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LAND USE TRANSITIONS IN THE CERRADO: IMPACTS ON ECOSYSTEMS AND FUTURE PATHS FROM THE PERSPECTIVE OF THE WATER, ENERGY, AND FOOD NEXUS

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Dissertation submitted to the Examination Committee at the Universidade de Brasília in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Graduate Program in Ecology.

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MUDANÇAS DE USO DO SOLO NO CERRADO: IMPACTOS NOS ECOSSISTEMAS E CAMINHOS FUTUROS SOB A PERSPECTIVA DO NEXUS ÁGUA, ENERGIA E ALIMENTOS

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LAND USE CHANGES IN THE CERRADO: IMPACTS ON ECOSYSTEMS AND FUTURE PATHS FROM THE PERSPECTIVE OF THE WATER, ENERGY AND FOOD NEXUS

Dissertation approved by the Examination Committee at the Universidade de Brasília in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Graduate Program in Ecology.

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ABSTRACT

The Brazilian Cerrado is the most biodiverse savanna in the world, yet 50% of its original cover has been cleared to make way for crops and pastures by 2022. These rapid land-use transitions are expected to influence regional climate and water balance, with implications for energy generation, food production, livelihoods, and biodiversity conservation. The demand for key commodities is likely to rise in the coming years, intensifying the pressure for the conversion of native vegetation areas to commercial export-oriented farms. Expanding agriculture over already cleared areas for pastures has been indicated as an opportunity to reconcile production and conservation. Still, deforestation in the Cerrado is advancing at a fast pace, with increasing rates in the last three years. Our goal is to understand the interaction between agriculture, climate, and water cycling in the Cerrado, focusing on accumulated impacts, future scenarios, and opportunities to increase commodity-driven production without further deforestation. Chapter 1 presents the theoretical framework that justifies and contextualizes this research. We investigated the water, energy, and food nexus (WEF Nexus) concept, its origins, applicability to understand human caused impacts on ecosystems, and current developments. Then, we discussed why the Cerrado is an emblematic case study of complex land use and land cover change dynamics, requiring an integrated nexus approach. In Chapter 2, we investigated how the accumulated land-use transitions (LUT) affect regional climate and water cycling in the Cerrado through changes in mean annual evapotranspiration (ET) and average land surface temperature (LST), as well as implications on future land use options. We performed regression analyses to quantify the effects of six common LUTs on ET and LST across the entire gradient of Cerrado landscapes from 2006-2019. Results indicate that clearing forests for cropland or pasture increased average LST by ~3.5°C and reduced mean annual ET by 44% and 39%, respectively. Transitions from woody savannas to cropland or pasture increased average LST

by 1.9°C and reduced mean annual ET by 27% and 21%, respectively. Converting native grasslands to cropland or pasture increased average LST by 0.9 and 0.6°C, respectively. Conversely, grassland to pasture transitions increased mean annual ET by 15%. To date, land changes have caused a 10% reduction in water recycled to the atmosphere annually and a 0.9°C increase in average LST across the biome, compared to the historic baseline under native vegetation (prior to large-scale human occupation). Global climate changes from increased atmospheric greenhouse gas concentrations will only exacerbate these effects. Considering potential future scenarios, we found that the absence of deforestation control enforcement or allowing legal deforestation to continue (at least 28.4 Mha) would further reduce yearly ET (by -9% and -3%, respectively) and increase average LST (by +0.7 and +0.3°C, respectively) by 2050. In contrast, policies encouraging zero deforestation and restoration of the 5.2 Mha of illegally deforested areas would partially offset the warming and drying impacts of land-use change. In Chapter 3, we investigated the potential for cropland expansion without new deforestation in the Cerrado, by assessing the spatial and temporal dynamics of land use transition over the past 35 years (1985-2021). We performed correlation analyses between four key types of land transitions in the Cerrado: (a) pasture expansion over native vegetation, (b) direct conversion of native vegetation to cropland, (c) cropland expansion over pasture, and (d) pasture abandonment. We also calculated the remaining area with high crop suitability over pastures and over native vegetation and spatio-temporal patterns of cropland expansion over pastures. Between 1985-2021, the expansion of pasture over native vegetation was the prevailing land use transition (18.8 Mha), followed by pasture abandonment (8.9 Mha). Even though deforestation for pasture has decreased, it is still the main land use transition, driving the loss of 414,000 ha yr^{-1} of native vegetation between 2011-2020. Pasture expansion over native vegetation and pasture abandonment are negatively correlated ($\rho = -0.38$), while cropland expansion over pasture is positively correlated to cropland expansion over native

vegetation ($\rho = 0.48$). Direct conversion from native vegetation to cropland has increased in the last three decades, amounting to 113,000 ha yr^{-1} in 2011-2020, mainly in the Matopiba region. Promoting pasture intensification could free land for cropland expansion without deforestation. There are 18 Mha of pasture with moderate to high crop suitability, mostly in the states of Goiás, Mato Grosso do Sul and Minas Gerais. Of the current 27 Mha of cropland in the Cerrado, 27% were established in the last 10 years and 28% (7.5 Mha) over pastures. A considerable area of croplands (2Mha) replaced newly created pastures (<7 yr), suggesting pastures may be an intermediate land use, before selling or renting for cropland production. There are 20 Mha of native vegetation areas with moderate to high crop suitability, signaling that stopping deforestation in the Cerrado will require a combination of conservation policies and incentives for cropland expansion over pastures. By looking into the impacts associated to cropland and pasture expansion over native cerrado vegetation and opportunities to reverse this process while increasing agricultural productivity, our results may help to foster a new development pathway to the Cerrado, with food, energy, and water security.

Keywords: deforestation, conservation, ecosystem services, Forest Code, restoration, savanna, soybean expansion, regional climate, land-use change

RESUMO

O Cerrado é a savana mais biodiversa do planeta, contudo, 50% de sua cobertura original foi desmatada até 2022, para abrir espaço para agricultura e pastagem. Espera-se que essa rápida transição influencie o clima regional e o balanço hídrico, com implicações para a geração de energia, produção de alimentos, modos de vida e conservação da biodiversidade. A demanda pelas principais commodities agrícolas possivelmente aumentará nos próximos anos, intensificando a pressão pela conversão de áreas de vegetação nativa para fazendas comerciais orientadas à exportação. A expansão da agricultura sobre áreas que já foram desmatadas para pastagem tem sido indicada como uma oportunidade de reconciliar produção e conservação. Ainda assim, o desmatamento do Cerrado avança em ritmo acelerado, com aumento das taxas nos últimos três anos. Nosso objetivo é entender a interação entre agricultura, clima e ciclagem de água no Cerrado, com foco nos impactos acumulados, cenários futuros e oportunidades para ampliar a produção de commodities agrícolas sem novos desmatamentos. O Capítulo 1 apresenta o marco teórico que justifica e contextualiza essa pesquisa. Nós abordamos o conceito do nexus água, energia e alimentos, sua origem, aplicações para entender os impactos antropogênicos nos ecossistemas e desenvolvimentos recentes. Em seguida, nós discutimos por que o Cerrado é um estudo de caso emblemático da complexa dinâmica de mudanças do uso e cobertura da terra, o que requer uma análise integrada de nexus. No capítulo 2, nós investigamos como as transições de uso da terra (LUT) acumuladas afetam o clima regional e a ciclagem de água no Cerrado, por meio de mudanças na evapotranspiração (ET) média anual e temperatura média de superfície (LST), bem como implicações sobre as opções de uso da terra futuros. Nós realizamos análises de regressão para quantificar os efeitos de seis LUTs usuais sobre ET e LST em todo o gradiente de paisagens do Cerrado, de 2006 a 2019. Os resultados indicaram que o desmatamento de florestas para agricultura ou pastagem aumentaram a LST média em ~3.5°C

