$), and non-significant trend, respectively. The blue and red color gradient for reference evapotranspiration analyses represents Mann-Kendall's S-statistics results for all pixels with a significant trend. (**c, e─i**) Regional changes detected by ERA5 reanalysis for total rainfall (mm/day), relative humidity (%) at 850-hPa, specific humidity (g.kg^{-1}) at 850-hPa, horizontal speed of zonal wind (m/s), horizontal speed of meridional wind (m/s) at 850-hPa, and vertical velocity (omega) (Pa/s) at 500-hPa, respectively. In all reanalysis, the dotted areas demonstrated a significant difference ($p< 0.05$) between the climate normals 1991─2021 and 1960─1990. The gray and green polygons show the official limits of the Brazilian Cerrado in the Mann-Kendall tests and reanalysis, respectively. Maps showing local scale trends were generated using ArcGIS (https://www.arcgis.com). The ET$_o$ results map was generated using Google Earth Engine (https://earthengine.google.com/). The ERA5 reanalysis maps were generated using GrADS-Grid Analysis and Display System (http://opengrads.org).

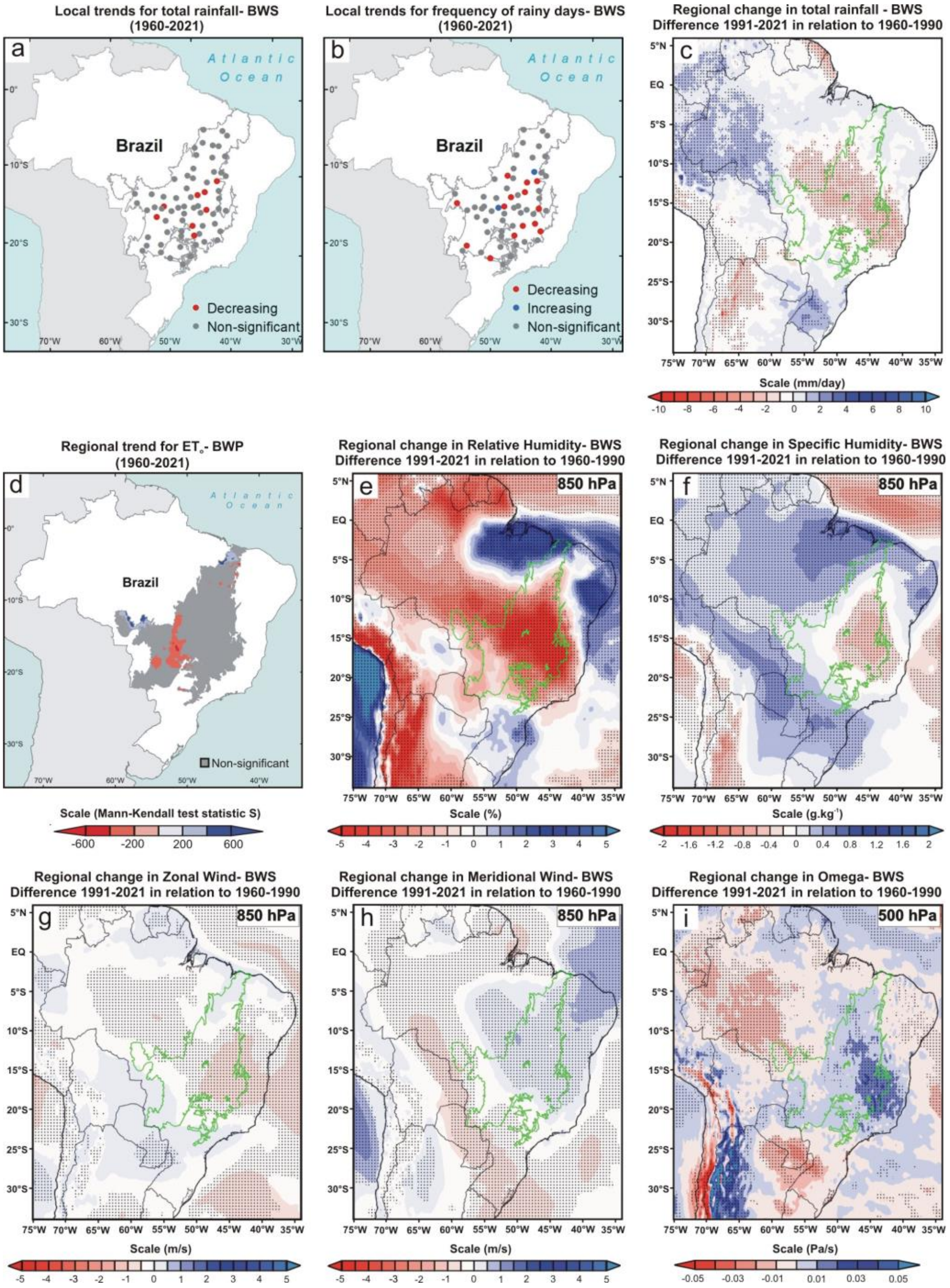


Fig. 5. Climate changes over the last six decades during the beginning of the wet season (BWS; October and November) of the Brazilian Cerrado. (**a, b, and d**) Mann-Kendall test over 1960─2021 for total rainfall (mm), frequency of rainy days, and reference evapotranspiration (ET_o; mm), respectively. The blue, red, and gray colors represent the areas with a significant increasing trend ($p < 0.05$), significant decreasing trend ($p < 0.05$), and non-significant trend, respectively. The blue and red color gradient for reference evapotranspiration analyses represents Mann-Kendall's S-statistics results for all pixels with a significant trend. **(c, e─i)** Regional changes detected by ERA5 reanalysis for total rainfall (mm/day), relative humidity (%) at 850-hPa, specific humidity (g.kg^{-1}) at 850-hPa, horizontal speed of zonal wind (m/s), horizontal speed of meridional wind (m/s) at 850-hPa, and vertical velocity (omega) (Pa/s) at 500-hPa, respectively. In all reanalysis, the dotted areas demonstrated a significant difference ($p < 0.05$) between the climate normals 1991─2021 and 1960─1990. The gray and green polygons show the official limits of the Brazilian Cerrado in the Mann-Kendall tests and reanalysis, respectively. Maps showing local scale trends were generated using ArcGIS (https://www.arcgis.com). The ET_o results map was generated using Google Earth Engine (https://earthengine.google.com/). The ERA5 reanalysis maps were generated using GrADS-Grid Analysis and Display System (http://opengrads.org).

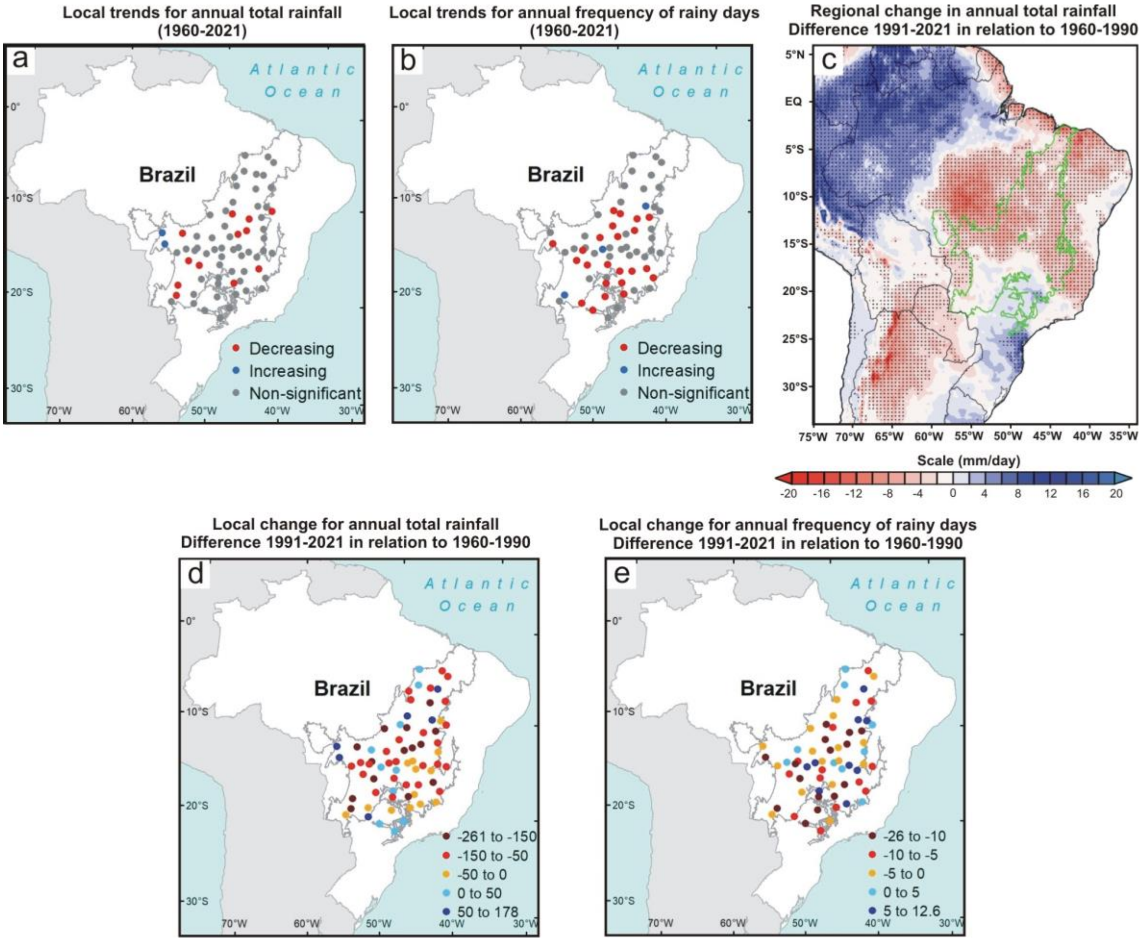


Fig. 6. Change in annual total rainfall and annual frequency of rainy days in the Brazilian Cerrado between 1960 and 2021. (a and b) Mann-Kendall test over 1960─2021 for annual total rainfall (mm) and frequency of rainy days, respectively. The blue, red, and gray colors represent the areas with a significant increasing trend ($p< 0.05$), significant decreasing trend ($p< 0.05$), and non-significant trend, respectively. (**c**) Regional changes detected by ERA5 reanalysis for annual total rainfall (mm/day). The dotted areas demonstrated a significant difference ($p< 0.05$) between the climate normals 2021─1991 and 1960─1990. (**d and e**) Local changes in annual total rainfall and annual frequency of rainy days by comparing the climate normal 1991─2021 to the climate normal 1960─1990, respectively. Maps showing local scale trends were generated using ArcGIS (https://www.arcgis.com). The ERA5 reanalysis map were generated using GrADS-Grid Analysis and Display System (http://opengrads.org).

On the other hand, we recorded a reduction in evapotranspiration in extensive areas of the Cerrado in the DS and BWS (Figs. 4, 5d). This ETo reduction is not directly associated with land use and land cover changes because its formulation uses a static reference land cover. Instead, the increase in evaporative demand during the DS in Cerrado may have been so high that it possibly exceeded the pre-established physiological capacity for the grass reference surface in the Penman-Montieth equation (i.e., a fixed "bulk" surface resistance of 70 sm^{-1})[33]. Contrary to the assumption in the calculation of ETo, where there is no water restriction for grass reference surface, the plants of Cerrado are subject to a severe limitation of water supply during the DS and BWS[32], which probably potentiates the reduction of real evapotranspiration. Even if we could not explicitly consider land use and land cover changes in our study, this process results in the evapotranspiration decrease in Cerrado because, contrary to what happens in agricultural areas, the deep root system of part of the Cerrado native vegetation allows high evapotranspiration rates in DS and BWS[5,6]. For all these reasons, we conclude that the trend of reduction in evapotranspiration during these two periods is a reality and that it can be aggravated if the suppression of Cerrado native vegetation is maintained in the coming years.

We recorded significant reductions in relative humidity in the 850-hPa layer (i.e., ~ 1.5 km above sea level) between the two climate normals in all periods analyzed (Figs. 2, 3, 4, 5e). However, the same approach found no significant changes in specific humidity in the same atmospheric layer (Figs. 2, 3, 4, 5f). This apparent contradictioncan be explained by the regional warming4 and the intensification of the SASA over the past three decades, leading to increased subsidence over the Cerrado. The compression of the air mass during the subsidence process leads to adiabatic heating, raising the vapor pressure deficit and reducing the relative humidity. Additionally, the air subsidence prevents deep convection, explaining why we do not observe a significant increase in specific humidity during the wet season and at the beginning of the dry season, periods in which we recorded rises in surface evapotranspiration. Here we demonstrate this enhancement of the SASA by the increase in the horizontal speed of air moving toward the west during the dry season and the beginning of the wet season (i.e., negative values of the zonal wind; Figs. 4, 5g) and increase in the vertical velocity of wind (omega) in all periods (Figs. 2, 3, 4, 5i). We highlight the increase in vertical velocity of the wind at 500-hPa (i.e., ~ 5.5 km above sea level), but we also revealed omega changes in other layers of the troposphere in four meridians that cover almost the entire longitudinal extension of the Cerrado (Supplementary Figs. S3–S6).

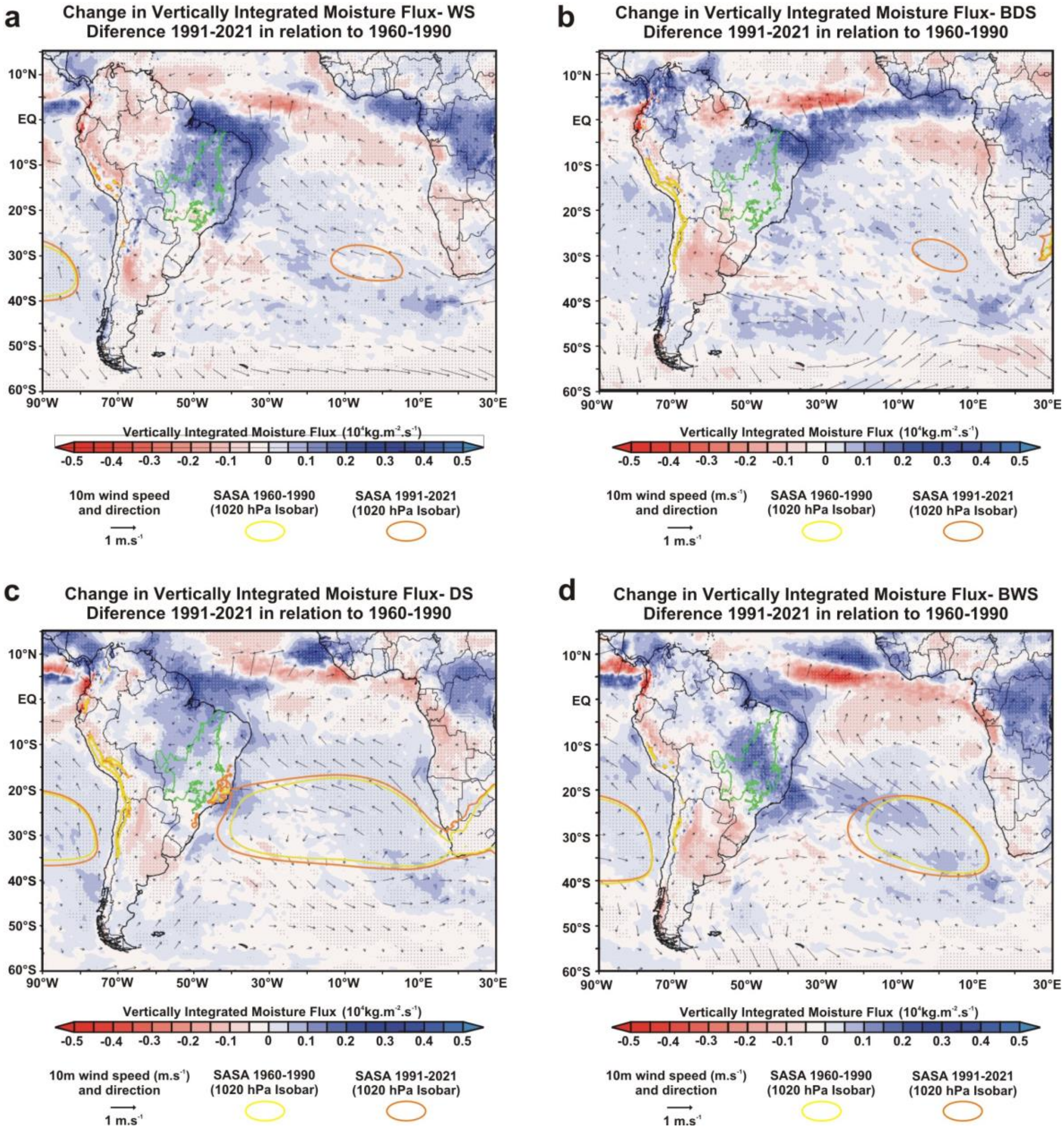


Fig.7. Changes in the Vertically Integrated Moisture Flux and the intensity and direction of 10m Wind between 1960─2021 in the South America/South Atlantic domain. (a─d), Changes in Vertically Integrated Moisture Flux and 10m Winds recorded by ERA5 reanalysis in the Wet Season (WS), Beginning of Dry Season (BDS), Dry Season (DS), and Beginning of Wet Season (BWS), respectively. The dotted areas demonstrated a significant difference ($p< 0.05$) in the Vertically Integrated Moisture Flux between 1991─2021 and 1960─1990 climate normals. Black vectors show the changes in direction and intensity of 10m Wind. The green polygon shows the official limits of the Brazilian Cerrado. The yellow and orange ellipses represent the 1020 hPa isobar and show the South Atlantic Subtropical Anticyclone (SASA) position/extension in 1960─1990 and 1991─2021, respectively. Maps in the upper level were produced using GrADS-Grid Analysis and Display System (http://opengrads.org).

Finally, to demonstrate the role of SASA intensification/expansion in reducing rainfall in the Cerrado, we performed two additional analyses where we expanded the spatial scale of the study to include the entire South America/South Atlantic domain.

Again, we used the same approach as in the previous analyses and compared the 1991–2021 and 1960–1990 climate normals for all four periods. First, we analyzed the Mean Sea Level Pressure to demonstrate the increase in SASA intensity (Supplementary Fig. S7). Second, we analyzed and overlapped the Vertically Integrated Moisture Flux and the intensity and direction of 10 m Wind in the same figure (Fig. 7). In both analyses, we used the 1020 hPa isobar to show the SASA position/extension, the criterion used by other recent studies[35,36]. The results of these two analyses confirm the expansion of the SASA by the increase of the area occupied by the 1020 hPa isobar during the DS and BWS, in addition to its appearance in the WS and BDS in the period 1991–2021 (note that it did not occur in the South Atlantic between 1960 and 1960; Fig. 7). The intensification of the anticyclone can also be seen by the increase in Sea Level Pressure under most of the South Atlantic and South America (Supplementary Fig. S7) and by the length of the 10 m Wind vectors flowing from the SASA towards the Brazilian coast (Fig. 7). As a result of the SASA intensification, there is an increase in moisture divergence under the tropical region of Brazil that includes most of the Cerrado in all periods analyzed. In other words, the positive values of the Vertically Integrated Moisture Flux indicate that the moisture is spreading out of the Cerrado and converging to other regions of South America (Fig. 7). In this sense, we highlight some changes in meridional winds at 850-hPa that can indicate the fate of this moisture. During the BWS, we found an increase in the horizontal speed of air moving northwards over the central and northern portions of the Cerrado (Fig. 3h). At the same time, we registered a possible intensification of the South American Low-Level Jet in the extreme west edge of the Cerrado, represented by a narrow strip of air flux moving southwards at 850-hPa. In addition to the increase in meridional wind speed, the South American Low-Level Jet also has a significant humidity rise that extends to southern Brazil (Fig. 3f), probably associated with increased rainfall in this region (Fig. 3c), including the occurrence of extreme events of precipitation such as explosive cyclones[37]. Regarding the Cerrado, the increase in the horizontal speed of air moving toward the north during the BWS and WS in its central portion may also be associated with reduced rainfall, as the primary moisture sources for the region in these periods come from the northern sector, especially from the Amazon[26,38].

3.3 DISCUSSION

Here we presented analyses that confirmed the observations and predictions of empirical and theoretical studies, respectively, and demonstrated rainfall reduction in the Cerrado over the last six decades on local and regional scales[7–10]. Additionally, we found significant changes in evapotranspiration, air humidity, and atmospheric circulation that help to understand the rainfall reduction in each period of the year. By a visual comparison of the results shown in Figs. 2, 3, 4, 5, one can perceive a high spatial overlap between the reduction of total rainfall and relative humidity at 850-hPa with the increase in the vertical velocity of wind at 500-hPa, suggesting that this is a major factor driving changes in the hydrological cycle of the Cerrado because it hampers the vertical development of clouds and water condensation. In this sense, the role played by the omega intensification is more evident during WS, when we found a pronounced reduction and relative humidity at 850-hPA, even with a significant tendency to increase regional evapotranspiration in Cerrado. As explained earlier, this reduction in relative humidity at 850-hPA occurs due to adiabatic heating during the air subsidence process. Our results also showed an intensification of the SASA has led to broad changes in the atmospheric circulation in the South America/South Atlantic domain and transferred the moisture from the tropical regions of Brazil to the other areas of South America, such as the northwest Amazon and the La Plata Basin. We reiterate that this climate change transcends the Cerrado boundaries and reduces rainfall in other Brazilian ecoregions such as Caatinga, Pantanal, and southern Amazon [14,15,27,28]. Regarding Cerrado, the evapotranspiration reduction during the DS and the BWS acts in synergy with omega increase, causing an intensification and expansion of the dry period in the Cerrado30. The combination of effects from evapotranspiration reduction and moisture transference linked to changes in atmospheric circulation are also discussed and recognized as important by a recent study that evaluated the rainfall reduction during the dry season in the southwest of the Amazon in the last 40 years39. Although we have not been able to quantify the role of land cover change in this reduction in evapotranspiration, recent studies formally demonstrate these using different methodologies[5,6,32]. Therefore, a process similar to what occurs in the Amazon and which is notoriously related to the reduction of rainfall in this region[40]. Although probable, the effects of massive Amazon deforestation on rainfall in the Cerrado are still unknown. With the reduction of rainfall, there is a trend toward water deficits for most of the Cerrado[32], which will result in impacts and challenges for the region’s future.