e reduziram a ET anual média em 44% e 39%, respectivamente. Transições de savanas lenhosas para agricultura ou pastagem aumentaram a LST médio em 1.9°C e reduziram a ET anual média em 27% e 21%, respectivamente. A conversão de campos nativos para agricultura ou pastagem aumentaram a LST média em 0.9 e 0.6°C, respectivamente. Por outro lado, transições de vegetação campestre para pastagem ampliaram ET média anual em 15%. Até o momento, transições de uso da terra causaram uma redução de 10% na água reciclada para a atmosfera anualmente e aumento de 0,9°C na LST média do bioma, comparado à linha de base histórica sob vegetação nativa (anterior à ocupação humana em grande escala). Mudanças climáticas globais por aumento das concentrações de gases de efeito estufa na atmosfera vão apenas exacerbar esses efeitos. Considerando possíveis cenários futuros, nós observamos que a ausência de controle do desmatamento ou a permissão para a continuidade do desmatamento legal (pelo menos 28,4 Mha) reduziria ainda mais a ET anual (em -9% e -3%, respectivamente) e aumentaria a LST média (em +0,7 e +0,3°C, respectivamente) até 2050. Ao contrário, políticas de est[imulo ao desmatamento zero e restauração dos 5,2 Mha de áreas desmatadas ilegalmente, compensariam parcialmente os impactos de calor e seca causados por mudanças do uso da terra. No capítulo 3, nós investigamos o potencial para a expansão agrícola sem novos desmatamentos no Cerrado, avaliando as dinâmicas espaciais e temporais da transição do uso da terra nos últimos 35 anos (1985-2021). Nós realizamos análises de correlação entre quatro tipos de transição de uso da terra no Cerrado: (a) expansão de pastagem sobre vegetação nativa, (b) conversão direta de vegetação nativa para agricultura, (c) expansão da agricultura sobre pastagem, e (d) abandono de pastagem. Nós calculamos, ainda, a área remanescente com alta aptidão agrícola sobre pastagem e sobre vegetação nativa e padrões espaço-temporais de expansão da agricultura sobre pastagem. Entre 1985-2021, a expansão de pastagem sobre vegetação nativa foi a transição de uso da terra prevalente (18,8 Mha), seguida do abandono de pastagem (8,9 Mha). Ainda que o desmatamento para pastagem tenha diminuído, ele ainda é a

principal transição de uso da terra, levando à perda de 414.000 ha ano^{-1} de vegetação nativa entre 2011-2020. A expansão de pastagem sobre vegetação nativa e o abandono do pastagem estão negativamente correlacionados (ρ = -0,38), enquanto a expansão de agricultura sobre pastagem está positivamente correlacionada à expansão de agricultura sobre vegetação nativa (ρ = 0,48). A conversão direta de vegetação nativa para agricultura aumentou nas últimas três décadas, somando 113.000 ha ano^{-1} principalmente na região do Matopiba. A intensificação do pastagens poderia liberar terra para expansão de agricultura sem desmatamento. Há 18 Mha de pastagem com aptidão agrícola moderada a alta, sobretudo nos estados de Goiás, Mato Grosso do Sul e Minas Gerais. Dos atuais 27 Mha de agricultura no Cerrado, 27% foram estabelecidos nos últimos dez anos e 28% (7.5 Mha) sobre pastagens. Uma área agrícola considerável (2 Mha) substituiu pastagens recentes (<7 anos), sugerindo que pastagem podem ser um uso da terra intermediário, antes da venda ou arrendamento para produção agrícola. Há 20 Mha de áreas de vegetação nativa com aptidão agrícola moderada a alta, indicando que para acabar com o desmatamento do Cerrado é necessária uma combinação de políticas de conservação e incentivos à expansão de áreas agrícolas sobre pastagem. Ao observar os impactos associados à expansão de agricultura e pastagem sobre a vegetação nativa do Cerrado e as oportunidades para a reverter esse processo com aumento de produtividade agrícola, nossos resultados podem ajudar a construir novos caminhos para o desenvolvimento do Cerrado, com segurança alimentar, hídrica e energética.

Palavras-chave: desmatamento, conservação, serviços ecossistêmicos, Código Florestal, restauração, savana, expansão da soja, clima regional, mudança no uso da terra

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1. INTRODUCTION

Cropland and grazing livestock occupy about one-third of the world's land area, excluding Antarctica and inland waters (FAO, 2021). Although agricultural land expansion has gradually decreased, it still happens at alarming rates in global hotspots in the tropics (Kong et al., 2021; Winkler et al., 2021). As developed countries outsourced most of their food production, large areas in the tropics reacted to these market opportunities by expanding agriculture (Ramankutty et al., 2018). The loss and degradation of habitats by agricultural expansion is one of the main vectors of biodiversity decline contributing to the current crisis of mass extinction of species (IPBES, 2019).

Besides the usual perspective of agriculture *versus* nature conservation, land use change involves dynamic interactions within social-ecological systems (Meyfroidt et al., 2018, 2022). Agricultural land use affects the interactions between the land surface and the atmosphere, altering the hydrological cycle, the carbon cycle, and the climate (Coe et al., 2011, 2017; Noojipady et al., 2017; Raucci et al., 2015). Management strategies moderate the effects of agriculture on biodiversity and ecosystem services, which may feedback on agricultural productivity, causing yield loss and making these areas more vulnerable to climate change (Chagas et al., 2022; Cordeiro et al., 2020; Gomes et al., 2019; Neto et al., 2010). Production of food, biofuel and other provisions can be greatly impacted (Flach et al., 2021). This is because agriculture heavily depends on ecosystem services such as pollination, biological pest control, soil structure and fertility maintenance, nutrient cycling, and hydrological services (Power, 2010; Ricketts et al., 2008). While agriculture changes the ecosystem, it suffers the impacts of those changes, in a feedback loop.

The scale of current land change is an important factor to understand its dynamics in Earth System functioning (Foley et al., 2005). High-input agriculture have allowed food production to keep up with the growing population, at the cost of extensive environmental impacts from the widespread use of fertilizers, irrigation water, and pesticides, along with large-scale habitat simplification (Ramankutty et al., 2018). Key ecological processes underpinning planetary boundaries have been affected, mainly related to biodiversity loss, greenhouse gases (GHG) emissions, changes in biogeochemical processes and freshwater withdrawals (Campbell et al., 2017). This agricultural model allowed major advances in food production, but it mirrors a carbon-intensive society, and a period when there was little concern with sustainability. Critical transformations are long overdue to achieve a well-below 2°C future (Clark et al., 2020).

The Cerrado is an emblematic case of land use change dynamics. As the second largest biome in South America, it sustains fundamental ecological processes for water supply, climate stability, biodiversity and agricultural production, with local, regional and global importance (Strassburg et al., 2017). It is considered the richest tropical savannas in the world, with high rates of endemism (Joly et al., 2019; Klink & Machado, 2005; Myers et al., 2000). The complexity and diversity of the biome is related to the evolutionary process of adaptation to seasonal precipitation and nutrient-poor, well-drained soils, geological and morphological characteristics, and the zones of contact to four other biomes (Oliveira-Filho & Ratter, 2002).

The ecological importance of the Cerrado, however, is not reflected in the political field (both by politicians and public policies). Since the 1970s, the biome has lost half of its natural vegetation mainly due to agricultural expansion (Alencar et al., 2020; MapBiomas, 2023; Mueller & Martha Júnior, 2008). In the next decade, deforestation in the Cerrado shows a tendency to continue as a response to economic opportunities in global markets for food production (OECD & FAO, 2022; Rochedo et al., 2018). Protected areas represent only 11% of the biome (Sano et al., 2019) and remaining native vegetation is distributed in fragmented patches, with extensive regions under the minimal threshold to sustain landscape connectivity (Grande et al., 2020).

The challenge for the Brazilian society, government and private sector is to balance the often-conflicting demands for food, energy, and water resources, while providing socio-environmental security in the Cerrado. In this dissertation, we addressed some of these issues. Our overarching goal is to understand the feedbacks between agriculture (cropland and pasture) expansion, climate and water cycling in the Cerrado, focusing on the impacts of replacing native vegetation with pasturelands and croplands and opportunities to minimize potential negative effects by improving the use of already converted areas.

In the first chapter, we presented the theoretical framework that justifies and contextualizes the research. We investigated the nexus concept, its origins, applicability to understand human caused impacts on ecosystems, and current developments. Then we discussed why the Cerrado is an emblematic case study of complex land use and land cover change dynamics, requiring an integrated nexus approach.

In Chapter 2, we investigated the effects of land-use transitions (LUT) on regional climate in the Cerrado, through changes on evapotranspiration (ET) and land-surface temperature (LST). We also evaluate the implications of future land use options on these climate variables. We modeled these effects considering LUT from major vegetation formations (forest formations, savanna formations and grassland) to the most abundant classes of land use (cropland and pasture) in Cerrado. This way, our model explicitly considered the implications of Cerrado vegetation heterogeneity, while addressing the interaction of land use change and regional climate in a region of South America that is underrepresented in climate and hydrology studies.