The environmental and social impacts of the reduction in the frequency of rainy days and total rainfall are complex and likely to transcend the Cerrado and reach other regions. For instance, this ecoregion contains the headwaters of some of the main Brazilian watersheds (e.g., Parnaíba, Paraná, Paraguay, Tocantins–Araguaia, São Francisco, and rivers tributary to the southern Amazon River)[41]. In this context, the Pantanal likely will be the region most affected by the reduction in rainfall because its floods cycle is directly associated with the flow of rivers from the Cerrado plateaus to the interior of this plain. From an ecological perspective, the decrease in rainfall directly impacts all Cerrado communities by reducing water availability and indirectly by changing plant phenology/reproduction[42] and alterations in interspecific interactions[43,44]. The environmental impacts of reduced in 2010 with a surface area of 21,884 ha, and Estreito in 2012 with a surface area of 40,000 ha). The expansion of the area occupied by dam lakes in Cerrado has not prevented recent episodes of a water crisis with water supply rationing to the population and temporary reduction/interruption of hydroelectric energy production. Furthermore, during severe drought events, the Brazilian population must also live with the sudden increase in food and energy prices which also affect other regions of the country[46]. Our results and projections of future scenarios generated by other studies also call into question the maintenance of the agricultural production model currently practiced in the Cerrado, particularly concerning the plantation system[38,47]. In recent years, studies have shown the relationship between agriculture expansion and streamflow reduction in Cerrado rivers, intensifying the debate between society and farmers in western Bahia[48,49]. As we demonstrate, this is one of the regions most affected by reduced rainfall in the Cerrado, and the water conflicts will probably become more frequent in the coming years. To conclude, we emphasize that the climate changes described here, especially the South Atlantic Subtropical Anticyclone strengthening, are causing the reduction of rainfall in Cerrado, which is more pronounced during the dry season and the beginning of the wet season.

3.4 METHODS

Our analyses were based on three independent datasets, which include direct observations (i.e., rainfall data) and the combination of model data with historical observations from satellites and conventional ground-based stations (i.e., ERA5 global reanalysis and TerraClimate). We have specifically chosen these datasets because they allowed us to compare the period before agricultural expansion in Cerrado and the first years of Hadley cell intensification with the present. In addition to precipitation data, we analyzed possible changes in atmospheric circulation, humidity, and evapotranspiration to elucidate the possible reasons for the reduction of total rainfall and frequency of rainy days on Cerrado. As mentioned earlier in the introduction section of this manuscript, we performed all analyses in four distinct periods according to the rainfall distribution patterns over Brazilian tropical areas throughout the year: the wet season (formed by December, January, February, and March), the beginning of the dry season (April and May), the dry season (June, July, August, and September), and the beginning of the wet season (October and November). We emphasize that data and analyses used in our study are open access and, therefore, could be applied in other Brazilian tropical ecoregions where climate changes are also taking place.

3.4.1 Evaluation of trends in rainfall and frequency of rainy days at the local scale

To access historical precipitation records between 1960 and 2021, we used the Hidroweb portal (https://www.snirh.gov.br/hidroweb), which compiles the data collected by different Brazilian agencies. We selected 70 pluviometric stations with consistent data series (i.e., without lacking information for long periods) in localities spread across all Cerrado subregions. The list of 70 pluviometric stations and other information is summarized in Supplementary Table S3. We organized the daily rainfall (mm) records of each station according to the four periods considered, and the missing values of each locality were filled with the data observed at the nearest pluviometric station. We established two rules for filling in the missing values: (i) the number of missing records could not exceed 15% of the total data; (ii) the distance between stations should be less than 60 km (see details in Supplementary Table S4). Localities that did not meet these rules were excluded. In cases where the pluviometric station started recording data after 1960, we did not consider the previous years as missing values and analyzed only the period after the beginning of the data recording (see the period for each pluviometric station in Supplementary Table S3). After organizing the daily data for each location, we calculated both variables, the total rainfall (i.e., the sum of precipitation accumulated in each period) and frequency of rainy days (i.e., the sum of the number of days with precipitation events in each period). From data from 70 pluviometric stations, we calculated the monthly means of these two variables for the period 1960–1990. Then, we plotted these means values to demonstrate the annual precipitation cycle in the Brazilian Cerrado in the four periods considered in our analysis (Fig. 1b).

Then, we used Mann–Kendall test to analyze the local trends in both variables between 1960 and 2021 (Figs. 1, 2, 3, 4, 5a and b). This non-parametric method is useful for identifying temporal patterns that may not be immediately apparent, and for testing hypotheses about the presence or absence of trends22. Many researchers described the procedures of the Mann–Kendall test23,24. First, it is calculated the sign (i.e., direction of trends) for each pair of observations in the time series xi ranked from i = 1 to n–1 and xj ranked from j = i + 1 to n data points, and each data observation xi is used as a reference observation and is compared with all other data observations xj. Next, the Kendall's S-statistics is computed from the sum of the signs and the variance of the S-statistics24. If the sum is positive, it suggests an upward trend in the data; if the sum is negative, it suggests a downward trend; and if the sum is close to zero, it suggests no trend. After that, a Z-test is used to determine the probability that the trend occurred by chance, given the sample size and the distribution of the data. If |Zs|> (Zobs = Zα/2) we can reject the null hypothesis, therefore indicating a significant trend at the α significance level, set to 5% (confidence level of 95%) in this stud. The Mann Kendall test is traditionally used in hydrological studies, especially for cases with high precipitation variance, such as the Cerrado50. The Mann–Kendall tests were performed using PAST.4.03. Lastly, we also quantified the changes in total rainfall and frequency of rainy days in each of the four periods by comparing the mean values of the last 31 years (1991–2021) to the 31 first years (1960–1990) for all 70 localities (Supplementary Figs. S1 and S2; Supplementary Tables S1 and S2). The same comparison for annual data is shown in Fig. 6d–e.

3.4.2 Changes in rainfall, air humidity, and atmospheric circulation at the regional scale

We evaluated large-scale regional changes in total rainfall, air humidity, and atmospheric circulation based on the reanalysis ERA5-Land. This is a meteorological reanalysis project carried out by the European Centre for Medium-Range Weather Forecasts, and its data are provided directly on the Copernicus Climate Change Service website (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview). This product reports global data hourly with 9 km spatial resolution and covers the period from 1950 to the present51. At first, we analyzed the total precipitation data (mm/day), comparing the climate normals 1991–2021 and 1960–1990 for all four periods (Figs. 2, 3, 4, 5c) and annually (Fig. 6c). We performed a Student's t-test with 95% significance to compare the changes between the values of two climatic normals, and the results were shown using the GrADS application52. We also used the same approach to analyze the fields of relative humidity (%) (Figs. 2, 3, 4, 5e), specific humidity (g kg-1) (Figs. 2, 3, 4, 5f), U-component of wind (m s-1) (i.e., the zonal or eastward component of wind; Figs. 2, 3, 4, 5 g), V-component of wind (m s-1) (i.e., the meridional or northward component of wind; Figs. 2, 3, 4, 5 h), and vertical velocity of wind (Pa s-1) (Figs. 2, 3, 4, 5i). For the analysis of the fields of humidity (relative and specific) and horizontal winds (U and V-components), we have chosen to use the 850-hPa geopotential height due to its recognized importance for zonal and meridional moisture transport in the Cerrado24,53. For vertical velocity of wind (omega) analyses, we evaluated the changes between 1000 and 100-hPa in four meridians (i.e., −45°, −47.5°, −50°, and −52,5°) that cover almost the entire longitudinal extension of the Cerrado (Supplementary Fig. S3–S6). However, in the main figures of the manuscript, we have chosen to show the changes in omega only at 500-hPa geopotential height for the entire region to maintain the same pattern adopted for the other variables (Figs. 2, 3, 4, 5j). Finally, in the reanalysis of Sea Level Pressure (Supplementary Fig. S7), Vertically Integrated Moisture Flux, and 10 m Wind, we expanded the spatial scale of the study to include the entire South America/Atlantic Ocean domain in order to demonstrate the changes in SASA position and intensity. In both analyses, we applied the criterion that Fahad et al.36 used to represent the SASA position/extension through the 1020-hPa isobar. In Fig. 7, we overlapped the Vertically Integrated Moisture Flux and the intensity and direction of 10 m Wind in the same figure to demonstrate an integrated analysis and dynamic interaction of these two variables and their consequent impacts on seasonal rainfall regimes over Cerrado.

3.4.3 Regional trends for evapotranspiration

Unfortunately, Brazilian meteorological agencies do not measure evapotranspiration in their weather stations. For this reason, we were forced to use data to access information about this variable in our study. The concept of the reference evapotranspiration assumes a reference grass surface across space, not short of water. Therefore, ETo is a climatic parameter that evaluates the evaporative demand of the atmosphere independently of vegetation or crop type, crop development, soil, and management practices33. To explore trends in ETo, we used information from the TerraClimate dataset, which combines observations and models to provide global climate and climatic water balance climate variables for terrestrial surfaces in the period 1950–2021 at 1/24° (~ 4 km) spatial resolution54,55. TerraClimate evaluates monthly ETo by applying the well-known Penman-Montieth approach. Comparisons via Pearson's correlations between ETo calculated in TerraClimate and data of 50 stations of the global network of FLUXNET were high, suggesting a good performance of the method, especially for non-forest ecosystems such as Cerrado54. We used the Google Earth Engine56, a cloud-based geospatial data analysis and visualization platform, to calculate the evapotranspiration trends between 1960 and 2021. We applied the Mann–Kendall test for all pixels included in the Cerrado area for all four periods evaluated (Figs. 2, 3, 4, 5d). To maintain consistency with the local analyzes of total rainfall and frequency of rainy days, we have chosen to display on the maps only the statistically significant trends with blue and red colors (for increasing and decreasing trends, respectively), while the gray color represented pixels with not-significant trends.

3.5 DATA AVAILABILITY

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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3.7 ACKNOWLEDGEMENTS

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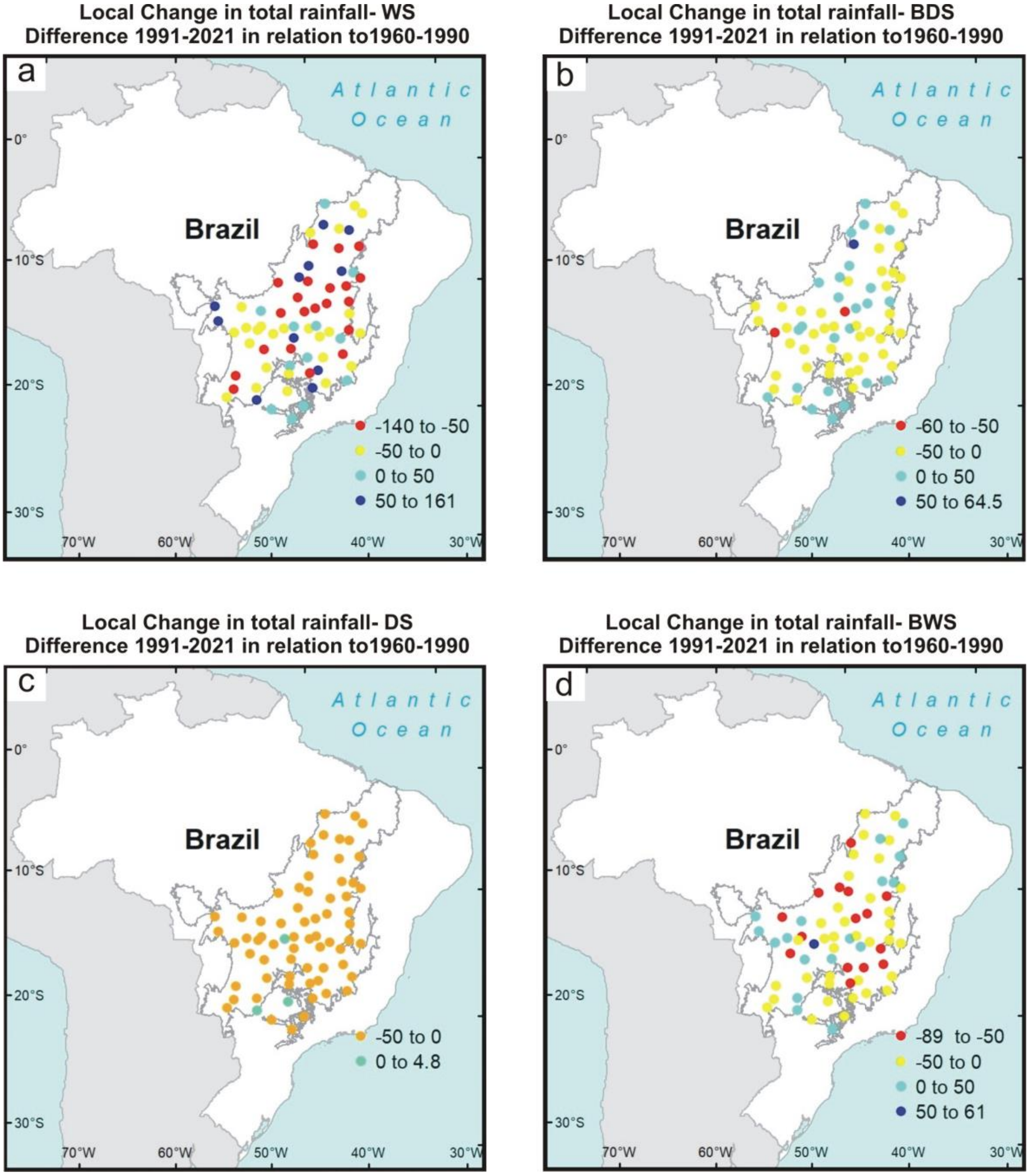
3.8 AUTHOR CONTRIBUTIONS

G.S.H., E.J.W., F.E.A., and M.F.C. conceived the main presented ideas and wrote the manuscript. R.C.S. and A.A.B. performed the analytic tests and helped revise this work's findings. L.F.B.O., R.J.V.A., H.H., and V.S. actively participated by providing ideas during the development of the study and helping to write the text. All authors contributed significantly to the final version of the manuscript.

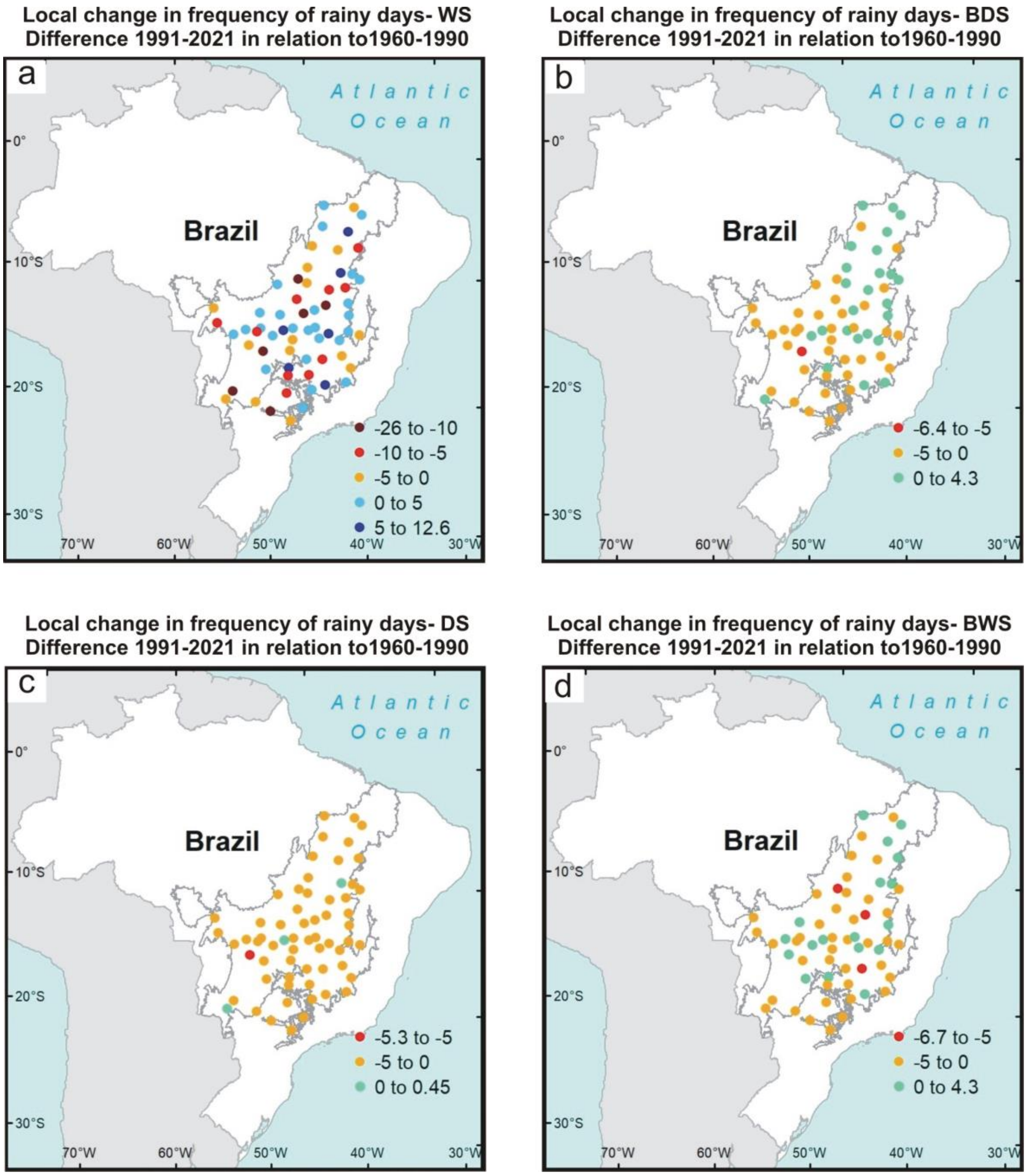
3.9 COMPETING INTERESTS

The authors declare no competing interests.

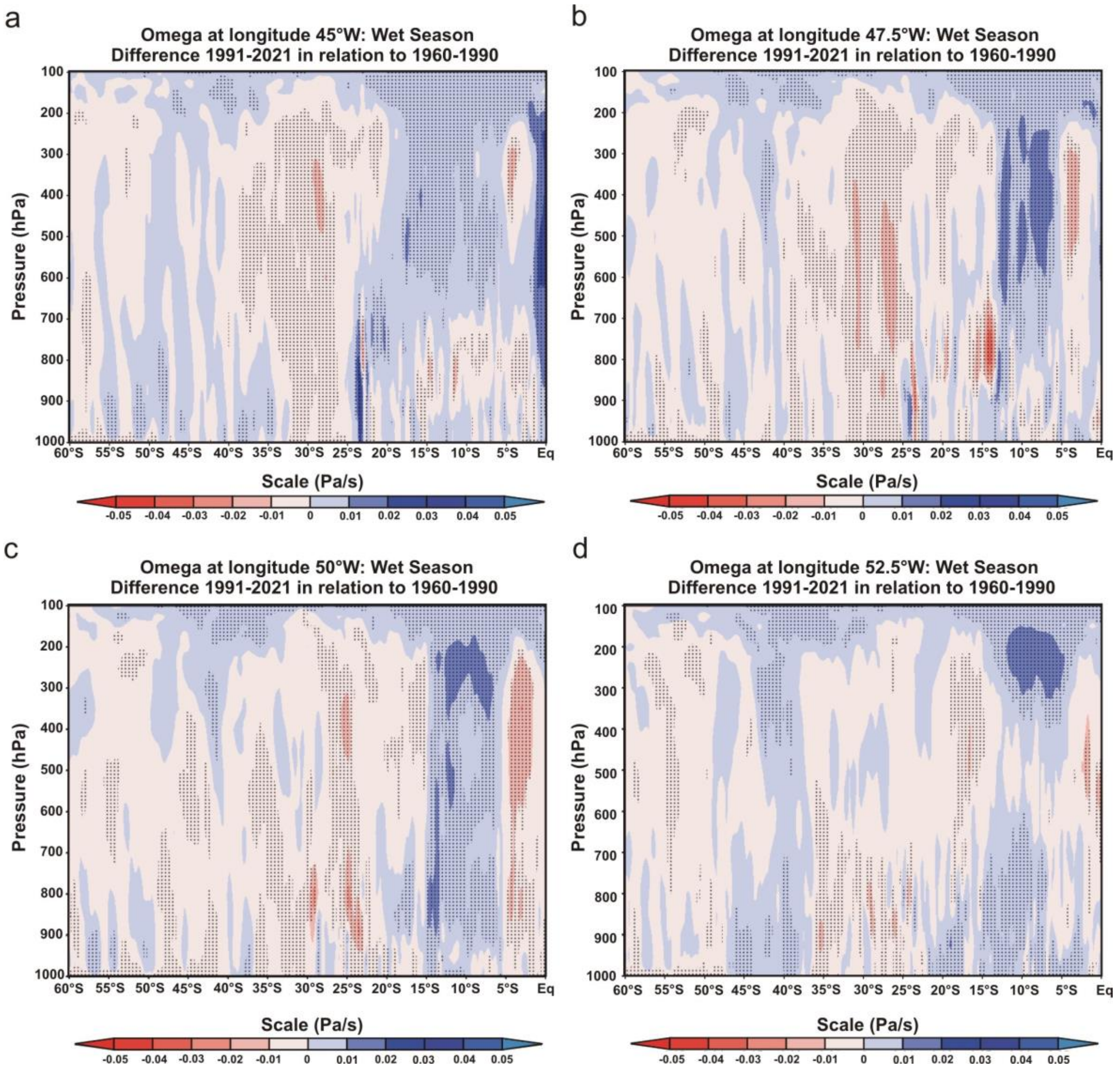
3.10 SUPPLEMENTARY MATERIAL



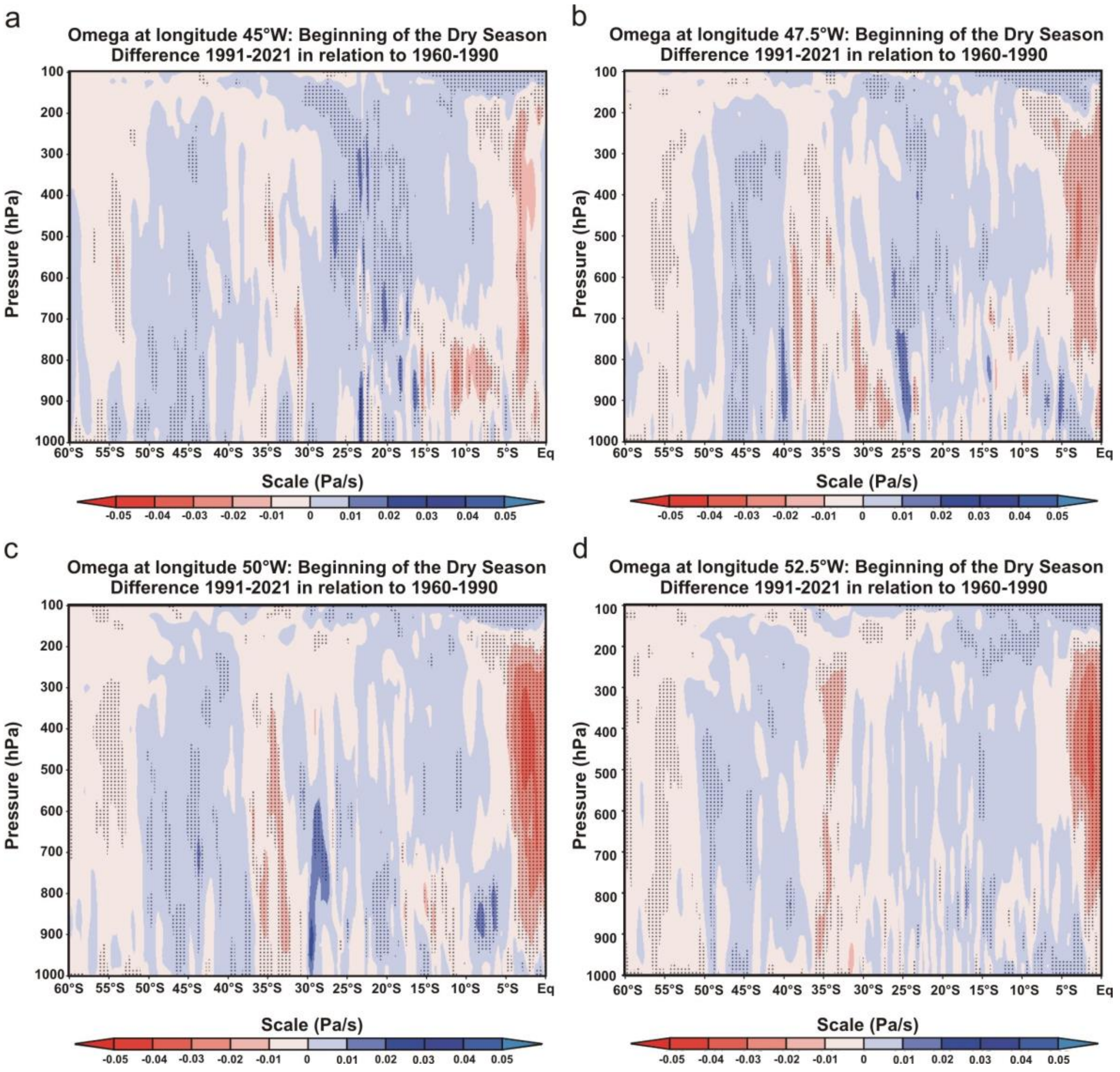
Supplementary Fig. S1. Local changes over the last six decades in total rainfall for all year periods. a─d, Local changes in total rainfall by comparing the climate normal 1991─2021 to the climate normal 1960─1990 in the wet season, the beginning of the dry season, the dry season, and the beginning of the wet season, respectively. The gray polygon show the official limits of the Brazilian Cerrado. Maps in the upper level were produced using ArcGIS (https://www.arcgis.com).