In Chapter 3, our main goal was to understand land cover and land use change dynamics in the Cerrado and the possibility to expand croplands over pasturelands, sparing land for nature. Therefore, to understand the potential for promoting better use of already cleared areas, it is important to examine various land use dynamics at different scales.

2. CHAPTER – Water, Energy, and Food Nexus in a global biodiversity hotspot

2.1. Introduction

Equitable access to sustainable and reliable sources of water, energy, and food is essential for improving the well-being of people around the world, underpinning the Sustainable Development Goals (SDGs). This challenge is becoming increasingly difficult as the planet continues to get warmer. IPCC's Sixth Assessment Report from Working Group II emphasizes that climate change has negatively impacted food and water security, making it difficult to achieve the SDGs (Intergovernmental Panel on Climate Change, 2023). Droughts have also reduced energy security, affecting hydropower generation (Intergovernmental Panel on Climate Change, 2023). Rising global demand for water, energy, and food due to growing economies, population, and changing consumption patterns raises the risk of shortages.

Water, energy, and food are interconnected in complex ways. Food systems consume 30% of world energy (including primary production, storage, post-harvest processing, distribution and cooking) and agriculture account for 70% of freshwater withdrawals (IRENA & FAO, 2021). Energy production requires a significant amount of water to implement innumerous processes, from cooling thermal power stations to irrigating biofuel crops, and hydropower contributes 16% to the global energy mix (International Energy Agency, 2023; Spang et al., 2014). Water withdrawal, desalination, distribution, and treatment depend heavily on energy (United Nations World Water Assessment Programme, 2014), while agriculture impacts water quality through pesticide and fertilizer runoff (Bustamante et al., 2015; Jensen, 2019). By focusing on sectoral policies, the whole picture is lost, creating increased risks of detrimental impacts. Choices of energy sources and farm management practices, for instance, may affect available options of water supply and demand. An integrated perspective of water, energy and food management has the potential to guide better decision making and help achieve the SDGs.

The Water-Energy-Food Nexus (WEF Nexus) approach offers a comprehensive framework to assess the synergies and tradeoffs among these sectors, with the goal of maximizing benefits and minimizing negative effects (Figure 2.1). The interdependence between water, energy, and food, and other social-environmental areas such as climate, land, and livelihoods, has been recognized for quite some time, even prior to the Brundtland Report, in 1987, that defined the concept of sustainable development and it’s guiding principles (Simpson and Jewitt, 2019). However, the WEF Nexus started gaining relevance after the publication of two reports in 2011. The first one was the summary of the World Economic Forum Water Initiative, entitled "Water Security: The Water-Food-Energy-Climate Nexus" (WEF 2011), and the second one was the background paper for the Bonn 2011 Nexus Conference, "Understanding the Nexus" (Hoff, 2011). Since then, the number of papers published on the WEF Nexus has increased (Figure 2.2).

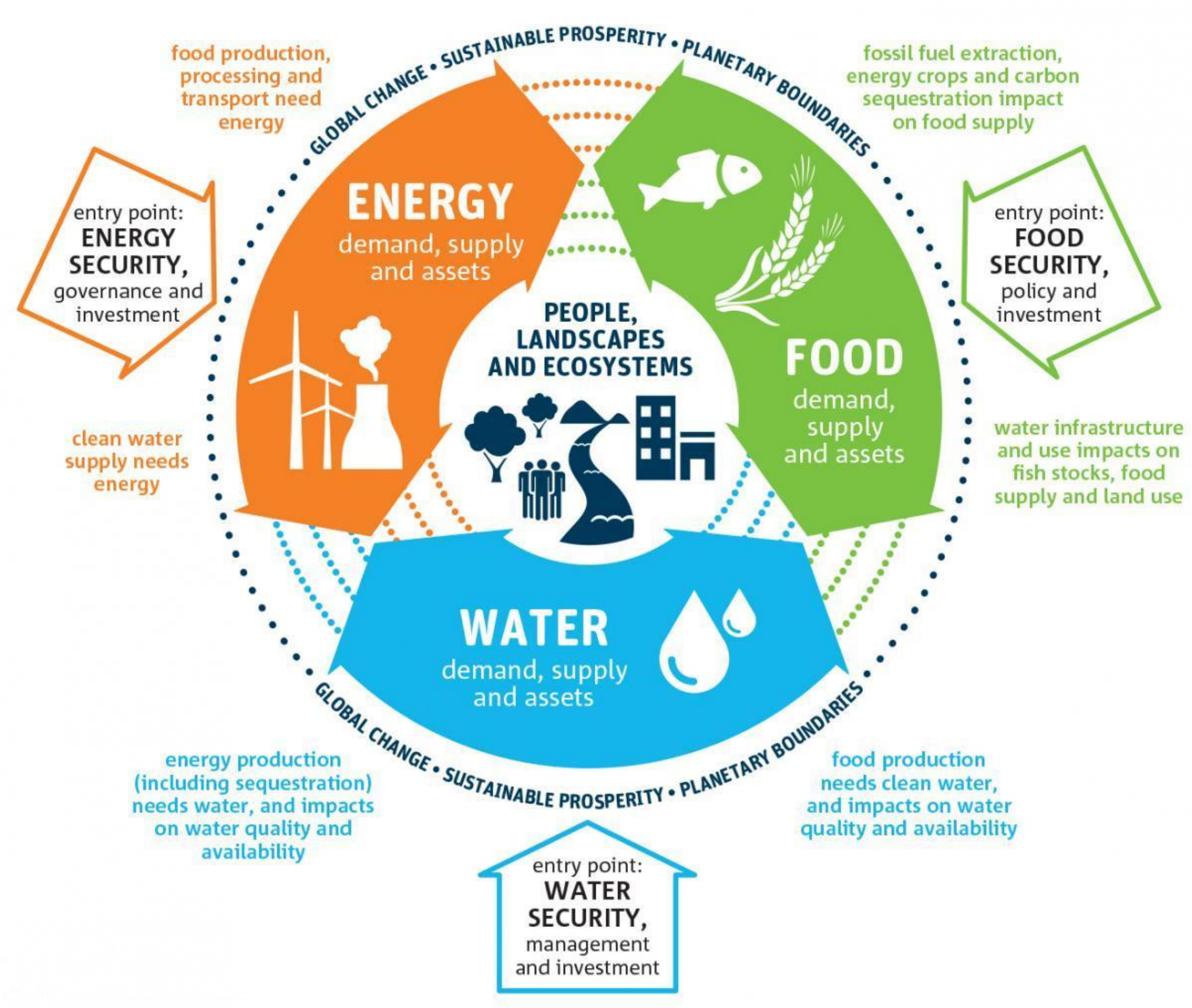

Figure 2.1. Water-energy-food Nexus (WEF Nexus) framework, depicting the feedback interactions between water ↔ food, food ↔ energy, and energy ↔ water, affecting people,
190 landscapes and ecosystems, while being constrained by global changes, sustainable prosperity and planetary boundaries (International Water Association, 2023). The figure also highlights entry points for governance, management, policies, and investments to intervene in the system and produce changes.

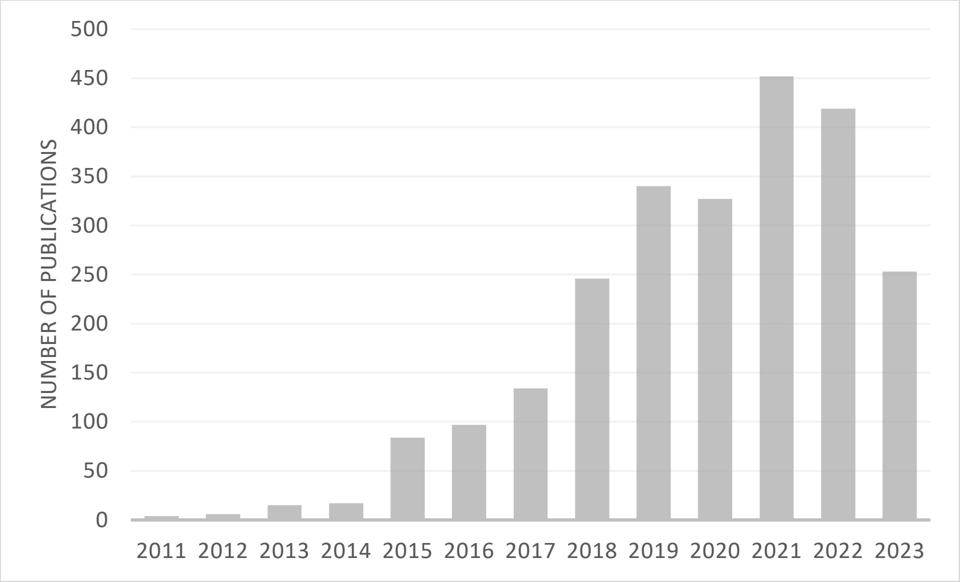

Figure 2.2. Number of published peer-reviewed papers about the WEF Nexus topic by year. The research was conducted in the Web of Science database, with open beginning date and end date in Sep. 27, 2023. The search retrieved 2394 papers, for the topic “water energy food nexus”.

The WEF Nexus was first presented as a tool for integrated resource management and decision-making (Hoff, 2011). With its multi-thematic approach, it became a popular topic of research in interdisciplinary sciences (Figure 2.3). Searching publications with the topic WEF Nexus in the Web of Science database, we found most studies come from the field of environmental sciences (1,214 papers). In the field of ecology, there were only 47 studies, indicating there is still an unexplored potential for ecological studies to contribute to the WEF Nexus debate, especially from ecosystems ecology. By targeting integrated water and nutrient cycling and energy fluxes in the environment, and how human-induced changes impact these processes, ecosystems ecology could help understand the feedbacks and tipping points in natural resources uses and come up with novel solutions that foster ecosystems multifunctionality. On the other hand, the low number of WEF Nexus publications in social sciences, including economics, sociology, political science, and law, may indicate not only a lack of interdisciplinary approaches that could help advance science, but a knowledge gap to implement effective integrated management strategies.

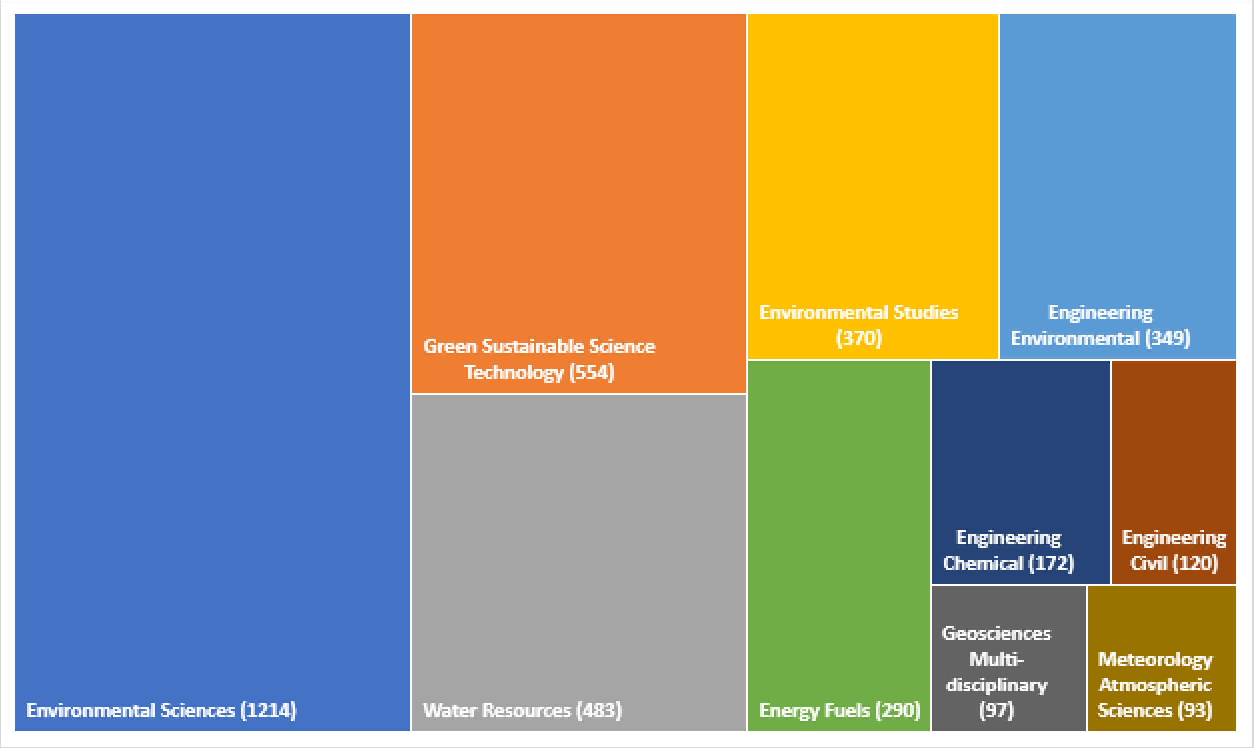

Figure 2.3. Tree map of the ten top fields of studies of WEF Nexus publications. The research was conducted in the Web of Science database and retrieved 2394 published peer-review papers for the topic “water energy food nexus”, until Sep. 27, 2023. The fields of studies are non-exclusive, which means the same publication can be classified within two or more different fields.

The Cerrado biome, in Brazil, is an emblematic study area to analyze the interactions of the WEF Nexus. Covering over 200 Mha, it is a global biodiversity hotspot (Myers et al., 2000) and the most biodiverse savanna in the world, with high levels of endemism (Klink & Machado, 2005), under severe threat due to the rapid land cover transition to agriculture (MapBiomas, 2023). In the last 38 years, the Cerrado lost 25% (32 Mha) of its native vegetation cover to pasture and cropland expansion (MapBiomas, 2023). Currently, only 48% (95 Mha) of the biome is covered by native vegetation, which is highly fragmented and poorly protected (Grande et al., 2020; MapBiomas, 2023).

Historically, it has been difficult to achieve reductions in Cerrado deforestation rates. Despite being half the size of the Amazon, Cerrado sustained higher deforestation rates from 2009-2015, during which time deforestation in the Amazon biome reached its lowest rates (INPE, 2023). Recently, in the first 10 months of 2023, the new Brazilian federal administration was able to reduce deforestation in the Amazon by 34%, compared to this same period in 2022. Conversely, in Cerrado, deforestation increased by 53% (reaching 629,000 ha) (INPE, 2023). Deforestation and expansion of agriculture over native vegetation not only contributes to biodiversity loss, but also exerts pressure on water and energy resources. By analyzing the current challenges in the Cerrado region through the lens of the WEF Nexus, we can develop sustainable integrated options to reduce environmental degradation throughout the biome. This chapter presents the theoretical framework of the WEF Nexus, discussing the major concerns related to each component and how they interact in the context of the Cerrado.

2.2. Water-Food Nexus in Cerrado

Brazil is a major producer of soybean, maize, and beef, with half of this production occurring in the Cerrado (Trase, 2017, 2020). Soybean is the primary crop in the Cerrado and covers 72% of the crop area (MapBiomas, 2023). This crop is grown using high-input systems and 80% of the production is directed towards the external markets, particularly China (Trase, 2020). The package deal of intensive farming practices (improved seeds, irrigation, fertilizers, pesticides, and machinery) used in soy production (Ramankutty et al., 2018) causes a series of well-documented detrimental effects over ecosystems, such as pollution, eutrophication of water bodies, changes in the soil biota, and biodiversity loss (Bustamante et al., 2015; Matson et al., 1997; Tilman, 1999). On the other hand, cattle are usually produced in extensive pastures under low-input systems (Ferraz & Felício, 2010; Oliveira et al., 2004). Beef production is 80% directed to the internal market. Both food and commodities production are highly dependent on water and climate conditions.

In Brazil, water is a particularly critical resource for economic development, as hydropower sources account for 66.6% of national electricity supply and 12.6% of all energy supply (Empresa de Pesquisa Energética, 2019). Water is also essential to the agricultural sector, which has generated around 20% of Brazil's gross domestic product in the last ten years. Although the country holds 12% of the world’s surface freshwater flows (National Water Agency & United Nations Environment Programme, 2007), water is unevenly distributed in time and space, requiring effective integrated management to meet several demands.

Over the past decade, prolonged droughts have caused economic losses in crop production and water scarcity in large urban centers, including major water crisis in São Paulo and several other Brazilian cities (Hirakuri, 2014, 2016; Marengo et al., 2018; Nobre et al., 2016). Droughts and extreme events are likely to become more frequent in Brazil under climate change scenarios (Alves et al., 2021). As climate becomes more variable, our ability to create resilient socioecological systems will require a better understanding of the complex interactions between climate and land use changes (Wohl et al., 2012).