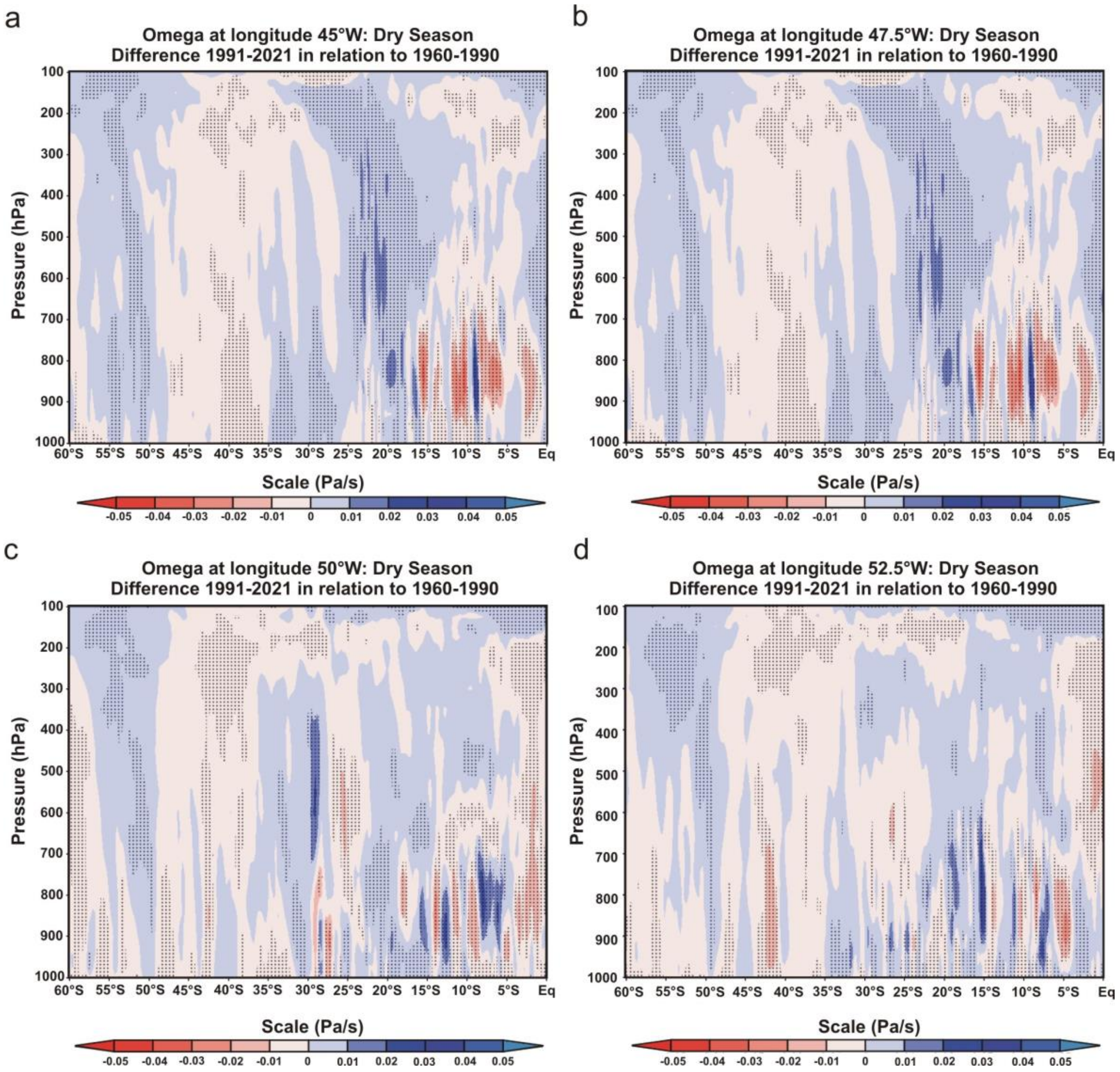
Supplementary Fig. S2. Local changes over the last six decades in frequency of rainy days for all year periods. a─d, Local changes in frequency of rainy days by comparing the climate normal 1991─2021 to the climate normal 1960─1990 in the wet season, the beginning of the dry season, the dry season, and the beginning of the wet season, respectively. The gray polygon show the official limits of the Brazilian Cerrado. Maps in the upper level were produced using ArcGIS (https://www.arcgis.com).



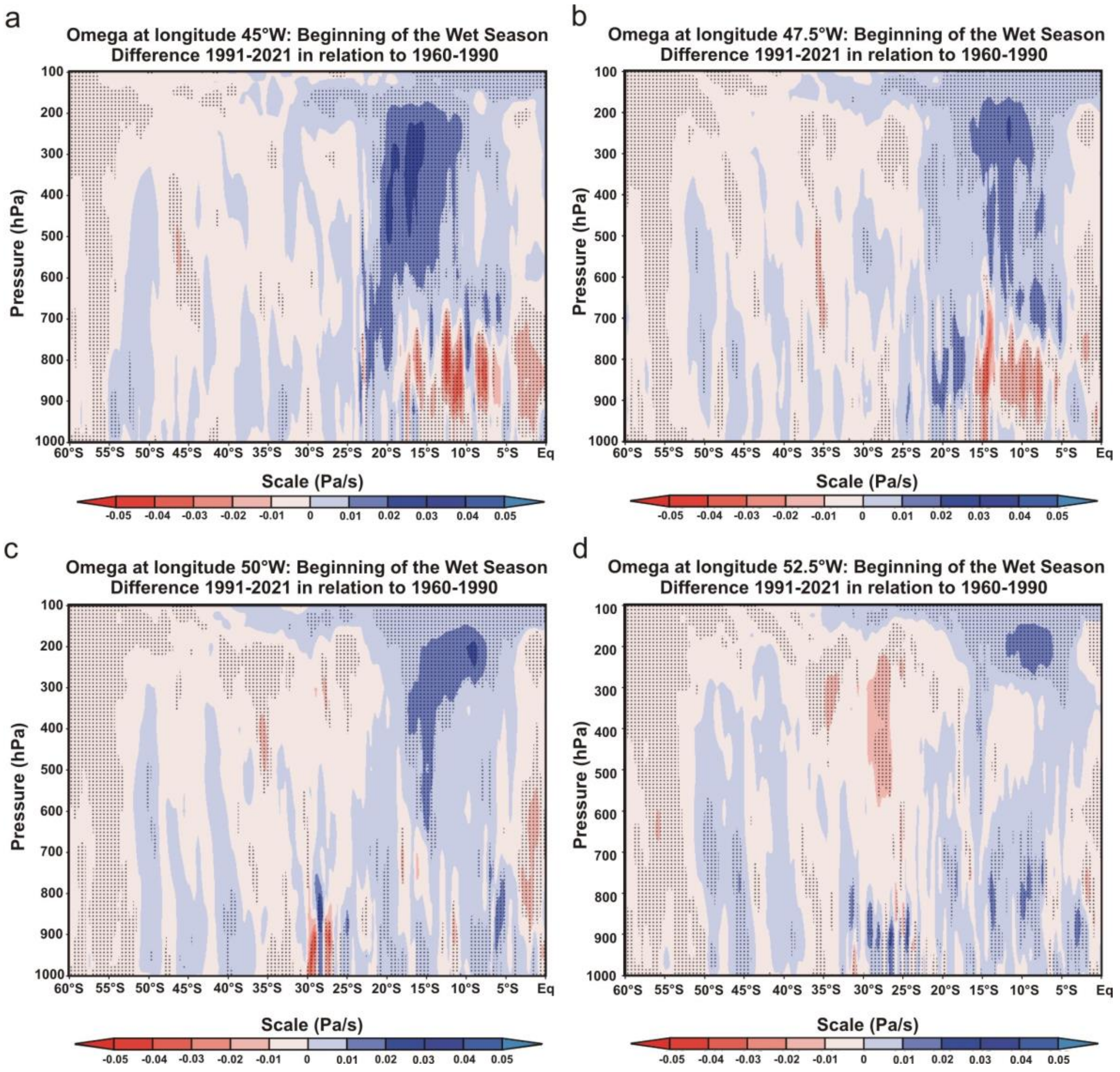
Supplementary Fig. S3. Changes in omega intensity between 1960-2021 during the wet season in the Brazilian Cerrado. a─d, Latitude-height cross sections of the vertical velocity of wind showing the changes in omega intensity (Pa/s) during the wet season in the meridians -45°, -47.5°, -50°, and -52,5°, respectively. The dotted areas represent locals with a significant difference ($p < 0.05$) between the climate normals 1991─2021 and 1960─1990.



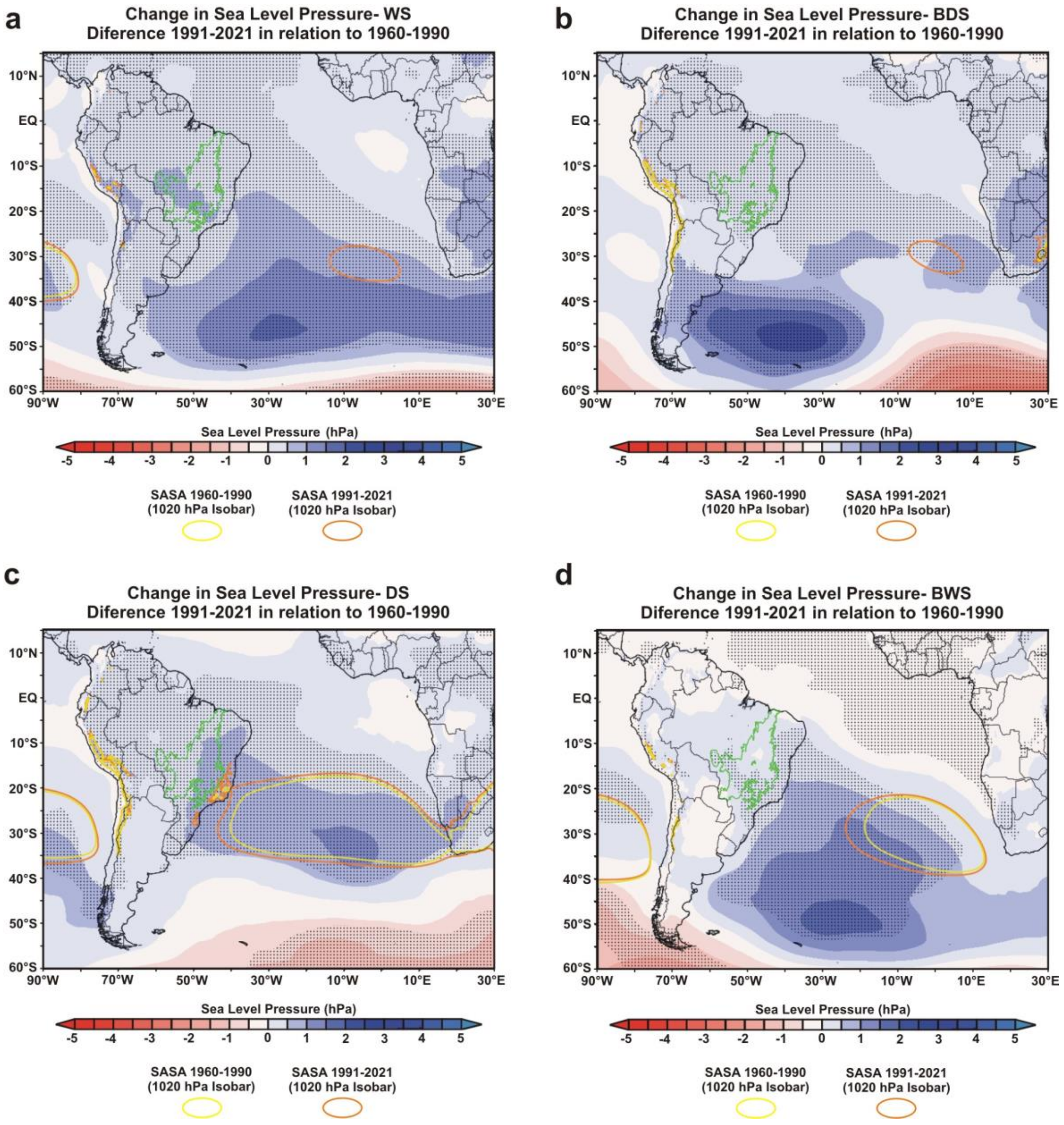
Supplementary Fig. S4. Changes in omega intensity between 1960-2021 during the beginning of dry season in the Brazilian Cerrado. a─d, Latitude-height cross sections of the vertical velocity of wind showing the changes in omega intensity (Pa/s) during the beginning of dry season in the meridians -45°, -47.5°, -50°, and -52,5°, respectively. The dotted areas represent locals with a significant difference ($p < 0.05$) between the climate normals 1991─2021 and 1960─1990.



Supplementary Fig. S5. Changes in omega intensity between 1960-2021 during the dry season in the Brazilian Cerrado. a─d, Latitude-height cross sections of the vertical velocity of wind showing the changes in omega intensity (Pa/s) during the dry season in the meridians -45°, -47.5°, -50°, and -52,5°, respectively. The dotted areas represent locals with a significant difference ($p < 0.05$) between the climate normals 1991─2021 and 1960─1990.



Supplementary Fig. S6. Changes in omega intensity between 1960-2021 during the beginning of wet season in the Brazilian Cerrado. a─d, Latitude-height cross sections of the vertical velocity of wind showing the changes in omega intensity (Pa/s) during the beginning of wet season in the meridians -45°, -47.5°, -50°, and -52,5°, respectively. The dotted areas represent locals with a significant difference ($p < 0.05$) between the climate normals and 1960─1990.



Supplementary Figure S7- Changes in Sea Level Pressure between 1960─2021 in the South America/South Atlantic domain. a-d, Sea Level Pressure changes recorded by ERA5 reanalysis in the Wet Season (WS), Beginning of Dry Season (BDS), Dry Season (DS), and Beginning of Wet Season (BWS), respectively. The dotted areas demonstrated a significant difference ($p < 0.05$) between 1991─2021 and 1960─1990 climate normals. The green polygon shows the official limits of the Brazilian Cerrado. The yellow and orange ellipses represent the 1020-hPa isobar and show the South Atlantic Subtropical Anticyclone (SASA) position/extension in 1960─1990 and 1991─2021, respectively. Maps in the upper level were produced using GrADS-Grid Analysis and Display System (http://opengrads.org).

Supplementary Table S1. Local changes in total rainfall over the last six decades in the Brazilian Cerrado. The absolute and proportional difference in total rainfall (mm) for each pluviometric station between 1991-2021 and 1960-1990. Where: WS- wet season; BDS- beginning of the dry season; DS- dry season; BWS- beginning of the wet season; Annual- total annual amount.