In the Cerrado, vulnerability to droughts is amplified by the extensive land cover change that has been happening in the last 50 years (Caioni et al., 2020; Hofmann et al., 2023). Half of the biome was converted to agricultural uses and the remaining vegetation is highly fragmented (Oliveira et al., 2017; Grande et al., 2020; MapBiomas, 2023). The magnitude of ecosystem degradation alters regional climate and water cycling, intensifying warming and drying effects of climate change, while reducing our ability to cope with the disturbance (Spera et al., 2020).

Deforestation has already decreased the average stream flow in Cerrado basins by ~9% (Salmona et al., 2023). If current trend continues, the projected conversion of native vegetation to agricultural uses, combined with the effects of climate change, can further reduce river flows by 34% until 2050 (Salmona et al., 2023).

Consequences may impact at least national hydroelectric generation, 72% of the irrigated area (MapBiomas, 2020), and around 173 million people, including an estimated 25 million engaged in family farming, 95 indigenous lands, 44 quilombola territories (belonging to Afro-Brazilian communities whose territory and ancestry are related to the resistance to the historical oppression suffered through enslavement) and numerous other territories occupied by indigenous peoples and local communities that are yet to be officially recognized (Critical Ecosystem Partnership Fund, 2018). It may also affect other regions, by reducing the freshwater recharge and distribution in eight of the twelve major Brazilian hydrological basins (Lima & Silva, 2005).

Another key factor that mediates ecosystem responses to land use change is the rainfall regime. Both annual mean and seasonal precipitation variability will ultimately affect ecosystems dynamics and water availability to meet human needs in local contexts (Konapala et al., 2020). Seasonal rainfall variability is yet more important in the Cerrado, where the risk of water scarcity is not evenly distributed throughout the year. The Cerrado is characterized by marked seasonality, with five to six months of water deficiency annually (Silva et al., 2008a). The large spatial distribution across its 204 Mha creates diverse rainfall regimes with annual precipitation ranging from 600 mm to 2000 mm, increasing from east (border with semiarid Caatinga) to west (border with the Amazon rainforest) (Sano et al., 2019). Thus, rainfall regimes in the Cerrado are heterogeneously distributed across space and time, making it harder to predict and understand annual and seasonal variations determining freshwater availability. Hofmann et al. (2023) identified a reduced trend in rainfall frequency and in the number of rainy days over northern and central Cerrado regions, especially during the dry season and beginning of the wet season. These changes affect water provision for multiple uses, including agriculture production (for both food production and cash crops, produced under rainfed and irrigated systems, as well as livestock production), hydropower generation and human consumption.

To maintain and improve agricultural productivity in a changing climate, increased water demand for irrigation is expected. In addition to global climate change, recent studies observed that crop production in Brazil is moving from places with more favorable climate conditions to hotter and dryer regions, with less predictable rainfall (Rattis et al., 2021). Currently, irrigation responds to 70% of water consumption in the country and 40% of the irrigated area (2 Mha) is in the Cerrado (MapBiomas, 2023). Potential irrigated area in Brazil could increase by 11 times, going from the current 5.3 Mha to 55.8 Mha, which means irrigating 22% of the current agricultural area (Ministério do Desenvolvimento Regional & Escola Superior de Agricultura Luiz de Queiroz - USP, 2020). However, constraints from projected climate and runoff changes, and tradeoffs with multiple water uses may limit irrigation options and increase conflicts. The accelerated agribusiness expansion in Western Bahia (Polizel et al., 2021) has been supported by an intense increase in the area irrigated by center pivot systems, above the average increase observed in the Cerrado (MapBiomas, 2023). Crop expansion and irrigation have reduced the streamflow and water available to smallholder farming activity, pushing water use to its limit and triggering conflicts, especially in dryer years (Silva et al., 2021a; Pousa et al., 2019; Salmona et al., 2023; Santos et al., 2020a).

Irrigation and hydropower generation in Brazil may face a tradeoff between upstream and downstream water needs (Zeng et al., 2017), and some basins are approaching their limit of supply and demand (Mendes et al., 2015). Currently, there are 35 large hydropower dams and 124 small ones in the Cerrado, generating 35-60 MW of power. However, with the number of hydropower plants under construction or in their final planning stages, this number is set to increase almost threefold to 116 large dams and 352 small ones, increasing the pressure over Cerrado ecosystems. Most of these new plants (82%) are to be installed in areas with high ecological value, impacting not only the river flow and the aquatic biodiversity but also increasing the risk of deforestation and agriculture expansion in neighboring dam areas (Ferreira et al., 2022).

Due to climate changes and more severe droughts affecting most areas in the Cerrado, hydropower plants have experienced decreases in energy production since 2014, putting the system under critical condition. To avoid power shortages, the Brazilian government increased the participation of thermoelectric power plants in the energy mix, which resulted in an increase in energy prices (Cuartas et al., 2022). Higher energy prices may, in turn, affect agriculture and livestock production. These two economic sectors together consume only 4.8% of the primary energy production and 4.7% of the electricity (Empresa de Pesquisa Energética, 2023), a comparatively small percentage when compared to industries, which consume 32% of the national electricity supply. However, increased energy prices may have a direct impact on irrigation practices and agriculture profits, since energy is already costly to producers (Pousa et al., 2019).

Another important link between energy and agriculture in the Cerrado is the production of energy crops for biofuels. International discussions to reduce greenhouse gases emissions and keep global warming well below 2 °C have spurred the debate about biofuels. Globally, biofuels provide 3.5% of the energy for transport, and the demand has increased over the past 5 years (International Energy Agency, 2023). In Brazil, national regulations define mandatory percentages of ethanol and biodiesel added to the fuel (Empresa de Pesquisa Energética, 2023).

Sugarcane is the main energy crop in Brazil, accounting for 13.5% of primary energy production in 2022 (Empresa de Pesquisa Energética, 2023). In the Cerrado, sugarcane is the second-largest crop after soybeans, covering 12% of the cropland area (MapBiomas, 2023).

The area of sugarcane production in in Brazil and the Cerrado has remained relatively stable since 2015 (MapBiomas, 2023). However, there are concerns that the increasing international demand for ethanol could lead to the expansion of sugarcane production over pastures, pushing pastures to expand over native vegetation, resulting in indirect deforestation (Lapola et al., 2010). This could offset the gains from reduced biofuels emissions (Lapola et al., 2010). It is challenging to equate the increase in energy crop production with their potential direct and indirect impacts. It requires policies that combine WEF Nexus approaches and operate at multiple scales, from local to state and national levels, and involve international regulations and trading supply chains.

2.3. Concluding remarks

We discussed the complex interactions of the WEF Nexus in the Cerrado, affected by a broader context of socioeconomic implications and global climate change. We centered the discussion around key topics: production of commodities, irrigation, hydropower generation, water availability for multiple uses, and production of energy crops. From the WEF Nexus perspective, the decision to expand irrigation in the country, for instance, needs to consider the feedback loops with present and future demands for hydropower generation, the demand for multiple water uses by heterogenous social groups (including smallholder farmers, local communities, and indigenous peoples), and how the supply and demand for water resources is influenced by projected climate changes.

More than a theoretical framework that offers a perspective, a way to investigate the relationship among important resources, the WEF Nexus can be a tool to create multisectoral groups to discuss and implement integrated policies. Brazil has now the opportunity to advance this debate during the implementation of the sectoral plans to protect the Amazon and the

Cerrado, and the Climate Emergency Program. The disaggregated approach we have followed so far delivered these unfortunate results of reducing deforestation rates in the Amazon and increasing in the Cerrado. Ecosystems, as well as climate systems and social systems are connected, and so should be the political and collective decisions pertaining to these systems.

3. CHAPTER – Cerrado deforestation threatens regional climate and water availability for agriculture and ecosystems

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3.1. Introduction

Savannas occur over one-sixth of the Earth's land surface (2.3 billion hectares), forming the largest tropical biome(Solbrig, 1996). In a broad sense, savannas consist of a continuous grass layer with scattered trees and shrubs adapted to strong climate seasonality (Bourlière & Hadley, 1970). They play a vital role in the provision of ecosystem services globally and support high biodiversity, including many endemic plant species with unique adaptations to cope with fire, drought, and herbivory (Pennington et al., 2018). Savannas are also responsible for 30% of global terrestrial vegetation primary productivity and account for 21% of global evapotranspiration (Grace et al., 2006; Miralles et al., 2011).

Despite the global importance of savanna biomes, international and domestic conservation efforts tend to prioritize rainforests. Today savannas remain undervalued and poorly protected around the world (Neves et al., 2015; Pennington et al., 2018), often regarded as land reserves for agribusiness expansion (Gasparri et al., 2016; Lambin & Meyfroidt, 2011; Rattis et al., 2021; Strassburg et al., 2017). The Brazilian Cerrado provides a clear example

(Lahsen et al., 2016). This global biodiversity hotspot (Critical Ecosystem Partnership Fund, 2018; Mittermeier et al., 2011; Myers et al., 2000) has over 12,000 plant and 1,000 vertebrate species, with high levels of endemism (Joly et al., 2019; Klink & Machado, 2005), yet just 11% of the biome is protected as conservation units and Indigenous lands (Sano et al., 2019). This is far less than the 46% protected in the Amazon and still a long way from reaching Brazil's 17% commitment under the Convention on Biological Diversity (Convention on Biological Diversity, 2010). These low levels of protection threaten vital water resources, including the headwaters of major Brazilian rivers (the São Francisco, Tocantins-Araguaia, and Paraná) that feed national and international basins (Lima & Silva, 2005).

In addition to its vast ecological importance, the Cerrado is Brazil's largest established agricultural area, responsible for 12% of global soybean production (Russo et al., 2018) and 10% of global beef exports (Organisation for Economic Co-operation and Development & Food and Agriculture Organization, 2021; Trase, 2021). These two characteristics are increasingly in conflict (Rausch et al., 2019; Strassburg, et al., 2017). By 2019, 91.6 million hectares (Mha) (or 46%) of native Cerrado vegetation had been cleared (i.e., deforested) to make way for pastures (31%), soybeans (9%), sugarcane (2%), tree plantations (2%), and other crops (2%) (MapBiomas, 2020). Of the remaining vegetation, 80% is suitable for growing soybeans (Rudorff et al., 2015), and 69% for sugarcane (Strassburg et al., 2014) – two crops for which demand is projected to rise steeply in the coming decades (Organisation for Economic Co-operation and Development & Food and Agriculture Organization, 2019). Much of this new agricultural expansion is concentrated in the Matopiba (acronym for the states of Maranhão, Tocantins, Piauí, and Bahia) region, which spans 73 Mha of the Cerrado biome (Embrapa Territorial, 2020). Today, Matopiba contains the largest remnants of undisturbed native Cerrado vegetation, yet it is also Brazil's most rapidly expanding agricultural frontier (Lima et al., 2019; Souza et al., 2020a; Spera et al., 2016; Zalles et al., 2019).

Brazil’s current legal framework has failed to curb agricultural expansion and to protect native Cerrado vegetation (Vieira et al., 2018). The Brazilian Native Vegetation Protection Law (Law no. 12,651, of May 25, 2012), also known as the Brazilian Forest Code, requires landowners in the Cerrado to conserve between 20% (in most of the Cerrado) and 35% (in the Cerrado-Amazon transition) of native vegetation on their properties, a marked contrast to the 80% required in the Amazon. Under the law, at least 28.4 Mha (calculated from data published by Rajão et al., 2020) and as much as ~40 Mha (Guidotti et al., 2017; Rausch et al., 2019; Soares-Filho et al., 2014) of native cerrado vegetation could still be cleared legally in the coming decades. Though legal, such large-scale deforestation is far from sustainable – resulting in massive biodiversity losses and greenhouse gas emissions of ~3.2 GtCO2e (Russo et al., 2018). Even where protection exists, law enforcement is weak: an estimated 15% (1 Mha) of all Cerrado deforestation occurring from 2009-2018 was illegal (i.e., not compliant with the Native Vegetation Protection Law) (Rajão et al., 2020).

A growing body of work suggests that widespread deforestation in the Cerrado could have major consequences for the regional and global climate (Arantes et al., 2016; Loarie et al., 2011; Spera et al., 2016, 2020). As croplands and pastures replace native trees and shrubs, evapotranspiration (ET) tends to decrease because row crops and grasses have shallower rooting systems that limit their access to deep soil water during the dry season (Oliveira et al., 2005). They also generally have a shorter growing season and higher albedo than native woody species (Coe et al., 2017). While the increase in albedo could have a slight cooling effect, several studies suggest that this is more than offset by decreases in ET, which leads to a large net surface warming (Bonan, 2008; Loarie et al., 2011). Widespread regional warming and ET reductions could have important cumulative feedbacks, such as reducing rainfall (Keys et al., 2018; Spracklen et al., 2012), increasing surface air temperatures (Cohn et al., 2019; Davin & Noblet-Ducoudré, 2010; Winckler et al., 2019), and intensifying droughts in neighboring biomes.

Despite the potential scale of these unintended consequences, we know relatively little about how land-use transitions (LUT) affect climate in tropical savannas. While our understanding of forested ecosystems is relatively advanced, the heterogeneity of savanna ecosystems and non-forest vegetation formations is underrepresented in climate studies (Salazar et al., 2015). Along the structural gradient of Cerrado vegetation, from forests to sparse trees and grass-dominated landscapes, different mechanisms emerge to govern land-atmosphere dynamics in response to LUTs. For instance, native grasslands may resemble pastures with exotic grasses in terms of root depth, soil water use, albedo, and other characteristics, making it hard to predict the impact of LUTs on ET and land surface temperature (LST) in these areas. Since both native vegetation and subsequent land uses (e.g., annual crops, pasture, sugarcane) influence the net outcome, each LUT has a unique effect on the energy and water balance (ET, LST, and net energy) (Arantes et al., 2016; Silvério et al., 2015). Limited knowledge about the effects of specific LUTs on climate hinders our ability to evaluate future scenarios accurately and to develop regionally appropriate adaptation strategies. This is of particular concern since different land-use change pathways in the Cerrado could lead to drastically different local and regional climate outcomes.

To fill this gap, we combined remote sensing observations and spatial modeling to investigate the historic and potential future climate impacts of LUTs from three vegetation formations typical of the Cerrado (forests, savannas, and grasslands) to the two dominant land uses (pastures and croplands). We address three overarching questions: (1) How does each land-use transition alter regional ET and LST in the Cerrado?; (2) What is the cumulative effect of all historic LUTs on the present-day climate of the Cerrado?; and (3) How might future LUTs in the Cerrado further alter local and regional climate (ET and LST)?

3.2. Material and methods

3.2.1. Study area

Our analysis focuses on the Brazilian Cerrado biome (Figure 3.1), which is a mosaic of native grasslands, savannas, and forests (Ribeiro & Walter, 1998). Grasslands are characterized by the dominance of an herbaceous-shrub stratum, with sparsely distributed trees. Savannas have variable tree-shrub-grass strata, with canopy cover ranging from 50% to 70%. Forest formations are denser, with relatively larger and taller trees, no grass layer, and canopy cover ranging from 50% to 95% (Ribeiro & Walter, 1998). Annual precipitation ranges from 600 to 2000 mm yr^{-1} (Assad & Evangelista, 1994; Sano et al., 2019), with the lowest rainfall occurring in the northeast (i.e., bordering the semiarid Caatinga) and increasing towards the west (i.e., bordering the wet tropical forests of the Amazon). The typical rainy season occurs from October to May, with a well-defined dry season from June to September (Silva et al., 2008b). The annual mean air temperature ranges from 18 to 27 ºC, and the relative humidity ranges from 60 to 90% (Silva et al., 2008b) (Figure 3.2).

Figure 3.1. Map depicting the Cerrado biome (Brazilian Institute of Geography and Statistics, 2004) and highlighting the Matopiba region – a rapidly expanding agricultural frontier spanning the Cerrado portions of the states of Maranhão, Tocantins, Piauí, and Bahia.