Pluviometric station	**Absolute and proportional difference in Total rainfall (mm) between 1991-2021 and 1960-1990**				
	WS	**BDS**	**DS**	**BWS**	**Annual**
Alto Araguaia	-38,9 (-3,9%)	-21,8 (-12,7%)	-25,8 (19,5	-54,3 (-13,8%)	-141 (-8,3%)
Alto Paraíso de Goiás	-140,6 (-14,7%)	6,3 (+4,6%)	-23,3 (-31,5%)	-89,3 (-21,1%)	-245 (-15,4%)
Alto Parnaíba	-113,4 (-11,9%)	-25,9 (-13,4%)	-25,8 (-58,1%)	-0,1 (0%)	-163,7 (-11,4%)
Aragarças	-36,5 (-3,6%)	6,8 (6,7%)	-43,3 (-44,5%)	-78,4 (-20,4%)	-150,8 (9,4%)
Arinos	-23,2 (-3,1%)	-19,2 (-19,7%)	-29,3 (61,9%)	-41,6 (-13,1%)	-111 (-9,1%)
Avaré	6,5 (+0,8%)	12,3 (+7,7%)	-6,3 (-2,5%)	4,7 (+2,1%)	22,7 (+1,6%)
Bady Bassit	-6,2 (-0,8%)	0,2 (+0,2%)	4,8 (+3,8%)	-24,4 (-9,3%)	-27,1 (-2%)
Balsas	-30,1 (-3,8%)	-19 (-10,5%)	-33,9 (-57,4%)	13,5 (6%)	-67,3 (-5,3%)
Bambuí	-4,2 (-0,5%)	10,5 (+8,7%)	-14,3 (-13,4%)	-35,3 (-10%)	-45,4 (-3%)
Bandeirantes	-101,1 (-10,6%)	-42,7 (-19,6%)	-46,3 (-19,9%)	-14,2 (-4,2%)	-210,7 (-12,1%)
Barra do Corda	-43,7 (-5,8%)	-28,5 (-11%)	-19,8 (-30,6%)	-7,2 (-5,6%)	-97,1 (-8,1%)
Barreiras	-68,2 (-9,4%)	-9,4 (-9,5%)	-27,3 (-67%)	-73,1 (-24,9%)	-175,9 (-15,2%)
Benjamin Barros	-61,2 (-6,2%)	-47,9 (-24,5%)	-41,5 (-30,9%)	1,3 (+0,5%)	-151,4 (-9,6%)
Boqueirão	-61 (-9,9%)	-12,1 (-11,9%)	-6,9 (-39,7%)	-21,9 (-10,5%0	-100 (-10,6%)
Brasília	-15,8 (-1,8%)	17,5 (+11,4%)	-23,9 (-29,1%)	0 (0%)	-22,7 (-1,5%)
Campina Verde	-44,7 (-5%)	-20,6 (-13,9%)	-15 (-13,8%)	-26,7 (-8,4%)	-107,5 (-7,3%)
Carolina	56,5 (+5,4)	13 (+3,5)	-27 (-28,9%)	-32,4 (-9,9%)	15,6 (+0,9%)
Catalão	19,4 (+2,0%)	-3,3 (-3%)	-13,7 (-18,9%)	-60,8 (-17,7%)	-60,8 (-4,1%)
Colinas do Maranhão	-39,8 (-5,1%)	-48,5 (-10,7%)	-24,2 (-33,5%)	15,3 (+10,4)	-98,1 (-7,6%)
Colinas do Tocantins	-0,9 (-0,1%)	38,5 (+14,2%)	-46,6 (-38,2%)	-59 (-14,2%)	-64,1 (-3,5%)
Correntina	-99,5 (-15,2%)	1,2 (+1,7%)	-11,3 (-58,3%)	-9,3 (-3,5%)	-117 (-11,7%)
Cristiano de Castro	-67,4 (-10,7%)	-29,5 (-20,2%)	-13,1 (-63,4%)	9,1 (+5,6%)	-100 (-10,4%)
Cuiabá	111,3 (+13,9%)	-21,6 (-11,8%)	-9,4 (-9,5%)	33,2 (+12,1%)	110,8 (+8,2%)
Diamantino	161,6 (+16,3%)	-9,9 (-5%)	-22,8 (-18,3%)	48,6 (+13,4%)	178,1 (+10,6%)
Fazenda Bom Jardim	104,6 (+16,9%)	-7,2 (-7,4%)	-7,1 (-39,5%)	29,5 (+15,25)	121,8 (+13,1%)
Fazenda Ingazeiro	-130,5 (-16,1%)	25,7 (26%)	-6,2 (-18,4%)	-58,6 (-17,8%)	-171,2 (-13,5%)
Formosa	8,3 (+0,9%)	-17,7 (-13,7%)	-20,9 (-34,9%)	-11,9 (-3,7%)	-41,6 (-3%)
Franca	54,7 (+5,5%)	-13,6 (-9,4%)	-16,1 (-11,4%)	-28,6 (-0,2%)	-3,2 (-0,2%)
Goiânia	62,2 (+6,5%)	12,4 (+8,0%)	-12,2 (-16,1%)	-22,1 (-5,7%)	40,7 (+2,6%)
Goiás Velho	-4,4 (-0,4%)	-19,1 (-13,1%0	3,5 (+6,2%)	-26,6 (-6,5%)	-51,9 (-2,9%)
Gouveia	-40,2 (-5,2%)	-10,1 (-10,5%)	-23,9 (-32,5%)	-31,6 (-9,3%)	-103,6 (-8,1%)
Gurupi	90,2 (+10,1%)	29,6 (+22,2%)	-28,1 (-45,8%)	-61,8 (22,7%)	30,7 (+2,3%)
Imperatriz do Maranhão	12,9 (+1,4%)	36,5 (+15,2%)	-27,9 (-32,9%)	-6,4 (-3,2%)	22,7 (+1,5%)
Iporá	-8,2 (-0,8%)	-2,1 (-1,7%)	-21,1 (-27,6%)	61 (+20,8)	27,6 (+1,8%)
Itajá	-49,2 (-5,1%)	-27,7 (-16,8%)	-18,9 (-15,3%)	-14,9 (-4,8%)	-111,6 (-7,2%)
Ituiutaba	32,1 (+3,8%)	-0,7 (-0,6%)	-19,8 (-21,1%)	-11,9 (-4%)	1,8 (+0,1%)
Janaúba	-29,3 (-5,8%)	-14,5 (-28,2%)	-15 (-64,1%)	-8,4 (-3,9%)	-66,2 (-8,3%)
Jaraguá de Goiás	12,2 (+1,1%)	-19,2 (-12%)	-24,3 (-31,2%)	-45,4 (-11,2%)	-77,9 (-4,6%)
Maracaju	-29,8 (-4,4%)	25,7 (+14,8%)	-7,9 (-3,2%)	-1,8 (-0,6%)	-7,9 (-0,6%)
Mozarlândia	-64,1 (-5,8%)	-12,2 (-9%)	-4,4 (-7,5%)	-14,8 (-4,3%)	-92 (-5,6%)
Niquelândia	-106,5 (9,6%)	-50,3 (-33,3%)	-22,2 (-33,6%)	-48,2 (-11,5%)	-234,7 (-13,4%)
Nova Xavantina	38,7 (+4%)	-28,4 (-22,6%)	-6 (-10%)	7,8 (+2,3%)	13,5 (+0,9%)
Novo Santo Antônio	-140,8 (-13,2%)	3,7 (+3%)	-25,1 (-50%)	-63,5 (-15,8%)	-225,5 (-13,7%)
Paraguaçu Paulista	6,2 (+0,9%)	31,6 (+22,2%)	-0,7 (-0,3%)	-28,7 (-9,9%)	15,8 (+1,1%)
Paranatinga	-36,7 (-3,2%)	-17,1 (-10,1%)	-44,6 (-37,7%)	-54,1 (-12,5%)	-154,3 (-8,2%)
Pedras de Maria Cruz	-65,3 (-10,6%)	-15,1 (-28,1%)	-17,8 (-64,4%)	-14,3 (-5,6%)	-111,9 (-11,8%)
Pedro Afonso	-54 (-5%)	64,5 (+34,5%)	-28,9 (-35,5%)	-42 (-11,1%)	-56,7 (-3,3%)
Pedro Leopoldo	43,7 (+5,4%)	4,4 (+7%)	-7 (-10,2%)	-44,2 (-13,2%)	-2,4 (-0,2%)
Peixe	-90,1 (-8,8%)	-5,2 (-3,4%)	-17,7 (-32,8%)	-61 (-17,8%)	-172 (-10,9%)
Pontalina	-53,6 (-5,8%)	-19,8 (-28,4%)	-14,6 (19,7%)	21,5 (+7,3%)	-74,4 (-5,2%)
Ponte Firme	-27,8 (-2,8%)	-2,1 (-2,3%)	-11,9 (-22,2%)	-63,9 (-17,5%)	-105,6 (-7%)
Porangatu	-62,9 (-5,8%)	0,9 (+0,8%)	-30 (-45,8%)	-12,1 (-3,5%)	-103,2 (-6,4%)
Porto Nacional	91,1 (+9%)	49,9 (27%)	-10,9 (-18%)	-11,8 (-3,3%)	121,4 (+7,6%)
Porto Uerê	84,8 (+12.8%)	-20,4 (-11,2%)	2,2 (+1,15)	33,5(+14,6%)	97,1 (+7,6%)
Porto Velho	-11,9 (-1,6%)	6,3 (+4,4%)	-18 (-10,5%)	2 (+0,8%)	-23,1 (-1,8%)
Ribas do Rio Pardo	-0,5 (-0,1%)	-16,9 (-9,2%)	-8,7 (-4,9%)	-4,9 (-1,6%)	-34,2 (-2,4%)
Ribeiro Gonçalves	68,1 (+10,5)	17,4 (+11,4)	-7,3 (-23%)	-16,7 (-8,6%)	65,5 (+6,4%)
Rondonópolis	-6,3 (-0,7%)	-60,4 (-35,1%)	-11,8 (-11,5%)	17,7 (+6,2%)	-68,7 (-4,8%)
Salitre	70,5 (+8,5%)	-4,5 (-4%)	-18,7 (-17,1%)	-48,4 (-13,3%)	-1,8 (-0,1%)
Santa Juliana	-120,1 (-11,6%)	-1,1 (-0,9%)	-11,3 (-11,5%)	-84,4 (-21,6%)	-215,5 (-13,1%)
Santa Rita de Cássia	0,3 (0,1%)	-12,2 (-11,6%)	-9,9 (-50,9%)	12,6 (+5,8%)	-8,5 (-0,9%)
São Carlos	35,3 (+4%)	17,2 (+13,6%)	-3,8 (-2,5%)	-1,4 (-0,5%)	48,2 (+3,3%)
São Gonçalo	-19,8 (-3,3%)	-11,8 (-17,3%)	-2,4 (-13%)	-9 (-3,6%)	-41,5 (-4,4%)

São Romão	37 (+5,8%)	-8,4 (12,8%)	-6,8 (25,8%)	-53,3 (-18,9%)	-30,4 (-3%)
Taguatinga	-98,2 (-8,6%)	24 (+14,6%)	-25,4 (-52,7%)	-38,3 (-9,7%)	-137,1 (-7,8%)
Tesouro	-25,7 (-2,2%)	-25 (-14,1%)	-49,6 (-38,4%)	0,7 (+0,2%)	-98,3 (-5,3%)
Torixoreu	-49,1 (-5,3%)	23,8 (27,9%)	-19,8 (-24,6%)	-37,1 (-12,5%)	-82,1 (-5,9%)
Unaí	-18,2 (-2,2%)	-14,3 (-12,7%)	-15,8 (-30,5%)	1,3 (+0,4%)	-44,4 (-3,4%)
Varzea da Palma	-140,1 (-17,7%)	-36,8 (-43,9%)	-21,5 (-45%)	-63,8 (-19,4%)	-261,2 (-20,8%)
Vau do Balsamo	-111,1 (-14,7%)	-21,6 (-10,4%)	-11 (-4,9%)	-47,6 (-15,4%)	-197,2 (-13,2%)

Supplementary Table S2. Local changes in frequency of rainy days over the last six decades in the Brazilian Cerrado. The absolute and proportional difference in total rainfall (mm) for each pluviometric station between 1991-2021 and 1960-1990. Where: WS- wet season; BDS- beginning of the dry season; DS- dry season; BWS- beginning of the wet season; Annual- total annual amount.

Pluviometric station	Absolute and relative difference in number of rainy days between 1991-2021 and 1960-1990				
	WS	BDS	DS	BWS	Annual
Alto Araguaia	-0.7 (-0.9%)	-2.6 (-16.7%)	-5.3 (37.7%)	0.3 (1%)	-8.4 (-6.4%)
Alto Paraíso de Goiás	2.3 (+3.7%)	2.7 (+22.7%0	-2.4 (-32.5%)	-3.1 (-10.3%)	-0.5 (-0.4%)
Alto Parnaíba	-1.6 (-2.2%)	1.6 (+9.7%)	-2.1 (-37.5%)	-13.2 (-3.4%)	-5.5 (-4.6%)
Aragarças	1.1 (+1.6%)	-1.5 (-13.4%)	-3.4 (-34.6%)	-1.2 (-4.7%)	-5 (-4.3%)
Arinos	6.7 (+13.9%)	1 (+14.4%)	-1.2 (-26.2%)	-0.7 (-3.1%)	5.8 (+6.9%)
Avaré	-2.9 (-5.3%)	-1.6 (-11.6%)	-4.4 (-18.8%)	-0.7 (-4.1%)	-9.8 (-8.8%)
Bady Bassit	-7.4 (-14.9%)	-1.7 (-18.4%)	-2.4 (-20.3%)	-4 (-22.1%)	-15.5 (-17.4%)
Balsas	NA	NA	NA	NA	NA
Bambuí	6.4 (+11%)	1.7 (+15.4%)	-0.8 (-6%)	1.1 (+4.4%)	8.4 (+7.9%)
Bandeirantes	NA	NA	NA	NA	NA
Barra do Corda	-1.5 (-2.3%)	0.2 (+0.7%)	-2.1 (-18.3%)	-2.8 (-18.8%0	-6.3 (-5.3%)
Barreiras	-7.7 (-12.9%)	-2.5 (-18%)	-2.8 (-47.9%)	-6.7 (-25.7%)	-19.7 (-18.7%)
Benjamin Barros	-11.1 (-14%)	-6.4 (-33.7%)	-4.6 (-34.4%)	-4 (-16.3%)	-26 (-19.1%)
Boqueirão	2.3 (+5.5%)	0.5 (5.5%)	-0.8 (-31.3%)	0 (0)	1.9 (+1.9%)
Brasília	4.6 (+6.5)	0.6 (+4.4%)	-1.3 (-13.4%)	-0.2 (-2.9%)	3.8 (+2.9%)
Campina Verde	-6.5 (-9.9%)	-3.3 (-24.7%)	-4.5 (-32.8%)	-1.5 (-6.8%)	-15.9 (-13.8%)
Carolina	1.2 (1.6%)	-2.1 (-6.8%)	-3 (-26.8%)	-2.9 (11.5%)	1 (+0.7%)
Catalão	0.2 (+0.2%)	-0.4 (-3.2%)	-1.9 (-19.1%)	-0.9 (-3.3%)	-3.1 (2.6%)
Colinas do Maranhão	0.6 (+1.1%)	1.2 (+3.6%)	-2 (-24.3%)	0.7 (+5.4%)	-0.2 (-0.2%)
Colinas do Tocantins	NA	NA	NA	NA	NA
Correntina	0.4 (+1%)	+0.6 (+9.5%)	-1 (30%)	-0.8 (-4.1%)	-0.8 (-1.1%)
Cristiano de Castro	-6.5 (-14.7%)	-2.8 (-22.6%)	-0.4 (-17.9%)	0.5 (+4.4%)	-9.2 (-13.1%)
Cuiabá	-7 (-9.6%)	-3.1 (-18.2%)	-3.3 (-27.4%)	-4.1 (-16.9%)	-17.5 (-13.5%)
Diamantino	-0.9 (-1.3%)	-0.8 (-5%)	-0.3 (-3.8%)	-1 (-3.7%)	-3 (-2.5%)
Fazenda Bom Jardim	5.7 (+16.4%)	2.5 (+43.1%)	0 (0)	4.3 (+12.6%)	12.6 (+23.3%)
Fazenda Ingazeiro	-11.9 (-20.9%)	-1.1 (-12.6%)	-1.2 (-31.6%)	-6.2 (-26.1%)	-20.4 (-21.8)
Formosa	0.2 (+0.2%)	-0.1 (-0.8%)	-1.8 (-25.3%)	0.8 (+2.8%)	-1 (-0.9%)
Franca	0.1 (+0.1%)	-2 (-13.8%)	-3.4 (-20.6%)	-1.6 (-5.8%)	-6.9 (-5.3%)
Goiânia	-1 (-1.3%)	-0.7 (-4.7%)	-2.4 (-21.8%)	-1.1 (-3.3%)	-5.3 (-3.8%)
Goiás Velho	6.7 (+9.1%)	0.4 (+3.6%)	0.5 (+6.4%)	2.4 (+8.6%)	10 (+8.3%)
Gouveia	-3.6 (-6.4%)	-0.2 (-2.1%)	-1.4 (-13.3%)	-4.3 (-15.8%)	-9.4 (-8.9%)
Gurupi	-11.3 (-17.8%)	-2.7 (-21.6%)	-3 (-52.8%)	-5.4 (-25.7%)	-22.4 (-21.8%)
Imperatriz do Maranhão	0 (0)	2.6 (+11.6%)	-2.4 (-22%)	0.1 (+0.5%)	0.3 (0.3%)
Iporá	3.3 (+5%)	1.2 (+12.7%)	-0.8 (-11%)	2.2 (+9.1%)	5.9 (+5.5%)
Itajá	1.6 (+2.9%)	-2.3 (-20.2%)	-1.6 (-14.2%)	0.6 (+2.9%)	-1.7 (-1.8%)
Ituiutaba	9.1 (+17%)	1.3 (+15%)	-0.7 (-8%)	2 (+9.7%)	11.7 (+12.7%)
Janaúba	-0.8 (-2%)	-0.2 (-5%)	-2.3 (-64.3%)	-2.7 (-14.7%)	-6 (-9.4%)
Jaraguá de Goiás	1.7 (+2.7%)	-0.9 (-8.4%)	-2.9 (-37.9%)	-2.2 (-9.3%)	-4.4 (-4.4%)
Maracaju	-1.2 (-2.8%)	1 (+9%)	0.2 (+1.2%)	-0.1 (-0.3%)	-0.1 (-0.1%)
Mozarlândia	3.6 (+5.2%)	-0.2 (-1.4%)	-2.2 (-28.6%)	0.3 (+1%)	1.4 (+1.3%)
Niquelândia	-10 (-13.5%)	-4.6 (-31.8%)	-4.1 (-50.7%)	-6.7 (-21.3%)	-25.4 (-19.8%)
Nova Xavantina	3.6 (+5.2%)	-0.2 (-1.4%)	-2.2 (-28.6%)	0.3 (+1%)	1.4 (+1.3%)
Novo Santo Antônio	2 (+4%)	-0.4 (-4.3%)	-1.4 (-33%)	-0.5 (-2.8%)	-0.4 (-0.4%)
Paraguaçu Paulista	-10.4 (-19.7%)	-1.6 (-14.2%)	-4.8 (-23.1%)	-3.5 (-18.7%)	-20.1 (-19.4%)
Paranatinga	NA	NA	NA	NA	NA
Pedras de Maria Cruz	1.5 (+3.8%)	-0.4 (-7.2%)	-1.4 (-34.5%)	-0.9 (-4.9%)	-1.2 (-1.8%)
Pedro Afonso	-1.9 (-2.3%)	4.3 (+23.9%)	-2.8 (-28.9%)	-1.6 (-5.4%)	-1.9 (-1.3%)
Pedro Leopoldo	3.1 (+6.3%)	1.9 (+28.5%)	-0.2 (-1.9%)	-1.5 (-6.5%)	3.4 (+3.8%)
Peixe	-3.2 (-4.2%)	1.4 (+10%)	-3.3 (-46.6%)	-1.5 (-5.8%)	-6.6 (-5.4%)
Pontalina	-2.1(11.2%)	-1.5 (-13.2%)	-3 (-31.4%)	-0.1 (-0.3%)	-6.8 (-6.3%)
Ponte Firme	-7 (-12.8%)	-0.7 (-0.7%)	-1 (-20%)	-5.8 (24.4%)	-14.5 (-15.8%)
Porangatu	-6.2 (-9.8%)	-1.6 (-15.4%)	-2.3 (-43.4%)	-1.9 (-8.5%)	-11.9 (-11%)
Porto Nacional	-2 (-2.5%)	1.5 (7.9%)	-1.5 (-22.3%)	-2.3 (-8%)	-4.2 (-3.2%)
Porto Uerê	-1.9 (-5.2%)	-1.7 (-17.1%)	-1.6 (-12%)	-1.1 (-8%)	-6.3 (-8.5%)
Porto Velho	NA	NA	NA	NA	NA
Ribas do Rio Pardo	-10.6 (-18.5%)	-4.4 (-32.7%)	-4 (-25.8%)	-1.5 (-7.7%)	-20.5 (-19.4%)
Ribeiro Gonçalves	5.3 (+13.7%)	2.6 (+26.1%)	-1.4 (-39.8)	2.1 (+23%)	8.7 (14.1%)
Rondonópolis	0.7 (+1.1%)	-2.7 (-21.4%)	-2.3 (-23.2%)	-0.1 (-0.6%)	-4.4 (-4.1%)
Salitre	NA	NA	NA	NA	NA
Santa Juliana	-9.5 (-13.6%)	-2.9 (-22.6%)	-2.6 (-22.8%)	-4.8 (-17.8%)	-19.9 (-16.4%)
Santa Rita de Cássia	3.9 (+8.7%)	1.1 (+12.1%)	-0.5 9-22.4%)	0.6 (+3.8%)	5.2 (+7%)
São Carlos	2.5 (+4%)	-0.9 (-6.3%)	-1 (5.7%)	-1 (-4%)	0 (0)
São Gonçalo	2.5 (+5.9%)	0.5 (+7.7%)	-0.2 (-9.2%)	1 (+5.1%)	3.7 (+5.3%)

São Romão	4.8 (+11%)	0.4 (+6.5%)	-0.1 (-3.3%)	1.1 (+5.6%)	6.2 (8.6%)
Taguatinga	-6.6 (-8.4%)	0.5 (+3.2%)	-2.5 (-43.5%)	-4.1 (-13.5%)	-12.7 (-9.8%)
Tesouro	2.4 (+3.7%)	-0.9 (7.7%)	-2.4 (25.6%)	3.1 (+14.7%)	2.5 (+2.3%)
Torixoreu	-5.7 (-8.9%)	-2.1 (-21.9%)	-2.5 (-33%)	-3.8 (-16.3%)	-14 (-13.5%)
Unaí	4.9 (+9.1%)	0.6 (+6.8%)	-0.8 (-14.4%)	0.2 (+0.9%)	4.9 (+5.3%)
Varzea da Palma	-4.5 (-9.2%)	-1.1 (-15.1%)	-1.3 (-24.8%)	-2.8 (-12.2%)	-9.8 (-11.5%)
Vau do Balsamo	-11.8 (-21%)	-3.9 (-26.6%)	-3.8 (-20.3%)	-3.3 (-16.1%)	-22.8 (-20.7%)

Supplementary Table S3. Identification and location of pluviometric stations used in this study. List of pluviometric stations and their respective latitude, longitude, state agency, and data period analyzed in the study. Where: INMET- Instituto Nacional de Meteorologia; CPRM- Companhia de Pesquisa de Recursos Minerais; DAEE-SP- Departamento de Águas e Energia Elétrica do Estado de São Paulo.

Pluviometric station	Latitude	Longitude	Agency	Period analyzed
Alto Araguaia	-17,3	-53,22	CPRM	1969-2021
Alto Paraíso de Goiás	-14,13	-47,51	CPRM	1969-2021
Alto Parnaíba	-9,1	-45,93	INMET	1977-2021
Aragarças	-15,90	-52,24	INMET	1971-2021
Arinos	-15,92	-46,12	CPRM	1963-2021
Avaré	-23,1	-48,92	DAEE-SP	1960-2021
Bady Bassit	-20,92	-49,45	DAEE-SP	1960-2021
Balsas	-7,53	-46,03	INMET	1977-2021
Bambuí	-20,02	-45,96	CPRM	1960-2021
Bandeirantes	-19,91	-54,35	CPRM	1976-2021
Barra do Corda	-5,5	-44,93	INMET	1970-2021
Barreiras	-12,15	-45,01	INMET	1973-2021
Benjamin Barros	-17,70	-51,89	CPRM	1974-2021
Boqueirão	-11,36	-43,85	CPRM	1960-2021
Brasília	-15,78	-47,92	INMET	1963-2021
Campina Verde	-19,54	-49,48	CPRM	1976-2021
Carolina	-7,33	-47,46	INMET	1962-2021
Catalão	-18,15	-47,96	INMET	1961-2021
Colinas do Maranhão	-6,03	-44,23	CPRM	1969-2021
Colinas do Tocantins	-8,05	-48,48	CPRM	1972-2021
Correntina	-13,34	-44,65	CPRM	1972-2021
Cristiano de Castro	-8,81	-44,21	CPRM	1963-2021
Cuiabá	-15,62	-56,11	INMET	1960-2021
Diamantino	-14,41	-56,45	INMET	1969-2021
Fazenda Bom Jardim	-10,99	-10,99	CPRM	1978-2021
Fazenda Ingazeiro	-13,69	-46,57	CPRM	1969-2021
Formosa	-15,54	-47,33	INMET	1974-2021
Franca	-20,52	-47,20	DAEE-SP	1960-2021
Goiânia	-16,67	-49,26	INMET	1961-2021
Goiás Velho	-15,94	-50,14	INMET	1961-2021
Gouveia	-18,46	-43,74	CPRM	1960-2021
Gurupi	-11,74	-49,14	CPRM	1972-2021
Imperatriz do Maranhão	-5,54	-47,48	INMET	1977-2021
Iporá	-16,42	-51,12	CPRM	1974-2021
Itajá	-19,14	-51,53	CPRM	1973-2021
Ituiutaba	-18,94	-49,46	CPRM	1968-2021
Janaúba	-15,77	-43,27	CPRM	1970-2021
Jaraguá de Goiás	-15,76	-49,34	CPRM	1965-2021
Maracaju	-21,61	-55,13	CPRM	1973-2021
Mozarlândia	-14,74	-50,58	CPRM	1974-2020
Niquelândia	-14,48	-48,46	CPRM	1970-2021
Nova Xavantina	-14,67	-52,36	CPRM	1969-2021
Novo Santo Antônio	-12,29	-50,96	CPRM	1970-2021
Paraguaçu Paulista	-22,42	-50,87	DAEE-SP	1960-2020
Paranatinga	-14,42	-54,05	CPRM	1974-2021
Pedras de Maria Cruz	-15,6	-44,39	CPRM	1973-2021
Pedro Afonso	-8,97	-48,18	INMET	1978-2021
Pedro Leopoldo	-19,63	-44,05	CPRM	1960-2021
Peixe	-12,02	-48,35	INMET	1976-2021
Pontalina	-17,51	-49,44	CPRM	1974-2021
Ponte Firme	-18,03	-46,41	CPRM	1960-2021
Porangatu	-13,41	-49,16	CPRM	1974-2021
Porto Nacional	-10,76	-48,42	INMET	1960-2021
Porto Uerê	-21,73	-52,33	CPRM	1973-2021
Porto Velho	-20,80	-52,38	CPRM	1973-2021
Ribas do Rio Pardo	-20,44	-53,75	CPRM	1973-2021
Ribeiro Gonçalves	-7,56	-45,24	CPRM	1962-2021
Rondonópolis	-16,47	-54,66	CPRM	1971-2021
Salitre	-19,07	-46,79	CPRM	1967-2021
Santa Juliana	-19,31	-47,52	CPRM	1960-2021
Santa Rita de Cássia	-11,00	-44,52	INMET	1960-2021
São Carlos	-21,98	-47,88	INMET	1961-2021
São Gonçalo	-14,31	-44,46	CPRM	1960-2021
São Romão	-16,37	-45,08	CPRM	1960-2021

Taguatinga	-12,40	-46,41	INMET	1974-2021
Tesouro	-16,08	-53,55	CPRM	1972-2021
Torixoreu	-16,2	-52,55	CPRM	1975-2021
Unaí	-16,35	-46,89	CPRM	1965-2021
Varzea da Palma	-17,59	-44,70	CPRM	1960-2021
Vau do Balsamo	-20,99	-54,50	CPRM	1973-2021

Supplementary Table S4. Identification of alternative pluviometric stations used to fill in missing values from the main pluviometric stations. List of pluviometric stations and their respective missing values amount (%), alternative pluviometric station, state agency, and distance between pluviometric stations (km). Where: INMET- Instituto Nacional de Meteorologia; CPRM- Companhia de Pesquisa de Recursos Minerais; DAEE-SP- Departamento de Águas e Energia Elétrica do Estado de São Paulo; CEMADEN- Centro Nacional de Monitoramento e Alertas de Desastres Naturais; CODEVASF- Companhia de Desenvolvimento dos Vales do São Francisco e do Parnaíba.