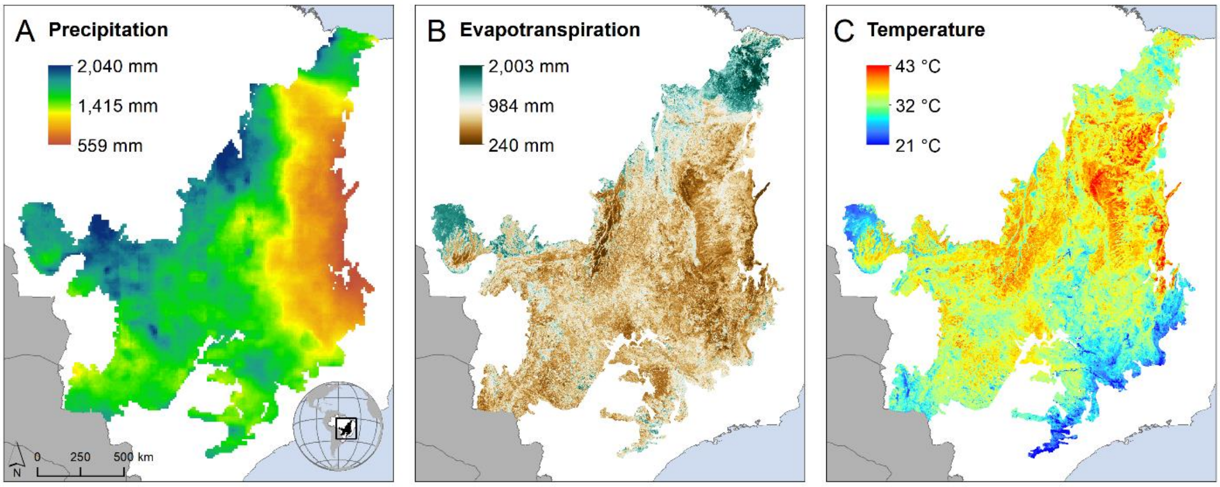


Figure 3.2. Maps depicting the average annual (a) precipitation, (b) evapotranspiration, and (c) land surface temperature across the Brazilian Cerrado. Climate variables were calculated for our study period (2006-2019) based on Global Precipitation Measurement data (Huffman et al., 2019) and MODIS-derived products MOD16A2 Version 6 (Running et al., 2017) and MOD11A2 Version 6 (Wan et al., 2015).

3.2.2. Quantifying LUT effects on climate

We performed regression analyses to evaluate the relationships between six LUTs (forest-to-cropland, forest-to-pasture, savanna-to-cropland, savanna-to-pasture, grassland-to-cropland, and grassland-to-pasture) and associated changes in ET and LST from 2006-2019. Following Silvério et al. (2015), we derived fractional LUTs based on existing time-series data of land use and land cover, ET, and LST.

To generate the fractional LUTs, we used maps from Collection 5 of the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas, 2020), which reports 75% classification accuracy based on visual interpretation of 21,000 points (Alencar et al., 2020). MapBiomas relies on Google Earth Engine’s cloud processing and automated classification algorithms to generate annual land use and land cover time series, available for Brazil at 30-m resolution (Landsat) from 1985-present (Souza et al., 2020b). The ET and LST time series came from MODIS-derived products that have been widely used and validated by previous climate and hydrology studies in the Cerrado (Hofmann et al., 2021; Loarie et al., 2011; Ruhoff et al., 2013). For ET, we used the MOD16A2 Version 6 product, which is available every 8 days at 500-m resolution (rescaled to 1 km) (Running et al., 2017). For daytime LST, we used the MOD11A2 Version 6, available every 8 days at 1-km resolution (Wan et al., 2015).

We first calculated the proportion of each 1-km grid cell occupied by a given vegetation class (forest, savanna, or grassland) or agricultural use (pasture or cropland) to obtain the fractional cover per pixel at 10% intervals. The computation was performed for each year of the 14-year time series (from 2006 to 2019), rescaling the 30-m land use data to match the spatial resolution of the MODIS-derived response variables. We then used the pixels within each of the six LUTs to fit linear regression models, treating the LUT fraction as the independent variable and ET and LST as dependent variables (S1). To control for the strong climate gradient across the Cerrado (Figure 3.2), we generated 2° × 2º grid cells (S2) and fitted regressions for each resulting climate region before summarizing the data for the entire biome.

3.2.3. Estimating the cumulative effect of past LUTs on regional climate

To quantify the cumulative influence of historic LUTs on the Cerrado's climate, we calculated the difference between present-day ET and LST (as of 2019) and what it would have been in the absence of deforestation. Briefly, we first calculated the total area that experienced each of the six LUTs identified above (MapBiomas, 2020). We then applied the slopes of the regressions calculated for each 2° × 2° grid and each LUT (i.e., the changes in ET and LST that occurred because of deforestation). If the regression in a particular grid cell proved insignificant ($p < 0.05$), we applied the average slope for the entire biome instead. Finally, we summed the total change in ET (mm of water per year) and the average change in LST (°C) across the entire biome.

To approximate the spatial distribution of native vegetation prior to large-scale human occupation (i.e., the historic baseline), we obtained a new and improved version of the map from the Fourth National Communication of Brazil to the United Nations Framework Convention on Climate Change (UNFCCC), elaborated under the coordination of the Brazilian Ministry of Science, Technology, and Innovations (2021). This map was adapted from the Vegetation Map of Brazil produced by the Brazilian Institute of Geography and Statistics (2017) at 1:250,000 scale, which reconstructs the presumptive native vegetation in Brazil (i.e., prior to large-scale land-use changes). We then identified the correspondences between native vegetation classes from the historic vegetation map with the classes used in the 2019 land use and land cover map (S3), based on the class descriptions in the Algorithm Theoretical Basis Document of MapBiomas Collection 5 (MapBiomas, 2020) and the Brazilian Vegetation Technical Manual (Brazilian Institute of Geography and Statistics, 2012) (Figure 3.3).

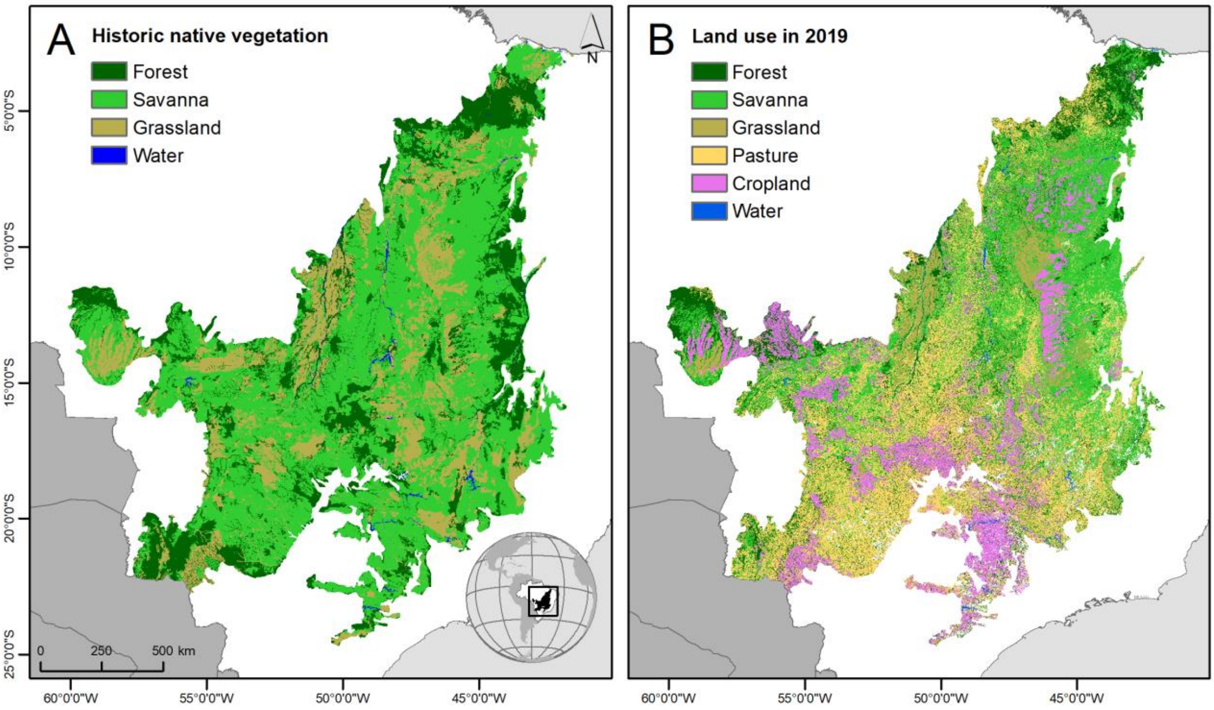


Figure 3.3. Maps of (a) presumptive native vegetation distribution prior to large-scale human occupation (historic baseline) (adapted from Ministry of Science Technology and Innovations, 2021) and (b) 2019 land cover and land use classes (MapBiomas, 2020) in the Cerrado.