Pluviometric station	Missing values	Alternative pluviometric station	Agency	Distance between pluviometric stations
Alto Araguaia	2%	Fazenda Babilônia	CPRM	13 km
Alto Paraíso de Goiás	4,5%	Alto Paraíso de Goiás	INMET	<5 km
Alto Parnaíba	8,5%	Alto Parnaíba	CPRM	<5 km
Aragarças	7,6%	Bom Jardim de Goiás	CPRM	35 km
Arinos	0,4%	Arinos	INMET	< 5km
Avaré	1,9%	Cerqueira Cesar	DAEE-SP	25 km
Bady Bassit	1,5%	São José do Rio Preto	DAEE-SP	12 km
Balsas	5%	Balsas	CEMADEN	< 5km
Bambuí	1,4%	Bambuí	INMET	< 5km
Bandeirantes	14,4%	Jaguarí	CPRM	21 km
Barra do Corda	0,5%	Flores	CPRM	34 km
Barreiras	4,7%	Barreiras	CODEVASF	<5 km
Benjamin Barros	3,1%	Jataí	INMET	25 km
Boqueirão	0,2%	Fazenda Macambira	CPRM	43 km
Brasília	0%	–	–	–
Campina Verde	0,5%	Campina Verde	INMET	< 5km
Carolina	0%	–	–	–
Catalão	3,7%	Três Ranchos	CPRM	26 km
Colinas do Maranhão	0,6%	Colinas	INMET	<5 km
Colinas do Tocantins	0,1%	Fazenda Primavera	CPRM	45 km
Correntina	8,6%	Correntina	INMET	<5 km
Cristiano de Castro	8,2%	Bom Jesus do Piauí	INMET	31 km
Cuiabá	4,1%	N.Sª. do Livramento	CPRM	26 km
Diamantino	2,5%	Nortelândia	CPRM	40 km
Fazenda Bom Jardim	2,1%	Formosa do Rio Preto	CPRM	37 km
Fazenda Ingazeiro	5,5%	Posse	INMET	47 km
Formosa	1,3%	Taquara	CAESB	20 km
Franca	6,9%	Franca	INMET	<5 km
Goiânia	0,8%	Trindade	CPRM	22 km
Goiás Velho	5,6%	Itaberaí	CPRM	35 km
Gouveia	3,3%	Usina Parauna	CPRM	31 km
Gurupi	1,8%	Gurupi	INMET	<5 km
Imperatriz do Maranhão	4,2%	Buritirama	CPRM	51 km
Iporá	3,8%	Israelândia	CPRM	25 km
Itajá	2%	Cassilândia	INMET	19 km
Ituiutaba	3,7%	Ituituva	INMET	< 5km
Janaúba	0,6%	Janaúba	INMET	< 5km
Jaraguá de Goiás	2,4%	Pirenópolis	INMET	40 km
Maracaju	2,7%	Maracaju	CEMADEN	< 5km
Mozarlândia	0,8%	Lagoa da Flecha	CPRM	46 km
Niquelândia	2,2%	Niquelândia	CEMADEN	<5 km
Nova Xavantina	0,9%	Nova Xavantina	INMET	<5 km
Novo Santo Antônio	1,3%	Vila Berrante	CPRM	60 km
Paraguaçu Paulista	3,4%	Lutércia	DAEE-SP	19 km
Paranatinga	3,4%	Passagem BR309	CPRM	17 km
Pedras de Maria Cruz	5,2%	Januária	INMET	14 km
Pedro Afonso	0,2%	Guaraí	CPRM	40 km
Pedro Leopoldo	1,3%	Ponte Raul Soares	CPRM	14 km
Peixe	2,5%	Peixe	CEMADEN	<5 km
Pontalina	1,9%	Morrinhos	CPRM	40 km
Ponte Firme	0,1%	João Pinheiro	INMET	41 km
Porangatu	1,2%	Entroncamento São Miguel	CPRM	34 km
Porto Nacional	2,4%	Fátima	CPRM	50 km
Porto Uerê	0,6%	Presidente Epitácio	DAEE-SP	20 km
Porto Velho	2%	Garcias	CPRM	28 km
Ribas do Rio Pardo	5,9%	Alegre	CPRM	31 km
Ribeiro Gonçalves	0,1%	Fazenda Tigre	CPRM	45 km

Rondonópolis	2,5%	Vale Rico	CPRM	46 km
Salitre	0,3%	Serra do Salitre	CPRM	12 km
Santa Juliana	0,4%	Perdizes	CPRM	24 km
Santa Rita de Cássia	1,2%	Mansidão	DNOS	58 km
São Carlos	5,1%	Vila Carmen	CPRM	<5 km
São Gonçalo	0,1%	Lagoa das Pedras	CPRM	11 km
São Romão	0,2%	São Romão	INMET	< 5km
Taguatinga	7,6%	Ponte Alta do Tocantins	CPRM	34 km
Tesouro	2,5%	Guiratinga	CPRM	36 km
Torixoreu	1,9%	Baliza	CEMADEN	<5 km
Unaí	2,9%	Unaí	INMET	< 5km
Várzea da Palma	0,9%	Pedra de Santana	CPRM	26 km
Vau do Balsamo	0,8%	Sidrolândia	CPRM	45 km

CAPITULO 4: CLIMATE CHANGE IN THE BRAZILIAN CERRADO: A LOOMING THREAT TO TERRESTRIAL BIODIVERSITY

Este artigo será submetido como um artigo de revisão na revista *Global Change Biology*. Portanto, o estilo e formatação do seguem as normas da revista.

Cerrado durante o auge do período seco, município de Minaçú (GO), ao norte da barragem de Serra da Mesa, próximo à divisa dos estados de Goiás e Tocantins. Foto: Luiz Flamarion B. Oliveira (5/9/2018)

Quando o Sol traga o Cerrado
Tudo fica amarronzado
Cai no chão densa folhagem
Um tapete de aninhagem
Para o solo não ser pó
Plantas tortas se protegem do forte Sol
A cortiça é o isolante
e a cutícula brilhante é o guarda-sol
Na seca o céu fica desestrelado
Muitos bichos enterrados
Grossas sementes dormindo
Ante o Fogo que vem vindo

Paulo Robson de Souza
Trecho extraído do poema Duas Estações

CLIMATE CHANGE IN THE BRAZILIAN CERRADO: A LOOMING THREAT TO TERRESTRIAL BIODIVERSITY

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ABSTRACT

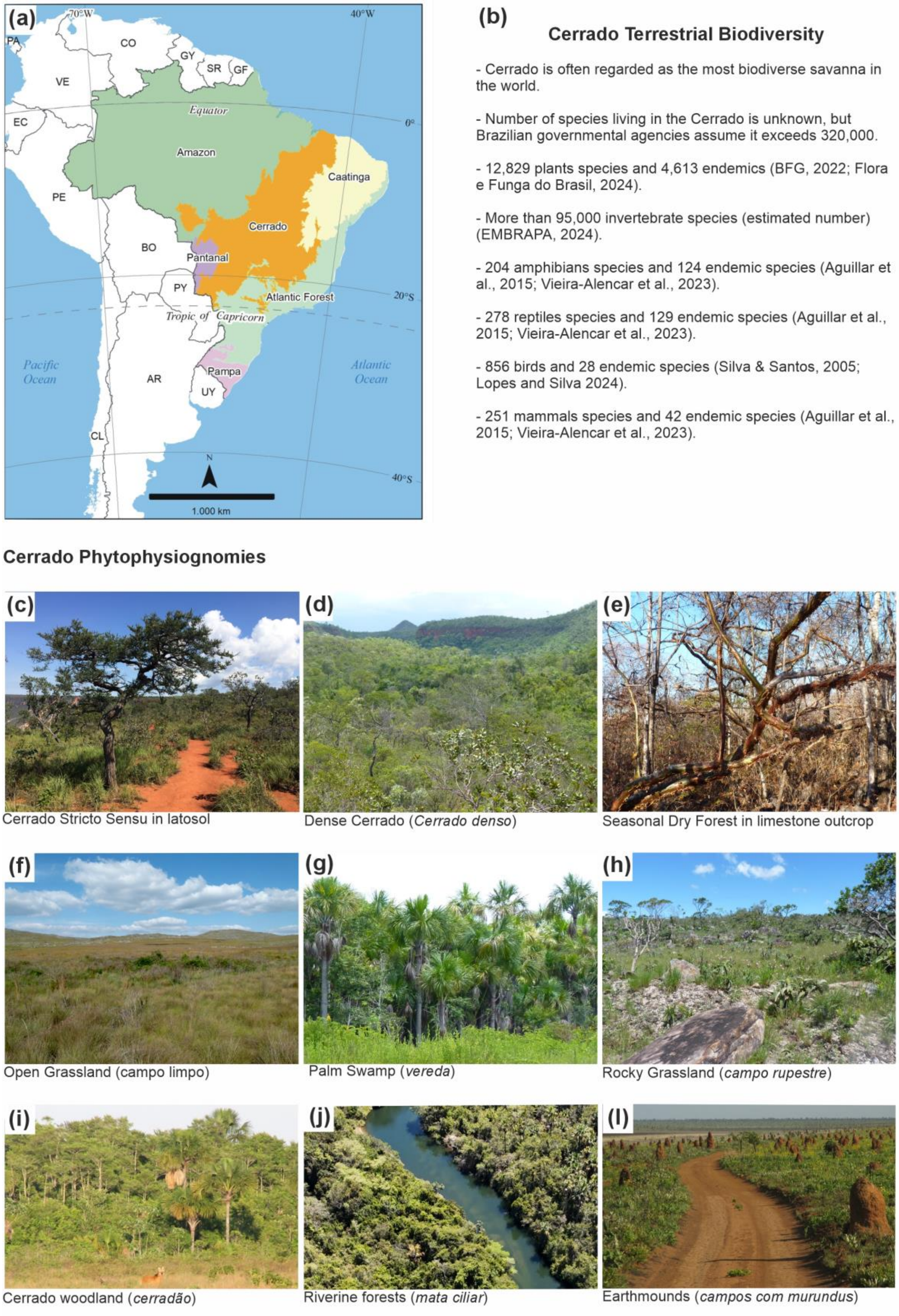
Over the past 5,000 years, the stable climate seasonality of the Brazilian Cerrado has played a crucial role in shaping the life history strategies of species and the structure of the ecological communities of this global biodiversity hotspot. However, recent studies have shown that this ecoregion is becoming progressively hotter and drier, with a notable lengthening and intensification of the dry season. In this review, we examine the origins and extension of climate change and its effects on various taxonomic groups of terrestrial biodiversity, with an emphasis on current impacts rather than hypothetical scenarios based on future projections. The decline in annual rainfall is attributed to three key factors: the intensification and expansion of the South Atlantic Subtropical Anticyclone, the warming of northern tropical Atlantic waters, and diminished evapotranspiration resulting from the large-scale conversion of native vegetation to agricultural land or pasture. The evapotranspiration drop also plays a pivotal role in regional warming, contributing to an increased vapor pressure deficit. Climatic change already affects the physiology, phenology, and reproduction of the Cerrado plants, while also driving community-level alterations, such as woody encroachment and ant–plant–herbivore interactions. Dry season lengthening is likely to reduce the biomass and alter the dynamics of microbial communities, with negative effects also extending to invertebrates. The pronounced warming reduces the amount and duration of dewfall, an important water source for insect pollinators and other animals with low vagility during periods of drought. Concerning vertebrates, the most suggested impact is the loss of specialist species or endemic with restricted distribution, and the expansion of generalist species, lowering the levels of β- and γ-diversity across the region and making communities more homogenized. In summary, climate change is actively reshaping Cerrado communities, and species' survival will largely depend on its phenotypic plasticity and dispersal capabilities.

Keywords: global biodiversity hotspots; savanna; South Atlantic Subtropical Anticyclone; evapotranspiration; agricultural impacts; biotic homogenization; phenotypic plasticity; ecosystems collapse.

4.1 INTRODUCTION

The Brazilian Cerrado (hereinafter called Cerrado) is the second-largest ecoregion in South America, and is recognized as a global biodiversity hotspot harboring thousands of endemic species (Klink & Machado, 2005). It spans around 2 million km², comprising a dynamic mosaic vegetation, including forests, savannas, and grasslands composed of a broad spectrum of species with different growth forms transitioning into one another in the landscape (Figure 1). While climate broadly defines the Cerrado boundaries, fire, competitive interactions, and edaphic factors interact and shape the different vegetation types at local scales (Mistry, 1998). The climate is characterized by elevated temperatures and seasonal rainfall distribution, with wet summers and dry winters, which remained stable throughout the Late Holocene (5,000 years ago to the present) (Behling & Hooghiemstra, 2001; Ledru et al., 2006). The duration and intensity of wet and dry seasons impact the biotic communities by alternating water availability, controlling plant phenology/reproduction, and mediating intra and interspecific interactions (Rossatto & Franco, 2023; Calixto et al., 2021).

The Cerrado is seriously threatened by human activities. Agricultural and pasture expansion, and thousands of anthropogenic wildfires annually, have caused widespread habitat loss (Strassburg et al., 2017). Regional climate change has emerged as an additional threat to regional biodiversity, as predicted more than two decades ago by theoretical studies simulating the effects of massive removal of native vegetation combined with increased concentration of greenhouse gases (Hoffmann & Jackson, 2000; Snyder et al., 2004; Costa & Pires, 2010). Observational data corroborate these predictions, with the most evident alteration being the lengthening and intensification of the dry season (Figure 2). Here, we review the most recent studies and highlight the processes involved in climate change in the Cerrado. We also project possible impacts on different taxonomic groups of terrestrial biodiversity. For comparison purposes, we used the same annual division proposed by Hofmann et al. (2023), with four distinct seasons according to the annual rainfall distribution: wet season (WS; December, January, February, and March), the beginning of the dry season (BDS; April and May), the dry season (DS; June, July, August, and September), and the beginning of the wet season (BWS; October and November).



Cerrado Terrestrial Biodiversity

- Cerrado is often regarded as the most biodiverse savanna in the world.

- Number of species living in the Cerrado is unknown, but Brazilian governmental agencies assume it exceeds 320,000.

- 12,829 plants species and 4,613 endemics (BFG, 2022; Flora e Funga do Brasil, 2024).

- More than 95,000 invertebrate species (estimated number) (EMBRAPA, 2024).

- 204 amphibians species and 124 endemic species (Aguillar et al., 2015; Vieira-Alencar et al., 2023).

- 278 reptiles species and 129 endemic species (Aguillar et al., 2015; Vieira-Alencar et al., 2023).

- 856 birds and 28 endemic species (Silva & Santos, 2005; Lopes and Silva 2024).

- 251 mammals species and 42 endemic species (Aguillar et al., 2015; Vieira-Alencar et al., 2023).

Cerrado Phytophysiognomies

Cerrado Stricto Sensu in latosol

Dense Cerrado (*Cerrado denso*)

Seasonal Dry Forest in limestone outcrop

Open Grassland (campo limpo)

Palm Swamp (*vereda*)

Rocky Grassland (*campo rupestre*)

Cerrado woodland (*cerradão*)

Riverine forests (*mata ciliar*)

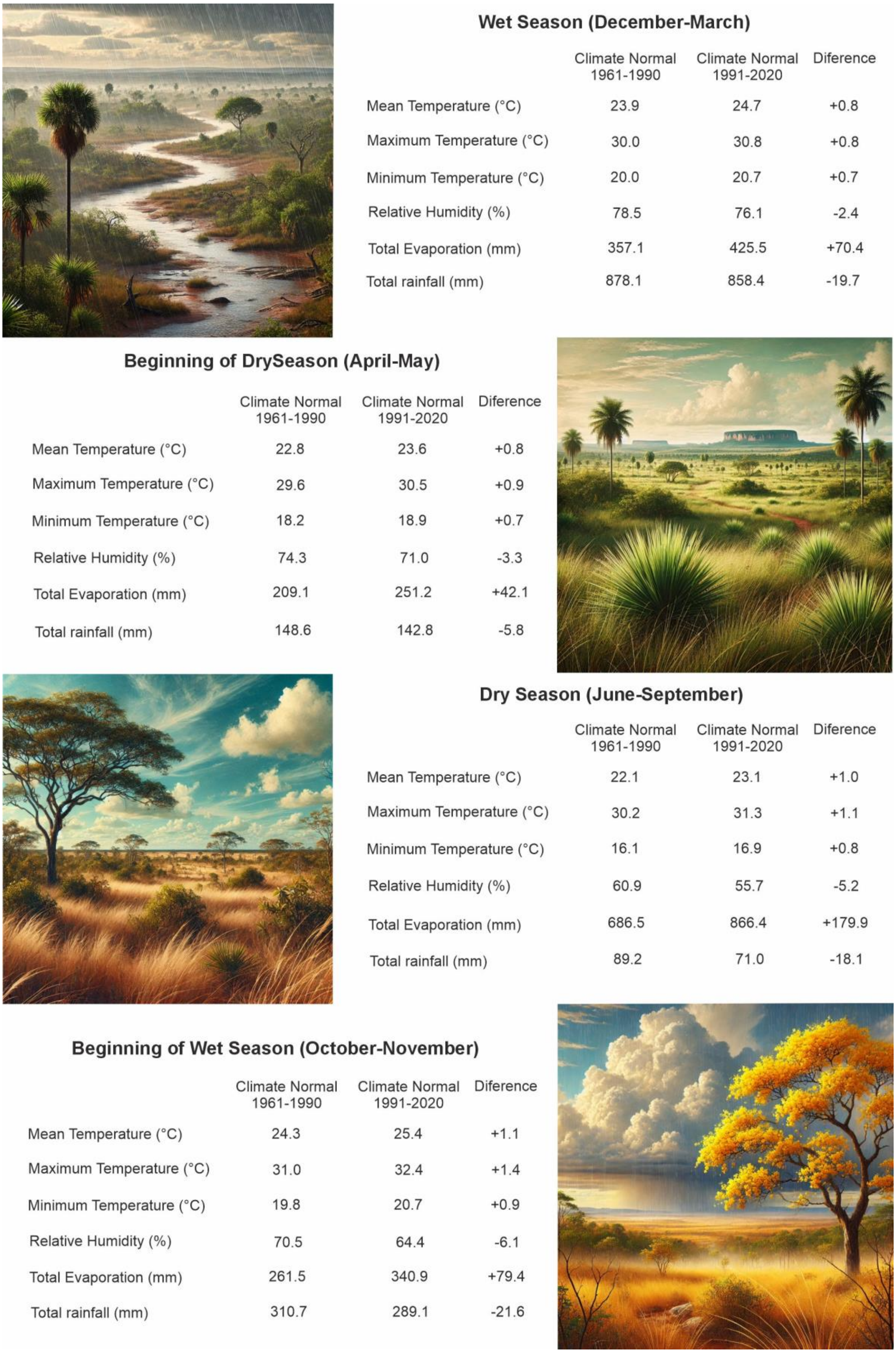
Earthmounds (*campos com murundus*)

Figure 1. Location of the Brazilian Cerrado, its terrestrial biodiversity, and main phytophysiognomies. (a) Official limits of the Cerrado and other Brazilian ecoregions. (b) Cerrado Terrestrial biodiversity information compiled in the recent literature. (c) Cerrado Stricto Sensu vegetation in the Jalapão State Park, state of Toncantins. (d) and (e) Dense Cerrado (cerrado denso) and Seasonally Dry Forest (mata seca) areas, recorded near Mambaí municipality, state of Goiás. (f)

Open Grassland (campo limpo) vegetation in the Serra da Canastra National Park, state of Minas Gerais. (g) Palm Swamp (vereda) in Sesc Serra Azul Park, state of Mato Grosso. (h) Rocky Grassland (campo rupestre) area, recorded near of Chapada dos Veadeiros National Park, state of Goiás. (i) Cerrado woodland (cerradão) vegetation in the Emas National Park, state of Goiás. Riverine forests (mata ciliar) vegetarion, recorded in Porto Cajueiro Private Natural Heritage Reserve, state of Minas Gerais. Earthmounds fields (campos com murundus) in the Emas National Park, state of Goiás.

4.2 REGIONAL CLIMATE CHANGE IN CERRADO

The extension and intensification of the DS led to a reduction in rainfall and in the frequency of rainy days in the Cerrado, as documented by several studies in recent years (Campos & Chaves, 2020; Marengo et al., 2022; Hofmann et al., 2023; Stríkis et al., 2024). The reduction varies regionally between 5 and 15% of total annual precipitation, and three factors have been identified to explain the negative trend. First, regional precipitation change seems to have started in the late 1960s (Hofmann et al., 2023; Stríkis et al., 2024), concomitantly with an elevation in atmospheric pressure at sea level in the South Atlantic Ocean due to the expansion/intensification of Hadley cell circulation (Choi et al., 2014). Shifts in Hadley cells are likely linked to rising greenhouse gases and decreasing stratospheric ozone concentrations, leading to significant changes in Southern Hemisphere atmospheric circulation, particularly the intensification and expansion of the South Atlantic Subtropical Anticyclone (SASA) (Choi et al., 2014; Reboita et al., 2019). A recent study comparing 1991─2021 and 1960─1990 periods showed that SASA alterations led to a regional increase in sea level pressure (Figure 3), in addition to a strengthening of zonal winds and vertical velocity of wind (i.e., air subsidence) that resulted in atmospheric moisture transference from the Cerrado to other South American regions (Hofmann et al., 2023). These changes hamper vapor condensation and the vertical development of clouds, thus contributing to the regional reduction in precipitation and in the frequency of rainy days. Alterations in atmospheric circulation induced by the intensification and expansion of SASA permeate the Cerrado throughout the year. Yet, they are more pronounced during DS and BWS when the anticyclone is strengthened and positioned closer to the Brazilian coast (Hofmann et al., 2023).



Wet Season (December-March)

	Climate Normal 1961-1990	Climate Normal 1991-2020	Diference
Mean Temperature (°C)	23.9	24.7	+0.8
Maximum Temperature (°C)	30.0	30.8	+0.8
Minimum Temperature (°C)	20.0	20.7	+0.7
Relative Humidity (%)	78.5	76.1	-2.4
Total Evaporation (mm)	357.1	425.5	+70.4
Total rainfall (mm)	878.1	858.4	-19.7

Beginning of DrySeason (April-May)

	Climate Normal 1961-1990	Climate Normal 1991-2020	Diference
Mean Temperature (°C)	22.8	23.6	+0.8
Maximum Temperature (°C)	29.6	30.5	+0.9
Minimum Temperature (°C)	18.2	18.9	+0.7
Relative Humidity (%)	74.3	71.0	-3.3
Total Evaporation (mm)	209.1	251.2	+42.1
Total rainfall (mm)	148.6	142.8	-5.8

Dry Season (June-September)

	Climate Normal 1961-1990	Climate Normal 1991-2020	Diference
Mean Temperature (°C)	22.1	23.1	+1.0
Maximum Temperature (°C)	30.2	31.3	+1.1
Minimum Temperature (°C)	16.1	16.9	+0.8
Relative Humidity (%)	60.9	55.7	-5.2
Total Evaporation (mm)	686.5	866.4	+179.9
Total rainfall (mm)	89.2	71.0	-18.1

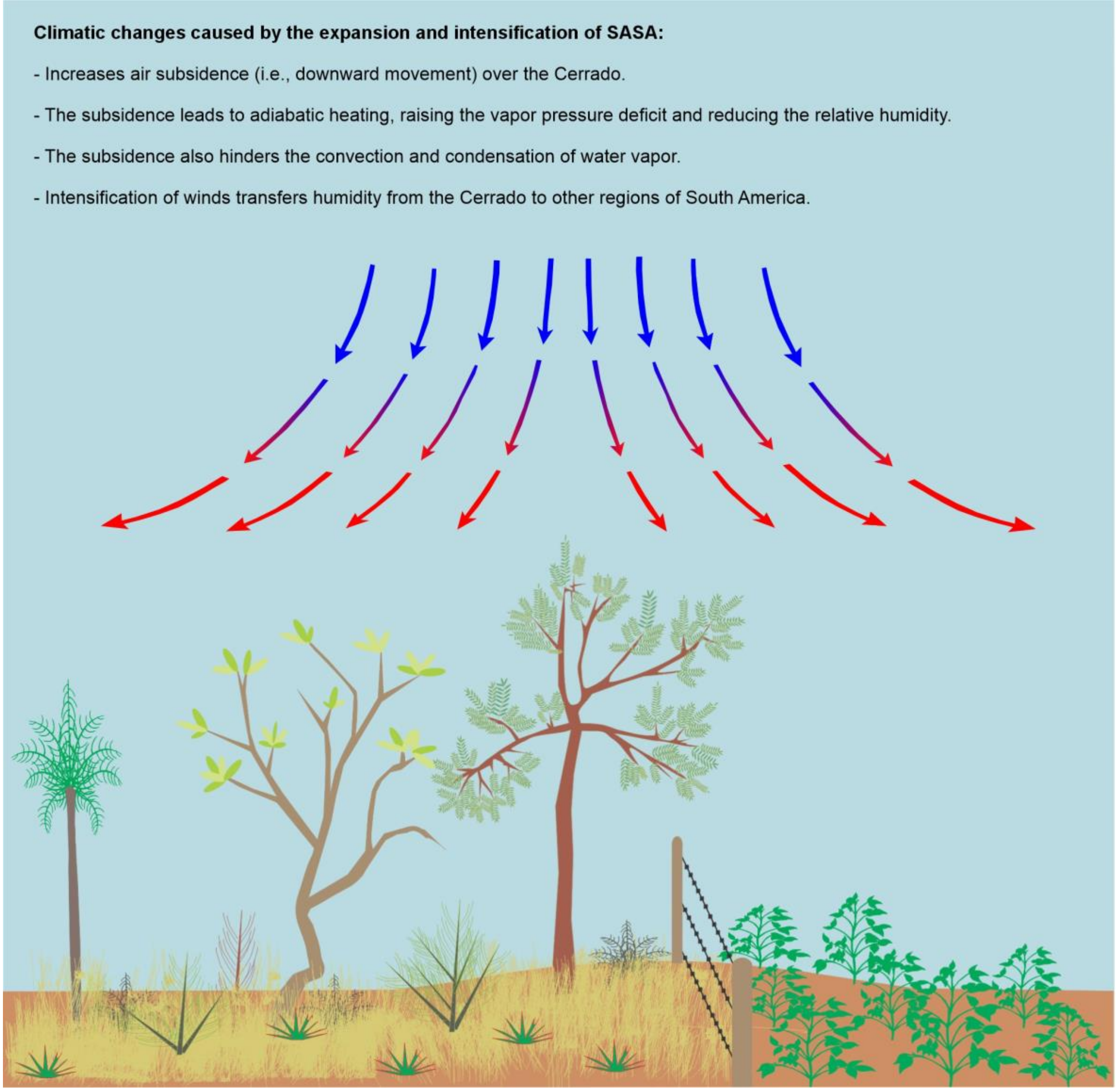
Beginning of Wet Season (October-November)

	Climate Normal 1961-1990	Climate Normal 1991-2020	Diference
Mean Temperature (°C)	24.3	25.4	+1.1
Maximum Temperature (°C)	31.0	32.4	+1.4
Minimum Temperature (°C)	19.8	20.7	+0.9
Relative Humidity (%)	70.5	64.4	-6.1
Total Evaporation (mm)	261.5	340.9	+79.4
Total rainfall (mm)	310.7	289.1	-21.6

Figure 2. Change in the main climate variables recorded in the Brazilian Cerrado in the last two normal climates (i.e., 1991─2020 and 1961─1990) during the wet season, the beginning of the dry season, the dry season, and the beginning of the wet season. Seasonal values of mean temperature,

maximum temperature, minimum temperature, relative humidity, and total evapotranspiration were calculated from the arithmetic mean of normal data from 45 meteorological stations (Supplementary Table 1) published by the National Institute of Meteorology (INMET, 2024). Total rainfall seasonal values were extracted from Hofmann et al. (2023), representing the arithmetic mean of 70 rainfall stations of the Brazilian Cerrado. Images depicting the four seasons were generated using the DALL-E Artificial Intelligence Image Generator, based on photographs of Cerrado landscapes.

A second factor attributed to the decline in Cerrado rainfall is a change in atmospheric circulation caused by the warming of the northern tropical Atlantic Ocean. This phenomenon contributes to attenuate the moisture transport from the sea towards inner regions of South America, consequently diminishing atmospheric water vapor content in central and northern Cerrado, particularly in the Amazonian border (Espinoza et al., 2016; Marengo et al., 2022). Finally, the third factor is a regional reduction in the supply of vapor to the atmosphere due to a decrease in evapotranspiration, which may seem unlikely given the rise in air temperature and evaporative demand (Figure 4). However, it had already been predicted by models of climatic consequences of the massive suppression of native vegetation in the Cerrado, and was also confirmed by field measurements and remote sensing data (Costa & Pires, 2010; Oliveira et al., 2005; Spera et al., 2016). The main cause of evapotranspiration drop is a diminution in rooting depth by land use change, although other factors also contribute, such as albedo increase, reduced leaf area, and turbulence of the pasture/crops (Costa & Pires, 2010). Conversion of Cerrado forests and savannas to pasture and cropland reduces evapotranspiration by between 20% and 45%, depending on the type of transition (Rodrigues et al., 2022). During DS and BWS, evapotranspiration from the native vegetation far surpasses that of agricultural areas due to the capacity of root systems of trees to extract water from the soil at greater depths (Spera et al., 2016; Oliveira et al., 2005). As water bodies represent less than 1% of the Cerrado surface and the amount of water in the soil of dry pastures and fallow crops is scarce during DS, an increase in evaporation in response of higher air evaporative demand (Figure 2) is not enough to compensate the decrease in transpiration due to the massive removal of native vegetation. Therefore, the effects of the second and third factors converge to diminish the regional air moisture content, reinforcing the effects of SASA changes and prolonging the DS duration in Cerrado.



Climatic changes caused by the expansion and intensification of SASA:

- Increases air subsidence (i.e., downward movement) over the Cerrado.
- The subsidence leads to adiabatic heating, raising the vapor pressure deficit and reducing the relative humidity.
- The subsidence also hinders the convection and condensation of water vapor.
- Intensification of winds transfers humidity from the Cerrado to other regions of South America.

Figure 3. Synthesis of the main climate changes driven by the expansion and intensification of the South Atlantic Subtropical Anticyclone (SASA) in the Cerrado. Atmospheric circulation changes intensify the air subsidence over the Cerrado, leading to adiabatic heating, a decrease in relative humidity in the cloud-forming atmospheric layers (1.5 to 5.5 km above sea level), and a hamper of deep convection. Consequently, there is a rainfall reduction, especially between June and October, lengthening the Dry Season in most subregions of the Cerrado.

In addition to the impacts on the hydrological cycle, native vegetation suppression also acts as a radiative forcing by altering energy budget components (Costa & Pires, 2010). Thus, evapotranspiration reduction assumes a pivotal role in regional warming because it diminishes the latent heat flux, leaving more energy for the sensible heat flux, which leads to a pronounced rise in surface and air temperatures (Loarie et al., 2011; Marengo et al., 2022). Long-term temperature data unveils different warming trends for nocturnal and diurnal periods, respectively represented by the minimum and the maximum temperatures. Whereas minimum temperatures have risen gradually since the 1960s (i.e., probably associated with the global greenhouse effect intensification), maximum temperatures seem to have started rising sharply after the beginning of the 1980s, coinciding with large-scale agribusiness expansion in the region (Hofmann et al., 2021). Additionally, both diurnal and nocturnal warming are more pronounced during DS and BWS, with monthly rates ranging from 0.3 to 0.7°C per decade. These periods are the same ones in which a reduction in regional evapotranspiration is observed, which is attributable to the expansion of pastures and crops (Hofmann et al., 2021; Marengo et al., 2022). Regional warming has also caused an increase in vapor pressure deficit in the Cerrado (Marengo et al., 2022), as well as a reduction of relative humidity over recent decades (Hofmann et al., 2021). Both are a consequence of air expansion with increasing temperature, which is why they are greater during BWS, when warming is more pronounced. The Cerrado warming has also increased dew point depression at night, hampering vapor condensation on the surface and potentially reducing the amount and duration of dewfall (Hofmann et al., 2021).

The increased vapor pressure deficit resulting from regional warming, combined with reduced rainfall, has been prolonging the months of water deficit in the Cerrado, matching projections of previous theoretical studies (Hoffmann & Jackson, 2000; Snyder et al., 2004; Costa & Pires 2010). More recently, Stríkis et al. (2024) compared contemporary climate data with geochemical proxies in speleothems, revealing that the ongoing drying trend has been unprecedented over the past seven hundred years. Several studies have already described the environmental consequences of regional climate change. The decrease in regional rainfall and increasing water use in agricultural areas led to a trend of fewer floods and more droughts in Cerrado (Chagas et al. 2022). Another recent investigation, which analyzed a 33-year time series encompassing 81 river basins within the Cerrado, found water flow reduction in 71 basins (Salmona et al. 2023). The adverse effects of climate change intensify during severe drought events, when dry weather associated with heatwaves cause reduction in soil moisture, terrestrial water storage, evapotranspiration, and primary productivity (Lopes Ribeiro et al. 2021; Rossi et al. 2023). Severe drought events in the Cerrado typically align with robust El Niño occurrences or intervals characterized by anomalous warm conditions in the Tropical North Atlantic (Marengo et al. 2022). In 2023, for example, a year of strong El Nino, most of the Cerrado experienced the warmest start to spring in at least 63 years, with scorching conditions extending to the end of BWS (Perkins-Kirkpatrick et al. 2024).

Regarding projections for the end of the 21st century, climate model forecasts indicate an amplification of regional climate change currently in progress. There is robust evidence that increasing the concentration of greenhouse gases will intensify the Hadley circulation, induce atmospheric moisture divergence, and reduce the tropospheric relative humidity in the tropics (Lau and Kim 2015). Therefore, this process will probably increase the tropospheric and surface dryness of the Brazilian tropical region, including the Cerrado. Considering only the most pessimistic scenario generated by the Intergovernmental Panel on Climate Change (SSP5-8.5), the CMIP5/CMIP6 model's projections for the Cerrado suggest slightly increased precipitation during the WS and reduction in other periods, especially during BWS (Ortega et al. 2021). Furthermore, the forecasts show a clear warming trend with an average increase of 6°C by the end of the 21st century, with the strongest projected temperature rise in South and Central Americas predicted to occur in the Cerrado during the BWS period. Therefore, undoubtedly, the Cerrado is becoming hotter and drier.

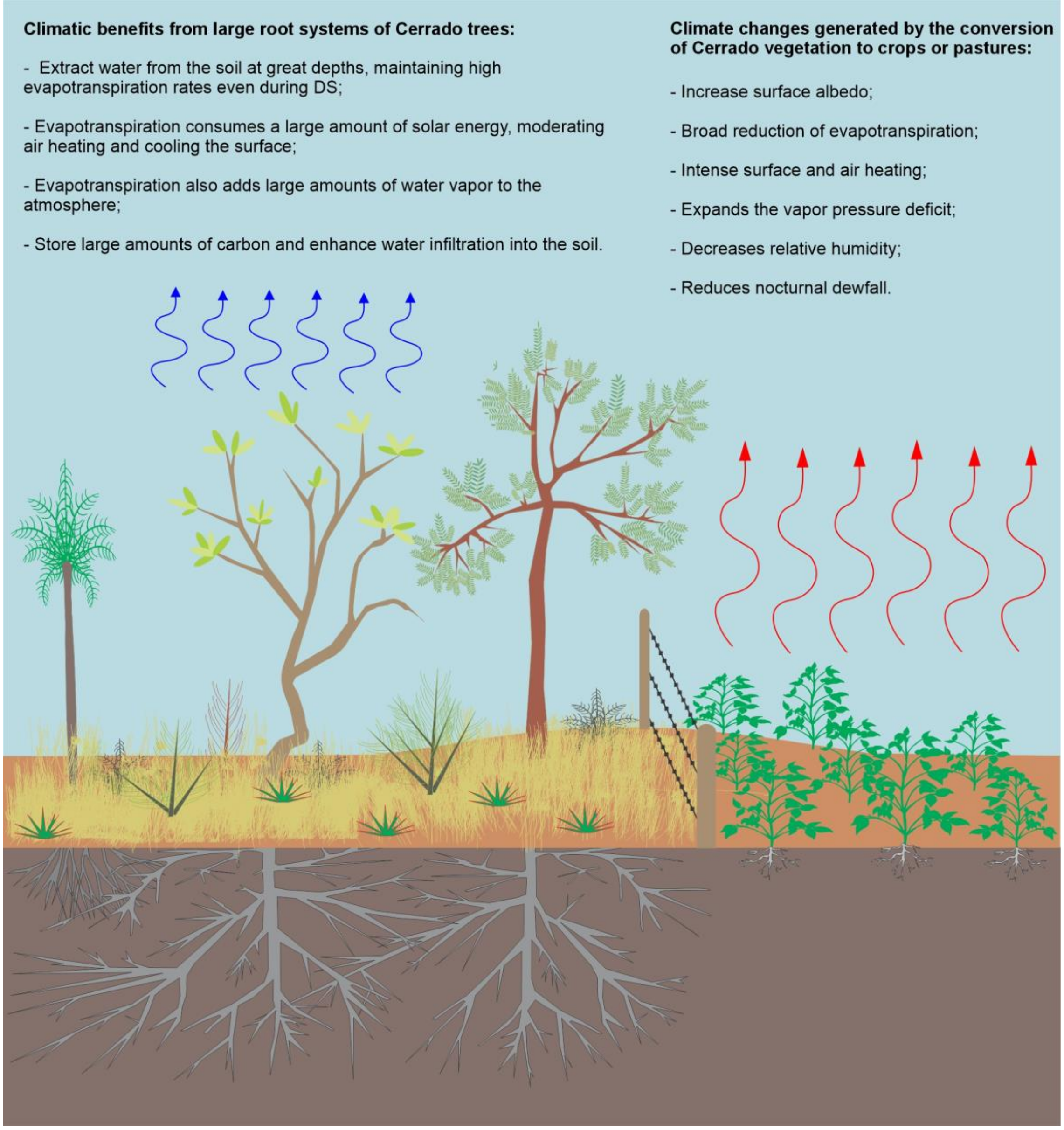


Figure 4. Synthesis of the main climate changes driven by Cerrado native vegetation conversion to crops or pastures. Land use and land cover changes impact the hydrological cycle and energy budget components. The drastic reduction in regional evapotranspiration recorded during DS and BWS causes surface and air warming, expanding the vapor pressure deficit.

4.3 IMPACTS ON TERRESTRIAL BIODIVERSITY

4.3.1 Vegetation

The new environmental conditions due to climate change impact plant functioning, survival, and geographical distributions (Soudzilovskaia et al., 2013). In the Cerrado, increased temperatures, vapor pressure deficit, reduced rainfall, and prolonged DS will likely impose strong selective pressure on plant physiology, affecting their persistence. This regional climate change acts as an environmental filter, shaping plant community structures and trait composition. Functional trait combinations that promote a positive carbon balance, tighter water control, and higher investment in hydraulic safety and thermal tolerance are expected to be selected (Heilmeir, 2019). Species' responses will depend on their capacity to adapt to a hotter, drier environment, influenced by genetic composition and phenotypic patterns (Franco et al., 2014; Souza et al., 2016). Phenotypic plasticity, the ability to produce different phenotypes in response to environmental changes, will be critical for species' survival, influencing geographical ranges and, consequently, the distribution and boundaries of vegetation types (Valladares et al., 2007). In the Cerrado, leaf fall peaks in the DS (Rossatto, 2013). However, many native plants renew their foliage at the end of DS and during the BWS, when climate change is most intense, and the atmosphere evaporative demand is at its maximum (Giambelucca et al., 2009). Bud break and leaf expansion in the dry season can only occur if the plant is fully hydrated. Trees and other growth forms can do this because of their physiological mechanisms to deal with the high evaporative demand and the water shortage imposed by rainfall seasonality. The mechanisms involved are tight stomata control of transpiration, water storage tissues, deep roots systems, and mechanisms linked with hydraulic safety and an efficient water transport system to keep pace with the transpiration rates without causing an excessive drop in leaf water potential, which would induce cavitation and loss of xylem conductivity (Goldstein et al., 2008).

Phenological responses to DS prolongation and increased vapor pressure deficit are not well known, but the rainfall reduction during DS and WS transition will undoubtedly affect plant water balance and soil water recharge, while the evapotranspiration of native plants will tend to increase drastically (Christoffersen et al., 2014). As the plant water potential gradually drops (i.e., becomes more negative), cavitation would spread widely within xylem conduits, decreasing the water supply to the foliage, and increasing the risk of tissue dehydration (Bucci et al. 2008). Under severe dehydration, vegetative tissues may experience irreversible cellular damage and death. Tighter control of plant water loss would then be crucial for plant survival, and water leaks by leaf cuticles or through the bark, which represent a small fraction of the water lost by transpiration, can become increasingly important (Oliveira et al., 2003; Bertolino et al., 2019). The limited available information suggests that xylem vulnerability to drought-induced cavitation may become widespread in Cerrado trees under a changing climate scenario, as was found for Atlantic Forest species (Hollunder et al., 2024). In this sense, more information still needs to be on other growth forms, such as grasses, herbs, and small shrubs, which play a fundamental role in the dynamics of the Cerrado plant communities. Although the vulnerability to hydraulic failure is closely related to the ability to resist xylem embolism, we highlight that the presence of large plant water reservoirs or access to deep, moist soil layers might act as alternative mechanisms to cope with the risk of hydraulic failure (Liu et al., 2021; Loram-Lourenço et al., 2022).

Tighter stomatal control of transpiration comes at the cost of reducing CO_2 uptake by the foliage and might select for an increase in water use efficiency, expressed as the amount of carbon assimilated per unit of water loss (Goldstein et al., 2008). However, transpiration is an important mechanism of leaf cooling for plants of the Cerrado (Bucci et al., 2008). With the DS extension and the rise of vapor pressure deficit, young leaves would need tighter control of stomatal apertures, and higher leaf temperature would be inevitably exposed as they are to the high irradiances that prevail in the Cerrado in this period. This scenario could negatively affect leaf carbon balance due to higher rates of respiration and photorespiration and increase the risk of photoinhibition and thermal damage to the leaf tissues (Kirschbaum, 2004). While the rising CO_2 levels of the atmosphere might partially offset the impacts on the plant carbon balance of tighter stomatal control of transpiration, a higher risk of thermal injury would be inevitable.

The response of Cerrado plants to escalating temperatures remains uncertain, mainly because the limited existing research on thermotolerance is restricted to trees (Araujo et al., 2021; Tiwari et al., 2021; Silva & Rossatto, 2022). In Cerrado, it is known that forest species are less thermotolerant than trees from savannah formations, and photosynthesis in savannah trees is drastically affected when leaf temperature reaches 48 to 52°C (Silva & Rossatto 2022). The damages imposed by high temperatures on photosynthesis can affect plant persistence, leading trees to lose leaves more frequently. These thermotolerance aspects were reported for tree species under water availability. Thus, under drought, as the stomatal aperture is strongly limited, leaf temperature can increase even more, and damage could be substantially larger, leading to a possible widespread mortality of tree canopies. The Cerrado warming combined with the DS prolongation can have additional impacts, particularly on plant reproduction. Higher temperatures and heat waves can eventually impair flower and seed production, seedling establishment, and species regeneration and persistence in the environment (Abeli, et al. 2012). A pioneering in situ experiment that examined the effects of increased temperature on the inflorescences of the Cerrado native tree species *Byrsonima pachyphylla* found no impact on viable pollen production; however, it recorded a significant reduction in fruit production (Werkmeister et al., 2024). These findings may have important implications for the reproductive success and long-term persistence of *B. pachyphylla*, with potential consequences for interspecific relationships at the community level. It is yet to be determined whether rising CO_2 levels can mitigate or increase the impacts of climate change on native plants, but the responses might depend on plant functional type (e.g., C3 and C4).

Rising CO_2 levels in the atmosphere could impact the Cerrado plant community in other ways besides regional warming. Woody encroachment is a widespread phenomenon in African savannas, and CO_2 enrichment has been implicated as a key driver of this process, despite other factors such as overgrazing and land degradation are also involved (Devine et al., 2017; Tabares et al., 2020). Remote sensing data and field observations show woody encroachment in the Cerrado northern region and transition areas with the Amazon and the Pantanal (Rosan et al., 2019). In addition to the increased atmospheric CO2, the woody encroachment in the Cerrado also appears to be associated with fire suppression and land use abandonment. On the other hand, other studies in African savannas have provided some evidence that increased dry spell length and frequency in the growing season may benefit grasses. Grasses can rapidly recover when moisture becomes available regardless of the season, while tree growth is mostly restricted to a specific period of the year (Wigley et al., 2024). Although Cerrado trees have this same growth pattern (Rossato et al., 2009), the vegetation changes in this region may be more subtle because of the high diversity and functional diversity of growth forms and species in the ground layer, despite the dominance of C4 grasses and the high tree diversity (Rossatto & Franco, 2017). Regardless of whether the Cerrado will become more open or woodier, climatic changes will likely affect ecosystem productivity, its ability to recover after disturbance, and its potential to sequester CO_2 from the atmosphere. Regional climate change can also alter the invasion process by exotic plants. Until now, ecological niche simulations have shown that native species would decrease in range due to the Cerrado warming (Simon et al., 2013; Ferreira et al., 2022), while invasive grasses would be less likely to be affected or even increase in range (Lopes et al., 2023).

Due to the vast expanse of the Cerrado and potential regional variations in climate change, plant responses may differ by location. Physiological traits related to water use and temperature tolerance suggest a general trend of increased tree mortality, particularly in drier areas like the Caatinga border, if species lack plasticity to withstand prolonged dry seasons and higher temperatures (Anderegg et al., 2013; Hartmann et al., 2022; Taccoen et al., 2022). At the landscape level, wetter vegetation types—such as gallery forests, wet grasslands, and palm swamps (*veredas*)—would suffer from reduced river flows and soil moisture in areas with significant rainfall declines (Gonçalves et al., 2022). On a broader scale, boundaries with other ecoregions could shift: Cerrado species might expand northward toward the Amazon, as seen in the past (Bueno et al., 2017), while Caatinga species could move southwestward into the Cerrado. In the south, the Cerrado may retreat to lower latitudes due to increased rainfall in southern Brazil (Hofmann et al., 2023).

4.3.2 Soil microbial communities

Throughout the Cerrado, contrasting vegetation physiognomies and differences in soil characteristics result in natural variations in soil microbial biomass, respiration, and activity (Rocha et al., 2019). However, transitioning from the rainy to the dry season consistently decreases microbial biomass C and N (Nardoto & Bustamante, 2003; Carvalho et al., 2018). The absence of available water during the dry season explains the high abundance of microbial genes related to the cell wall, capsule synthesis, as well as sporulation, suggesting dormancy during this period. Water-saturated soils in the WS present high oxygen concentrations, which, coupled with a high content of genes related to amino acids, DNA, and protein metabolism, indicate that these dormant microbial communities proliferate when water is available (Castro et al., 2016). Increased soil moisture in the wet season boosts organic matter from plant debris, stimulating microbial biomass (Eaton & Chassot, 2012) and enzyme activities like FDA, urease, dehydrogenase, β-glucosidase, and phosphatase (Carvalho et al., 2018). This heightened microbial activity enhances biogeochemical cycles, particularly C and N, and improves nutrient availability for plant growth, especially K and P.

The typical functioning of below-ground communities in Cerrado soils will be impacted by climate change. Altered water regimes and prolonged dry periods will reduce microbial biomass and alter the dynamics of microbial communities, especially in the upper 5-10 cm of soil. Prokaryotic groups like Solibacteres, Acidobacteriia, and Chloroflexi, associated with the dry season, will remain dominant for longer, while wet-season groups like Alphaproteobacteria and Sphingobacteria will have a shorter influence (Castro et al., 2016). Both bacterial groups drive C and N cycling, crucial for biogeochemical processes. However, increased microbial biomass and activity will elevate greenhouse gas emissions, such as CO_2, CH_4, and N_2O (Siqueira-Netto et al., 2021). Prolonged water stress in the dry season could further disrupt microbial dynamics and native vegetation growth.

4.3.3 Invertebrates

Invertebrates are the most diverse animal group, including a wide variety of feeding habits and ecological functions, connecting ecosystem compartments (Knight et al., 2005). Current terrestrial ecosystems have been shaped by these organisms, either as primary consumers or predators in “green” food webs, establishing resource-based mutualistic interactions with plants or as detritivores in “brown” food webs (Kitching et al., 2020; Eisenhauer & Hines 2021). The Cerrado has a high diversity and endemism of invertebrates, including gastropods, onychophorans, chelicerates, and insects (e.g., Diniz et al., 2022; Oliveira et al., 2015; Salvador et al., 2017; Lemes et al., 2020). Heterogeneity of habitats contributes to high values of beta diversity in different physiognomies (Brown & Gifford 2002; Pacheco & Vasconcelos 2012; Freire-Jr. et al., 2024), especially in ecotones with other Brazilian ecoregions (Beirão et al., 2017). However, research on invertebrates in the Cerrado has been taxonomically biased and limited to sites close to the main research groups (Lewinsohn et al., 2005). Many groups remain poorly understood, and significant biodiversity may be lost before it is even documented. This lack of knowledge about the ecological roles of these organisms in Cerrado ecosystems limits our ability to accurately project the impacts of climate change.

The reduction in rainfall and frequency of rainy days will likely alter the mesic and wetland ecosystems, potentially impacting their invertebrate communities. *Veredas* and gallery forests are refuges for invertebrates during DS and have high diversity compared to adjacent drier areas (Pinheiro et al., 2008; Araújo et al., 2014; Freire-Jr et al., 2024). In Cerrado, endemic species of wetland ecosystems with restricted distribution and top predators with aquatic larvae are highly threatened by changes that render their habitats unsuitable. For instance, the only known specimens of the world's largest diving beetle were collected in this ecoregion, but the species is now believed to be extinct (Hendrich et al., 2019). Nocturnal warming is likely to decrease the amount and duration of dewfall. Dew is an important water source for invertebrates with low vagility during the DS, such as honeybees and other pollinators (Joachimsmeier et al., 2012; Tomaszkiewicz et al., 2015). Moreover, climate change affects above and belowground invertebrates differently, particularly species that live in leaf litter and are less tolerant to moisture loss and rising temperatures (Parr & Bishop, 2022). In the case of soil invertebrates or those that lay eggs in the soil, increased environmental unpredictability and long periods of drought should select individuals with adaptations to these conditions, potentially leading to the extinction of populations with less phenotypic plasticity (Martins et al., 2017). Invertebrate species with greater phenotypic plasticity will probably survive climate change and should dominate the communities of the Cerrado, producing biotic homogenization. In this scenario, invertebrates with adaptations to drier physiognomies may expand their potential distribution area, and biological invasion by species adapted to drier regions may occur.

These changes in community composition and structure may jeopardize the wide range of ecosystem services provided by invertebrates in the Cerrado. For example, some physiognomies such as *campo com murundus* (earthmound fields) are formed by the action of social insects (Martin et al., 2018; Campos et al., 2023). Invertebrates, especially ants, play a fundamental role in nutrient cycling in *campos rupestres* areas (i.e., rocky fields; Fernandes et al., 2024), as observed in many African savannahs (Parr et al., 2016). Ecosystem engineering produced by wood-boring beetles and shelters created by gall-inducers influence the community structure of invertebrates on plants (Priest et al., 2021; Pereira et al., 2024). Sources of liquid foods such as extrafloral nectaries of plants and honeydew-producing insects on vegetation attract ants that facilitate or restrict the occurrence of herbivorous insects on plants (Oliveira & Freitas 2004). These communities of invertebrates on plants in the Cerrado are typically seasonal, following pulses of resource availability, and are affected by abiotic factors such as water availability (Calixto et al., 2021). The relative climatic stability of seasonal precipitation cycles has selected adaptive strategies specific to these organisms in the Cerrado, especially in endemic taxa.

Many species of the Cerrado have univoltine life cycles, with a long larval stage and a short reproductive period, which are generally associated with resources available in narrow phenological periods (Furtado, 2004). In this sense, invertebrate communities of the Cerrado are characterized by seasonal cycles and synchrony between consumers and preys (Silva et al., 2011; Vilela et al., 2018). Thus, changes in the phenological patterns of plants should affect all trophic levels, including populations of herbivorous insects and their natural enemies that depend on specific plant resources, such as insects that eat young leaves (Furtado, 2004; Muniz et al., 2012).

Daytime and nighttime warming will impact invertebrates, likely altering their daily activity rhythms or prompting dispersal to higher altitudes or latitudes (e.g., Battisti et al., 2005; Speights et al., 2017), with the ability of organisms to change their potential distribution depending on behavioral plasticity and dispersal ability. Additionally, many species depend on complex interactions with other organisms, such as specialized herbivorous insects (Bellaver et al., 2022). In this case, the survival of these organisms depends on the availability of these resources in new areas or the exploitation of alternative resources in newly colonized areas. Still, the extent of the shifts induced by regional warming on the daily activity patterns and distribution of invertebrates in the Cerrado remains insufficiently supported by empirical data.

3.4 Amphibians and reptiles

Amphibians and reptiles comprise the extant lineages of ectothermic tetrapods, with anurans and squamates being the most diverse groups within their respective classes. The Cerrado boasts a remarkable diversity of both (Figure 1). In addition to its high level of endemism, the region also has a significant number of species with restricted distributions (Vieira-Alencar et al., 2023). Although amphibians and reptiles share some ecological similarities, primarily related to size and thermal physiology, significant differences in their natural history, morphology, physiology, and behavior are likely to lead to varied responses to climate change (Huey, 1982; Duellman & Trueb, 1994; Deutsch et al., 2008). Even within these two groups, the extensive taxonomic diversity, phylogenetic distance, and specializations observed in the Cerrado's herpetofauna (Colli et al., 2002) strongly suggest that we can expect a broad range of responses to climate change (Winter et al., 2016). Several effects have been reported on herpetofauna, including, among others, that climate change may affect survival, growth, reproduction, and dispersal capabilities. It can also impact habitat and food availability, predator-prey relationships, competitive interactions, and alter pathogen-host dynamics (Blaustein et al., 2010).

Amphibians possess moist, highly permeable skin, rely on cutaneous respiration, have non-amniotic eggs, and often undergo a larval stage (with eggs and tadpoles typically aquatic) (Duellman & Trueb, 1994). As a result, the natural history of most species is closely tied to water availability and seasonality. Amphibians are particularly vulnerable to changes in humidity and temperature, as well as other environmental shifts driven by global climate change. They are the most threatened vertebrate class, with approximately 41% of species globally at risk. Climate change has been responsible for 39% of the extinction risk status deteriorations in the past 20 years (Luedtke et al., 2023). Reptiles, on the other hand, have scaly, less permeable skin, use pulmonary respiration, and produce terrestrial amniotic eggs without a larval stage. They are generally expected to be less sensitive to changes in humidity and water availability than amphibians. However, many species are diurnal and heliothermic and may be more vulnerable to lethal or suboptimal temperatures. Currently, at least 21.1% of reptile species are threatened, though the overall effects of climate change on this group remain more uncertain (Cox et al., 2022).

Amphibians and reptiles share an ectothermic physiology, making them heavily reliant on environmental temperatures to maintain their physiological functions. This dependence makes them more vulnerable to temperature fluctuations, especially when compared to endothermic vertebrates (Deutsch et al., 2008). Unfortunately, there is limited information on the thermal tolerances, water-conserving behaviors, and other ecophysiological traits of most species. Even when data are available, observational evidence of climate change effects remains scarce (Li et al., 2013; Winter et al., 2016). Despite many uncertainties, we can anticipate both direct and indirect impacts on the Cerrado’s herpetofauna, ranging from the organismal to the community level, with possible consequences for ecosystems given the vital role these groups play in food chains. Direct effects will likely be more related to temperature and water availability, while indirect effects will be more associated with food and habitat availability.

Both amphibians and reptiles typically cope with extreme climatic conditions by reducing or halting their activity to avoid exposure to lethal temperatures. As temperatures rise, we can expect significant impacts on their daily and seasonal activity patterns due to the thermoregulatory needs inherent to ectotherms. The projected warming in the Cerrado may increase the duration of environmental temperatures approaching or exceeding the thermal tolerance limits of many species, particularly during the day. Diurnal species, such as most lizards and Colubridae snakes, may be more affected by rising temperatures than crepuscular or nocturnal species, like most amphibians, Viperidae, Dipsadini, and Pseudoboini snakes. Diurnal amphibians are rarer in the Cerrado compared to rainforest biomes (Ribeiro et al., 2020). Similarly, terrestrial or arboreal species, such as Teiidae, Polychrotidae, and Leiosauridae lizards, Colubridae snakes, and Hylidae treefrogs, may be more affected by warming temperatures than fossorial or cryptozoic species, like many Dipsadidae snake lineages, Amphisbaenidae worm lizards, and microhylid frogs. Fossorial or semi-fossorial amphibians and reptiles are common in the Cerrado, likely as an adaptation to the region’s fire, rainfall, and temperature regimes (Colli et al., 2002; Ribeiro et al., 2020). Fossoriality, as other behavioral and reproductive specializations may offer some protection against climate change. For instance, many species of Leptodactylus build foam nests inside burrows, which help regulate temperature during a critical life stage. However, our ability to predict the full impact of climate change is limited by the scarcity of data on thermal tolerances and preferences. A recent compilation of voluntary thermal maximum temperatures (VTMax) for 53 species of amphibians and reptiles from the Brazilian Cerrado (31 sp.) and Atlantic Forest showed that lizards generally have higher VTMax than amphibians and snakes (Díaz-Ricaurte et al., 2020). However, species from the Atlantic Forest exhibit overall higher VTMax values than those from the Cerrado. Given that the greatest temperature increases in South America are expected in the Cerrado, its herpetofauna may be more physiologically vulnerable than that of the Atlantic Forest.

Rainfall and temperature determine the phenology of herpetofauna in the Cerrado, as in other tropical environments. Most anurans reproduce only during the WS, in temporary water bodies found in open vegetation areas (Vasconcellos & Colli, 2009). Since warming is expected to be more pronounced during the DS and BWS, many species may encounter challenging temperature regimes at the onset of their reproductive season. However, changes in water availability are likely to have a more significant impact on the reproduction of Cerrado herpetofauna. A reduction in rainfall and the frequency of rainy days is expected to shorten the reproductive season, thereby reducing the reproductive output of many populations. While this trend may affect the entire herpetofauna, amphibians are likely to be more heavily impacted. Prolonged and explosive breeders may experience different effects, as observed with other anthropogenic impacts (Gray et al., 2004; Ribeiro et al., 2020; Uloa et al., 2019). Prolonged breeders may be more affected by a shortened reproductive season, while explosive breeders may suffer from fewer opportunities for reproduction. Additionally, higher temperatures and lower humidity will reduce both the availability and duration of temporary ponds, a critical resource for the reproduction of many amphibian species.

Besides the direct effects of climate changes expected for amphibians and reptiles, indirect effects can also be equally significative (Blaustein et al. 2010). Indirect effects may be more diffuse and difficult to predict in terms of their consequences, due to the accumulated uncertainty of projections and the synergy between them. However, changes in prey availability and habitats are likely to be among the most significant indirect effects caused by climate change. All adult amphibians and most squamates are predators. Amphibians, small lizards, Amphisbaenidae, and a few snake species primarily prey on invertebrates, while snakes generally prey on small vertebrates. The degree of dietary specialization varies, but changes in prey availability are likely to affect the biotic suitability for many species. In parallel, changes in the landscape and the composition of different vegetation physiognomies in the Cerrado will certainly have an impact on amphibians and reptiles. Many species are habitat specialists, as exemplified by several lizards found primarily in rock outcrops, sandy soils, or patches of forested habitats (Colli et al., 2002). Changes in the availability or microclimatic conditions of these habitats are expected to affect the herpetofauna.

Currently, only four species of anuran amphibians and seven species of squamate reptiles are officially listed as threatened in the Brazilian Cerrado (ICMBio, 2024). These numbers are certainly underestimates, as the assessment of extinction risk is generally outdated in scenarios of accelerated environmental degradation. However, the ongoing and rapid environmental degradation of the Cerrado, coupled with the observed and projected impacts of climate change, is likely to exacerbate this situation in the coming years (Ribeiro et al. 2020). Even considering the uncertainties, due to limited information, projected climate trends for the Cerrado can bring severe shifts in amphibians and reptiles habitat suitability, distribution, richness and phenology along the next decades. We may expect biotic homogenization, through the loss of taxonomic, phylogenetic and functional diversity, since many relevant attributes to climatic resilience are correlated along the different scales of diversity. Climate change, coupled with other anthropic impacts, may pose a significant threat to the herpetofauna of one of the richest savannas in the world.

3.5 Birds

Cerrado bird species exhibit distinct geographic distribution patterns, ranging from endemics with restricted ranges to widely distributed species (Lopes & Silva 2024), exposing them to a broad range of habitats and climatic conditions (Borges & Loyola, 2020). The extent of a bird's range distribution partly reflects its tolerance to more extreme portions of thermal gradient (i.e., generalist versus specialist species), which significantly influences its capacity to adapt to climate change (Cohen et al., 2023). Cerrado birds are facing increasingly intense and warmer drought periods during DS and the BWS. Especially for diurnal species, maintaining activity at elevated temperatures will result in increased body temperature, heightened metabolism, and greater water loss through transpiration. All these physiological changes have high energy costs that can affect the fitness and survival of birds (McKechnie & Wolf, 2010; Cunningham et al., 2013), although physiological changes in native species of the Cerrado still lack empirical observations in the different ecosystems of the ecoregion. The rainfall reduction in the Cerrado already impacts species dependent on wetlands, such as *Mergus octosetaceus* due to decreasing the surfaces covered by water in natural habitats. Additional indirect impacts on reproductive success may also arise with the recent climate changes in the Cerrado, such as increased predation and parasitism of nests in altered habitats (Borges & Marini, 2010).

In addition to the physiological effects, regional climate change will likely be interacting synergistically with habitat loss, impacting the distribution of species, and potentially leading to a restructuring of bird assemblages (Şekercioğlu et al., 2008; Şekercioğlu et al., 2012; Pearce-Higgins et al., 2015; Borgman & Wolf 2016). Studies based on the climate niche modeling approach and future climate scenarios of greenhouse gas emissions suggest pronounced changes birds ranges sizes. Widely distributed species will tend to maintain 34% to 85% of their current distribution in optimistic greenhouse gas emissions scenarios (Borges & Loyola 2020). The same does not occur in pessimistic scenarios, where all species will suffer drastic reductions in their range size (Hidasi-Neto et al., 2022). A study on 26 Cerrado bird species revealed that changes in range size vary depending on habitat specialization, with dispersal scenarios ranging from a 5% increase to an 80% decrease (Marini et al., 2009a). In these projected scenarios, the largest potential loss in range size under full dispersal was predicted to be grassland and forest-dependent. Endemic species also could experience a loss of more than half of their current distribution area by 2099, as observed for *Myiothlypis leucophrys* (loss of 74%), *Syndactyla dimidiata* (-61%), *Geositta poeciloptera* (-68%), *Taoniscus nanus* (- 59%) and *Nothura minor* (- 57%), per example (Marini et al., 2009a). We highlight that the last three cited species of which are threatened with extinction. In most cases involving endemic and rare species, the core shift in range size has been projected toward the southeastern Cerrado, where higher latitudes and elevation result in lower temperatures (Alvares et al., 2014). However, these predicted range shifts for endemic and rare species are particularly concerning, as the southeastern region has one of the lowest proportions of remaining native vegetation in the Cerrado, coupled with a minimal representation of protected areas.

The projections using individual species distribution models also suggest an increase in overall bird species richness in the northern region and a reduction in the southern Cerrado (Hidasi-Neto et al., 2022). In both cases, community homogenization may occur due to local extensions and invasions (Kortz & Magurran, 2019; Hidasi-Neto et al., 2022). In general, endemic, rare species with restricted range sizes, or those that occupy specific niches are identified as the most sensitive to climate change in the Cerrado (Marini et al. 2009a, Borges et al. 2019, Borges & Loyola 2020, Hidasi-Neto et al. 2022). Borges and Loyola (2020) projected that four endemic species of the Cerrado (*Cercomacra ferdinandi, Paroaria baeri, Pyrrhura pfrimeri,* and *Synallaxis simoni*) will be entirely outside refuge areas under future climate scenarios. Thus, the establishment of new reserves that accommodate species in these projected conditions is crucial for the conservation of the Cerrado bird assemblage, particularly in the southeastern region (Marini et al., 2009b).

4.3.6 Mammals

The most striking potential effect of climate change on the over 200 species of mammalian fauna of the Cerrado is biotic homogenization. Altered predicted precipitation patterns and increased frequency of wildfires will exacerbate the effects of anthropogenic habitat loss and fragmentation, with several studies suggesting a reduction in mammal species richness in the future, indicating possible local extinctions of several species. Hidasi-Neto et al. (2019) anticipate that amidst this overarching decline, the Cerrado will exhibit nuanced patterns of phylogenetic overdispersion and clustering, alongside a pervasive trend of functional overdispersion within non-volant mammalian assemblages. So, while certain sites may witness a decline in overall diversity, the loss of specific species could precipitate an increase in the average phylogenetic or functional divergence among the remaining species. Temporal and spatial shifts in mammal species composition are anticipated, with heightened taxonomic turnover expected in the Northern Cerrado. Conversely, projections indicate that the Southern Cerrado is poised for biotic homogenization, whereby mammalian communities are expected to become increasingly similar taxonomically, phylogenetically, and functionally. Rising temperatures and declining rainfall are anticipated to alter activity patterns and niche overlap (both temporal and spatial) among potentially competing species or predator-prey pairs, especially those with diurnal habits in open environments (Hofmann et al., 2016). These changes are likely to produce unpredictable effects on the interacting species.

Mammalian extinctions in the Cerrado may arise from two mechanisms: severe declines in population sizes leading directly to extinction and range shifts wherein species vacate their historical distribution ranges. Climate change can disrupt the reproductive cycles and phenology of Cerrado mammals. Changes in rainfall, particularly the predicted drop in precipitation during the BWS, will affect the timing of leafing, fruiting, flowering and, consequently, insect emergence in the Cerrado, thereby affecting all trophic levels of mammalian assemblages. The predicted changes in the distribution and abundance of plants will affect food availability for mammals, leading to changes in feeding behavior, dietary preferences, and competition among species for limited resources, influencing population dynamics and assemblage structure. Mammalian reproductive patterns are intricately linked to the seasonal availability of food resources (Bronson, 1989) because parturition ideally takes place during periods of favorable environmental conditions, as the demands of lactation, a unique mammalian trait, impose significant costs on maternal time and energy (Speakman, 2008). Indeed, female energetic requirements more than double during lactation across several mammalian lineages (Gittleman & Thompson, 1988). Strikingly, the reproductive patterns of Cerrado mammals are greatly correlated with rainfall patterns. For example, in Cerrado didelphids, energetically demanding phases such as lactation and weaning are confined to periods of ample food availability coinciding with the WS (Lopes & Leiner 2015). Some species follow a semelparous life cycle, a strategy typically linked to habitats exhibiting strong seasonality and predictability (Zangrandi & Vieira 2023). However, under the reality of climate change, the synchronization between reproductive demands and food availability becomes increasingly precarious. Shifts in precipitation patterns and altered seasonality may disrupt the delicate balance between resource availability and reproductive cycles, jeopardizing the survival of species reliant on such synchronization. Consequently, the inability to adapt reproductive strategies to changing environmental conditions may elevate the extinction risk for marsupials and other species with similar ecological requirements. Several frugivore bats in the Cerrado exhibit seasonal bimodal polyestry with parturition and lactation concentrated during the WS, when fruit abundance and diversity are highest (Wilson, 1973; Willig, 1985). Regardless of environmental conditions, most species of bats are monotocous so, in the Cerrado, most females will generate at most two juveniles per year; the shortened duration of the WS may result in the loss of one of the yearly reproductive events, leading to a fast decline in population replacement rate.

Climate change may drive mammal species to adjust their ranges. According to our predictions, moisture-dependent vegetation types of the Cerrado like gallery forests, wet grasslands, and *veredas* are poised to face adverse impacts due to decreased river water flows and soil moisture, particularly in areas experiencing significant declines in rainfall, potentially forcing species more dependent on those habitats, to either go extinct or to disperse to suboptimal sites. However, the capacity of species to disperse and colonize new habitats is contingent upon functional connectivity, which hinges on factors such as the spatial arrangement of habitat patches, the quality of the surrounding landscape matrix, and the species' inherent ability to navigate across varied terrains. Regardless of the socio-economic pathways projected for the future, small nonvolant mammals endemic to the Cerrado are to experience species losses due to the anticipated reduction in environmentally suitable areas (Evaldt et al., 2024). Similarly, although in 2050 Cerrado bat species could potentially encounter analogous climate conditions approximately 281 kilometres southeast of their current ranges, failure to successfully transition to these newly suitable habitats could lead to substantial range contractions, with 36 bat species facing the prospect of losing over 80% of their distributional range

(Aguiar et al., 2016). The maned wolf, an emblematic Cerrado mesocarnivore, is expected to lose at least 33% of its distribution range by 2050 (Torres et al., 2013).

The anticipated shifts in mammalian assemblages in response to alterations in vegetation composition and phenology due to climate change are poised to initiate a feedback loop, further impacting whole ecosystem dynamics. The homogenization of the mammalian fauna across the Cerrado should trigger a cascade of effects, notably disrupting food chains and impacting ecosystem services. As Larcher et al. (2019) stated "mammal-defaunated seascapes and landscapes no longer exercise their full ecological, biogeochemical, or structural potential". The Cerrado will be no exception: here mammals hold pivotal roles in seed dispersal and pollination (Wolowski et al., 2019); top and mesopredators are known to regulate herbivory pressure on vegetation (Elmhagen et al., 2010). Consequently, the loss or displacement of those species could profoundly impact the structure and composition of vegetation. Moreover, mammals significantly contribute to nutrient cycling through grazing, defecation, and decomposition (Hobbs, 1996; Castillo-Figueroa, 2020). Their absence will disrupt these processes, leading to imbalances in nutrient availability and soil fertility. The diversity of mammals in the Cerrado is particularly noteworthy concerning ecosystem services related to disease control; these encompass vital functions such as disease surveillance, pest and disease management, and carrion management, all of which are crucial for safeguarding human health (Vale et al., 2023). The reorganization of mammal assemblages due to climate change is predicted to have profound implications for the structure of the mammalian virome, as highlighted by Carlson et al. (2022). With the potential for increased cross-species transmission events between naive host species, there is a heightened risk of viral sharing between mammalian species and the subsequent emergence of zoonotic viruses. Among the multitude of anticipated viral sharing events, high-risk zoonoses are expected to find new hosts, potentially increasing the likelihood of spillover events into human populations (Carlson et al. 2022). This escalation in zoonotic transmission potential raises concerns regarding disease outbreaks – in human and non-human mammals – leading to increased human-wildlife conflicts, which could exacerbate mammal persecution and escalate mortality rates, particularly serious among species already facing additional threats in the Cerrado.

4.3.7 Communities and biotic interactions

Although research on the effects of climate alterations and higher levels of biological organization in the Cerrado is limited, emerging evidence suggests that ecological communities and biotic interactions are experiencing significant reorganization due to regional climate change (Calixto et al., 2021; Franco et al., 2014; Marini et al., 2009b; Vasconcelos et al., 2018; Vilela et al., 2018). Climate effects on community reorganization can be detected at multiple spatial scales (Bastazini et al., 2021). In the Cerrado, at broader spatial scales, recent projections suggest that communities tend to become more homogenized due to the loss of specialist species, and the expansion of non-native generalist species, lowering the levels of β- and γ-diversity across the region (Hidasi-Neto et al., 2019). At more refined scales, climate change is also projected to restructure local communities (Vasconcelos et al. 2018), further suggesting a homogenization of species diversity across the region. This homogenization in species composition, and lower levels of β- diversity are likely to simplify biotic interactions across space. However, most of our knowledge comes from predictive stacked individual species distribution models (e.g., Borges & Loyola 2020; Hidasi-Neto et al., 2019, Vasconcelos et al., 2018). Thus, the deficiency in proper and empirical assessment of ecological community data is evident, requiring a need for conducting thorough and explicit empirical community assessments.

Woody plant encroachment is an example of how regional climate change can drive high levels of species turnover and changes in vegetation structure in northern Cerrado (Gonçalves et al., 2021, Rosan et al., 2019). This process leads not only to the loss of biodiversity associated with open formations but also to the reduction of wetland areas (Gonçalves et al., 2021), significantly altering species composition and the set of biotic interactions across spatial scales in the region. However, our understanding of how biotic interactions are being restructured in the Cerrado in response to climate change remains highly limited. The available information is restricted to insect-plant interactions and reveals substantial shifts in biotic relationships, underscoring a significant yet overlooked ecological reorganization within the complex Cerrado ecosystems (Braga & Diniz, 2022; Calixto et al., 2021, Vilela et al., 2018). Phenological changes have already affected mutualist and antagonist interactions in ant–plant–herbivore interactions, a ubiquitous and widespread ecological interaction across the Cerrado (Calixto et al., 2021; Vilela et al., 2018). Future climate scenarios are also expected to adversely impact caterpillars and their tritrophic interactions, particularly during the late DS in the Cerrado

(Braga & Diniz 2022). Furthermore, these interaction networks are likely to become less stable and more vulnerable to environmental disturbances in the future (Braga & Diniz 2022).

In summary, the changes in population-level responses will alter ecological community composition, species richness, and patterns of relative species abundance (Bellard et al., 2012; Bastazini et al., 2021; Bergamin et al., 2024; Gruner et al., 2017; Scheffers et al., 2016). Ultimately, these changes will reorganize the complex network of biotic interactions due to new conditions in temporal (e.g., phenological matching) and spatial (e.g., range) overlaps of interacting species (Bartley et al., 2019, Hallam & Harris, 2023). Positive and negative feedback loops also may emerge, emphasizing the complex nature of climate change impacts on higher levels of ecological organization.

4.4 CONCLUSIONS

Since the late 1960s, the Cerrado suffered 5% to 15% decrease in annual rainfall and rainy days, driven by intensified Hadley cells, warmer northern tropical Atlantic waters, and reduced evapotranspiration. This led to increased regional warming, more frequent droughts, reduced water flow, and lower primary productivity. Projections suggest a further temperature rise of 6°C by the end of the 21st, making the region hotter and drier, exacerbated by anthropogenic factors like vegetation suppression and wildfires, as well as ongoing greenhouse gas emissions. Over the past 5,000 years, the Cerrado's predictable temperature and water cycles shaped species life history strategies and community structure. Climate change is now reshaping ecological communities, leading to biotic homogenization. It is expected to significantly impact vegetation, favoring species with better water conservation and thermal tolerance while increasing plant water stress and causing xylem cavitation. Rising CO_2 levels might drive woody encroachment, though grasses could benefit from longer dry seasons. Soil microbial communities will shift towards drought-resistant microbes and experience disrupted nutrient cycles. Terrestrial fauna will face habitat loss and distribution shifts, leading to potential extinctions. As a result, climate change can significantly compromise the functioning of ecosystems and the provision of essential ecosystem services, which are crucial for human livelihoods in the region and the Brazilian economy.

Currently, the scarcity of long-term biodiversity data contrasts with the abundance of climate records, hampering our ability to understand how ecological communities are responding to climate change and designing effective mitigation strategies. Although long-term ecological research programs have been established in this ecoregion for decades (Marques et al., 2022), their limited spatial and thematic coverage contrasts with the extensive use of time series data and space-for-time approaches in other Brazilian ecoregions (Bergamin et al., 2024). Particularly, we are lacking knowledge on the structuring of biotic interactions and functional traits, key for understanding how species adjust and acclimate to the changing environment (Anadón et al. 2014). Bridging this knowledge gap with long-term, multi-taxa, monitoring programs is crucial to improving our ability to anticipate and respond to the undesirable effects of climate change on the Cerrado ecosystems. However, several management and conservation actions at the local and regional level are readily possible and urgently required. Species-specific conservation strategies should focus on enhancing the adaptive capacity of vulnerable species through measures like assisted migration and habitat restoration. Expanding and strengthening protected areas can safeguard endemic and threatened species; safeguarding key water resources, such as *veredas* and gallery forests, is essential for supporting biodiversity and local populations during extended dry periods. Restoring degraded lands, particularly those affected by deforestation and wildfires, will bolster ecosystem resilience and carbon sequestration. Sustainable land use practices, like agroforestry and regenerative agriculture, should be promoted to maintain biodiversity while ensuring food security. Fire regimes must be carefully monitored and managed through controlled burning protocols and community-based fire programs to mitigate wildfire risks. Implementing such general measures will help mitigate the most severe effects of climate change on the Cerrado, preserving biodiversity and maintaining ecosystem services critical to humanity.

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CAPÍTULO 5: CONSIDERAÇÕES FINAIS

Fotografia mostrando a paisagem da região do Parque Estadual do Jalapão, Mateiros (TO), durante o início da estação seca do cerrado (29/04/2019).

O sertão é um vale fértil. É um pomar vastíssimo, sem dono. Depois tudo isto se acaba. Voltam os dias torturantes; a atmosfera asfixiadora; o empedramento do solo; a nudez da flora; e nas ocasiões em que os estios se ligam sem a intermitência das chuvas -o espasmo assombrador da seca.

Euclides da Cunha

Trecho extraído do livro Os Sertões

5. CONSIDERAÇÕES FINAIS

Embora esse não seja exatamente um fim, visto que ainda existem uma enorme quantidade de temas sobre as mudanças climáticas no Cerrado e suas implicações para biodiversidade ainda a serem explorados, este capítulo inegavelmente representa um fechamento de um longo e importante ciclo. A tarefa de concatenar assuntos tão amplos e complexos como mudanças climáticas, circulação atmosférica, mudança de uso e cobertura do solo e biodiversidade de uma ecorregião tão diversa como o Cerrado foi uma tarefa extremamente desafiadora e que demandou grande esforço e dedicação pessoal, além da colaboração de outros pesquisadores muito qualificados. Neste sentido, é possível concluir que objetivo inicial de se ampliar o conhecimento a respeito das mudanças climáticas que já se encontram em curso no Cerrado brasileiro e sua relação com a expansão do agronegócio nesta região foi cumprido. Quando iniciamos esta tese, o conhecimento a respeito destes processos ainda se encontrava disperso na literatura, estando restrito ao plano teórico ou a estudos localizados. Nosso artigo de 2021 (*The Brazilian Cerrado is becoming hotter and drier*) tem o mérito de ter sido um dos primeiros trabalhos que efetivamente procurou avaliar e descrever a extensão das mudanças climáticas para todo território do Cerrado. Embora tenhamos feito projeções para o futuro, centramos nossos esforços em descrever as mudanças que já ocorreram ao longo dos últimos 60 anos. Talvez esta também tenha sido umas principais contribuições desta tese de doutorado, pois os resultados desta abordagem acabaram despertando grande interesse da comunidade acadêmica e da sociedade, devido a ampla repercussão na grande mídia. Pouco tempo depois da publicação de nosso primeiro artigo, diversos artigos científicos foram publicados e corroboraram grande parte dos nossos resultados e conclusões. A partir deste conhecimento gerado, foi consolidada a ideia de que a supressão da vegetação nativa para expansão das lavouras e pastagens atua como uma forçante climática positiva, amplificando local e regionalmente a tendência global de aquecimento do Cerrado.

Como mencionado anteriormente durante a seção de apresentação, após a publicação do primeiro manuscrito, nosso plano original era seguir explorando as relações entre as alterações do uso do solo e as mudanças climáticas regionais do Cerrado, particularmente as questões relacionadas à redução da evapotranspiração. Sempre esteve claro para nós que essa uma questão chave para as mudanças climáticas que observamos inicialmente. Dois fatos foram decisivos para que este plano não tenha seguido adiante.

Primeiro, a pandemia de COVID-19 que havia encerrado todas as atividades presenciais na UFRGS entre março de 2020 até praticamente o final de 2021. Na medida em que a quantificação de mudanças no uso do solo necessitaria de grande capacidade de processamento computacional, isso se tornou uma tarefa inviável naquele momento. Como as mudanças na precipitação pluvial no Cerrado ainda eram um tema pouco explorado e a organização de um banco de dados era uma tarefa que poderia ser realizada em sistema remoto, alteramos temporariamente nosso plano original. Posteriormente, a publicação do excelente artigo de Rodrigues et al. (2022) quantificou e comprovou nossa ideia central sobre a relação entre uso do solo no Cerrado e a redução da evapotranspiração. Este foi o segundo fato determinante para que abandonássemos a ideia de um artigo dedicado a evapotranspiração e mergulhássemos na possível redução da chuva no Cerrado.

Embora os dados de precipitação sejam relativamente fáceis serem obtidos, por esta ser a variável climática mais observada nas diferentes localidades espalhadas por todo o Brasil, e também pelos dados estarem acessíveis nos bancos de dados de acesso público, a sua utilização é difícil e trabalhosa, visto a inconsistências nos períodos de observação. Grandes regiões como o Pantanal ou o estado do Mato Grosso do Sul carecem de dados confiáveis, dificultando muito avaliações destas regiões. Outra grande dificuldade na análise de mudanças no regime hidrológica é quanto ao estudo das causas que impulsionam as alterações, devido à natureza dinâmica e extremamente complexa da circulação atmosférica. Como ficou demonstrado em nosso segundo artigo publicado (*Changes in atmospheric circulation and evapotranspiration are reducing rainfall in the Brazilian Cerrado*), alterações ocorridas a milhares de quilômetros de distância da área de estudo podem exercer um papel central nas mudanças no regime pluviométrico regional. Neste contexto, o estudo do Anticiclone Subtropical do Atlântico Sul (SASA) foi uma excelente oportunidade de estabelecer a colaboração com outros pesquisadores e pós-graduandos do Centro Polar Climático da UFRGS, além de incluir o tema das teleconexões em nosso trabalho. As alterações do SASA já haviam sido elencadas anteriormente como uma possível causa para a diminuição da precipitação no Sul da Amazônia, mas provavelmente fomos o primeiro estudo a formalizar essa relação para o Cerrado. No entanto, este tema está longe de ser totalmente compreendido. As consequências da supressão de vegetação para diminuição das chuvas ainda precisam ser melhor compreendidos, com questões relacionada a possível redução de compostos orgânicos voláteis, por exemplo. O efeito das queimadas também precisa ser melhor avaliado, devido ao processo conhecido como *Rainout Effect*, causado pela estabilização da atmosfera e pela emissão de aerossóis provenientes da queima da vegetação. Finalmente, a influência de outros fatores como a temperatura dos oceanos, e dos modos de variabilidade como ENOS e SAM também precisa ser aprimorada.

Ainda em relação a chuva no Cerrado, ressaltamos também a importância dos dados observados sistematicamente nas estações meteorológicas e pluviométricas, que permite utilizar uma diversidade de abordagens metodológicas, como, por exemplo, análise de séries temporais, e também para validação de resultados obtidos com outros métodos, como modelagem ou sensoriamento remonto. Em um período onde os órgãos meteorológicos estão sofrendo com a falta de recursos e os postos de observação sendo fechados por todo país, fica o questionamento sobre o futuro do monitoramento meteorológico no Brasil. Esta dúvida também se estende sobre o futuro da geração de conhecimento e sobre capacidade do Poder Público em apresentar respostas aos atuais desafios impostos pelas mudanças climáticas.

Em nosso último, e ainda inédito, artigo sobre o efeito da mudança climática na biodiversidade do Cerrado, nos deparamos com a ausência de levantamentos sistemáticos de longo prazo que possam ser comparáveis no tempo e no espaço com os dados climatológicos. Como exposto em praticamente todos os grupos taxonômicos durante o artigo, os efeitos das mudanças climáticas na flora e fauna do Cerrado ainda são muito pouco conhecidos. Nossa ideia original elaborada durante a fase de criação do projeto era realizar experimentos em campo, focando em alguns grupos taxonômicos específicos como plantas e mamíferos. Contudo, a pandemia impediu qualquer tentativa nesse sentido. Sendo assim, a única opção para manter o tema da biodiversidade incluído na tese foi a elaboração de um trabalho de revisão/perspectivas. Neste manuscrito fica evidente que mudança climática afetará a biodiversidade em todos os níveis de organização ecológica, ou seja, desde a capacidade dos organismos em sobreviver e se reproduzir, passando pelas complexas relações intra e interespecíficas, e repercutindo também na produtividade dos ecossistemas e ciclos biogeoquímicos. As populações com distribuição reduzida, com baixa capacidade de dispersão, e com menor plasticidade fenotípica deverão ser as mais vulneráveis as mudanças climáticas descritas nessa tese. No Cerrado, as mudanças climáticas também irão atuar em sinergia com outros fatores antrópicos que afetam a biodiversidade, como, por exemplo, a massiva perda de habitat e as queimadas. A homogeneização biótica das comunidades já é o principal sintoma destes processos, como detectado por Louise Emmons no já distante ano de 2009 (ver seção de apresentação). Embora não tenhamos nos dedicado exclusivamente a responder as questões por ela levantadas em seu artigo, nós mantivemos o interesse na questão da redução do orvalho noturno, incluindo este tema no primeiro e terceiro artigos. Embora seja difícil em termos práticos, a continuação de estudos relacionados a essa temática não é descartada.

Como apontado na seção de conclusões do terceiro artigo, as possíveis soluções para mitigação dos efeitos das mudanças climáticas para sociedade e biodiversidade passam obrigatoriamente por revisão do atual modelo de produção agropecuária no Cerrado. A reversão das tendências de desmatamento e de queimadas, aliadas a uma utilização mais racional da terra e a adoção de práticas mais sustentáveis, possuem grande potencial para garantir no longo prazo a produção de alimentos e de energia, sequestro de grandes quantidades de carbono, e a conservação dos recursos hídricos e da biodiversidade. A restauração de áreas degradadas, particularmente aquelas associadas aos recursos hídricos como veredas e matas ciliares, é um passo obrigatório para dar suporte à biodiversidade e às populações locais durante longos períodos de seca. A expansão e o fortalecimento das áreas protegidas também deve ser uma prioridade para salvaguardar as espécies endêmicas e ameaçadas. O controle rígido do Estado sobre o uso da água superficial e subterrânea em atividades agrícolas também é de máxima urgência, visto os conflitos sociais que já vêm sendo registrados em municípios no Oeste da Bahia. Essa prática amplamente adotada no MATOPIBA, representa uma séria ameaça as comunidades locais e de áreas a jusante do Cerrado, como o Pantanal e as regiões do baixo e médio São Francisco.

Como mensagem final de encerramento desta tese, optamos por reproduzir uma sequência de quadrinhos que sintetiza em grande parte os resultados do nosso trabalho. Ela foi produzida por um cartunista e morador do Cerrado chamado Evandro Alves, criador da série Cerrado em Quadrinhos. Todo o acervo da série Cerrado em Quadrinhos pode ser encontrando nas redes sociais como Facebook e Instagram (https://www.instagram.com/cerrado.em.quadrinhos.oficial/).

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