To identify hotspots of reduced ET and increased LST, we used Anselin's Local Moran's I statistics (Anselin, 1995) implemented in ArcMap 10.6.1. This method performs a local spatial autocorrelation analysis to identify significant association patterns (local clusters or local spatial outliers) for a variable and its neighbors, compared to the null hypothesis of spatial randomness. We first averaged ET and LST slopes per municipality, and then calculated per pixel ET and LST change from historic native vegetation (Ministry of Science Technology and Innovations, 2021) to 2019 land use (MapBiomas, 2020). We then resampled the resulting raster layers of ET and LST change from 30 m to 500 m and converted them to point features. We used an inverse distance row-standardized spatial weights matrix to define the relationships among the features and calculated Anselin's Local Moran's I (Anselin, 1995) for the ET and LST datasets. The analyses identified statistically significant clusters of above-average LST increase or ET loss (hotspots), and below-average LST increase or ET loss (coldspots). They also identified spatial outliers with values that differed significantly from their neighboring pixels, including below-average LST increases or ET losses, surrounded by high values, and vice versa. Statistical significance was calculated at 95% confidence interval, from 499 Monte Carlo simulations. Emerging hotspots were interpolated using the inverse distance-weighted method to produce a final map.

3.2.4. Evaluating the effect of potential future land-use scenarios on Cerrado climate

We used relationships derived from our analyses of historic land-use change to calculate expected changes in LST and ET under three plausible future scenarios. To examine how future land-use decisions might alter regional climate, we averaged the slopes of the regression model within each municipality and calculated the difference from current baselines. Transitions from grasslands to other land uses were excluded from all scenarios due to methodological limitations. Grasslands are the least abundant of the native cerrado vegetation formations (MapBiomas, 2020) and showed relatively low classification accuracy compared to forests and savannas (Alencar et al., 2020). As a result, grassland transitions had a relatively small sample size within the local regressions (for each grid) used to calculate the scenarios, showing higher variability and often non-significant ($p > 0.05$) relationships with local climate variables. The modeled scenarios were based on different degrees of compliance with the Native Vegetation Protection Law, as described in previous publications (Rajão et al., 2020; Rochedo et al., 2018) and summarized below:

a. Cerrado Collapse (accelerating legal and illegal deforestation). This worst-case scenario assumes an additional 63.6 Mha of native vegetation being converted to cropland or pasture by 2050, with an average deforestation rate of 1.7 Mha yr^{-1} (twice the deforestation in 2021; National Institute for Space Research, 2022). Under this scenario, the native vegetation of the Cerrado would ultimately be reduced to ~20% (S4) of its original cover. This scenario assumes a rollback of conservation policies, including the abandonment of deforestation controls such that projected future rates of annual vegetation clearing resemble the inverse trend from 2004-2014, capped at the 2004 peak of 1.8 Mha yr^{-1}. Previous successes in reducing vegetation clearing would thus be reversed and both legal and illegal deforestation would accelerate. The scenario was originally developed by Rochedo et al. (2018) using the OTIMIZAGRO countrywide land-use change model (Soares-Filho et al., 2016) adopting 2012 as the baseline for annual projections through 2050.

b. Cerrado Struggling (legal deforestation). This intermediate deforestation scenario is already extreme since it assumes clearing of all 28.4 Mha of native vegetation allowable under the law (calculated from data published by Rajão et al., 2020). Because these remaining areas of native vegetation exceed minimal conservation requirements (20-35% of the property) under the Native Vegetation Protection Law, they could be cleared legally if a deforestation permit is issued to the landowner. This scenario projects the consequences of strong policy or market-driven measures to curb illegal deforestation only. Such new restrictions could effectively push agricultural expansion into areas of native vegetation inside private properties, barring additional incentives for landowners to conserve these areas and thus avoid legal deforestation.

To implement this scenario, we relied on recent data on property-level compliance with the Native Vegetation Protection Law, calculated by Rajão et al. (2020) using the Dinamica EGO environmental modeling platform (Soares-Filho et al., 2002) and data from Brazil’s environmental registry of rural properties (CAR), combined with deforestation data until 2018. While it is mandatory for all rural landowners to register their properties in the CAR database, just 83% of eligible areas had been registered by 2019 (Rajão et al., 2020), suggesting that 28.4 Mha may be an underestimate of the current native vegetation area that could be legally converted. We used data reported at the municipal level and imputed deforestation over forest and savanna formations based on the proportional area of each physiognomy remaining in 2019 (MapBiomas, 2020).

We accounted for the transition to different agricultural classes (cropland or pasture) by using the average value of the regression slopes (derived empirically in this study) for ET and

LST change in each municipality. To assess the effects of future LUTs on ET and LST, we projected the conversion to agriculture (cropland or pasture) of all the 28.4 Mha of native vegetation that could be legally converted. Considering the average deforestation rate observed in the Cerrado over the last 10 years (0.9 Mha yr^{-1} from 2012-2021; National Institute for Space Research, 2022), we estimate that it would take ~31 years to carry out all legal deforestation, spanning the period from 2019-2049.

c. Cerrado Recovering (zero deforestation and restoration). This best-case scenario for the Cerrado assumes no further deforestation, as well as restoration of 5.2 Mha of illegally cleared vegetation until 2018 (calculated from data published by Rajão et al., 2020). This scenario assumes incentives that go beyond the current legal framework to stop both legal and illegal deforestation and begin recovering ecosystem services and landscape connectivity through ecological restoration in intensely modified areas. We calculated estimates from Rajão et al. (2020) of Cerrado areas that had been illegally cleared (i.e., above the legal limits, considered 'vegetation debts') up to 2018 and would require restoration to comply with the Native Vegetation Protection Law. Illegal deforestation includes vegetation removed from ecologically important areas such as riparian forests and areas with high slopes, both of which are legally protected as Areas of Permanent Protection (APPs). It also includes deforestation over Legal Reserves (LRs), the 20-35% of areas that should be set aside on most rural properties.

Illegal clearing within APPs and LRs has affected 0.5 Mha and 4.7 Mha, respectively (calculated from data published by Rajão et al., 2020). To comply with the law, landowners must develop and execute a restoration plan. We estimated the restoration potential for these areas of "vegetation debt" based on the proportion of forest and savanna that existed in each municipality according to the historic native vegetation map (Ministry of Science Technology and Innovations, 2021). We then quantified the climatic effects (on ET and LST) of restoring all 5.2 Mha of native vegetation that were illegally cleared. Considering that the area under regeneration has increased by about 0.5 Mha yr^{-1} over the last 10 years (from 2009-2018; MapBiomas, 2021), we estimate that it would take ~10 years (from 2019 until 2028) to achieve the additional restoration projected in this scenario.

Complementing this analysis, we calculated the impact of restoring riparian APPs using the land use and land cover data produced by the Brazilian Foundation for Sustainable Development (Brazilian Foundation for Sustainable Development, 2019). They used supervised classifications and vectorization of 5-m resolution Rapid Eye images from 2013, at 1:10,000 scale, with at least 95% classification accuracy (Brazilian Foundation for Sustainable Development, 2019; Rezende et al., 2018). Based on the FBDS (2019) dataset, we estimated the vegetation debt in riparian APPs considering the sum of built areas, anthropic areas, and forestry in each municipality (S5).

3.3. Results

3.3.1. LUT effects on regional ET and LST

Our analyses show that the transition from native Cerrado vegetation to cropland or pasture generally reduces ET and increases LST (Figures 3.4 and 3.5). The magnitude of the effects of LUTs on ET and LST tended to increase with increasing tree cover density of the original vegetation formation (i.e., the effect of clearing grasslands < savannas < forests). The conversion of forest formations to cropland or pasture reduced mean annual ET by 44% and 39%, respectively, and increased day-time average LST by ~3.5 °C (for both transitions). Transitions from savannas to cropland or pasture reduced mean annual ET by 27% and 21%, respectively, and increased average LST by 1.9 °C (for both transitions). Conversion from native grasslands to cropland or pasture increased average LST by 0.9 ℃ and 0.6 ℃, respectively. In contrast to other LUTs, grassland-to-pasture transitions increased mean annual ET by 15% and grassland-to-cropland transitions had no significant effect on ET ($p > 0.05$). Overall, increased clearing of native vegetation in a given area was associated with linear increases in LST and linear decreases in ET (except for grassland-to-pasture, as noted above). These trends were consistent over the entire 14-year period, despite interannual data variability.

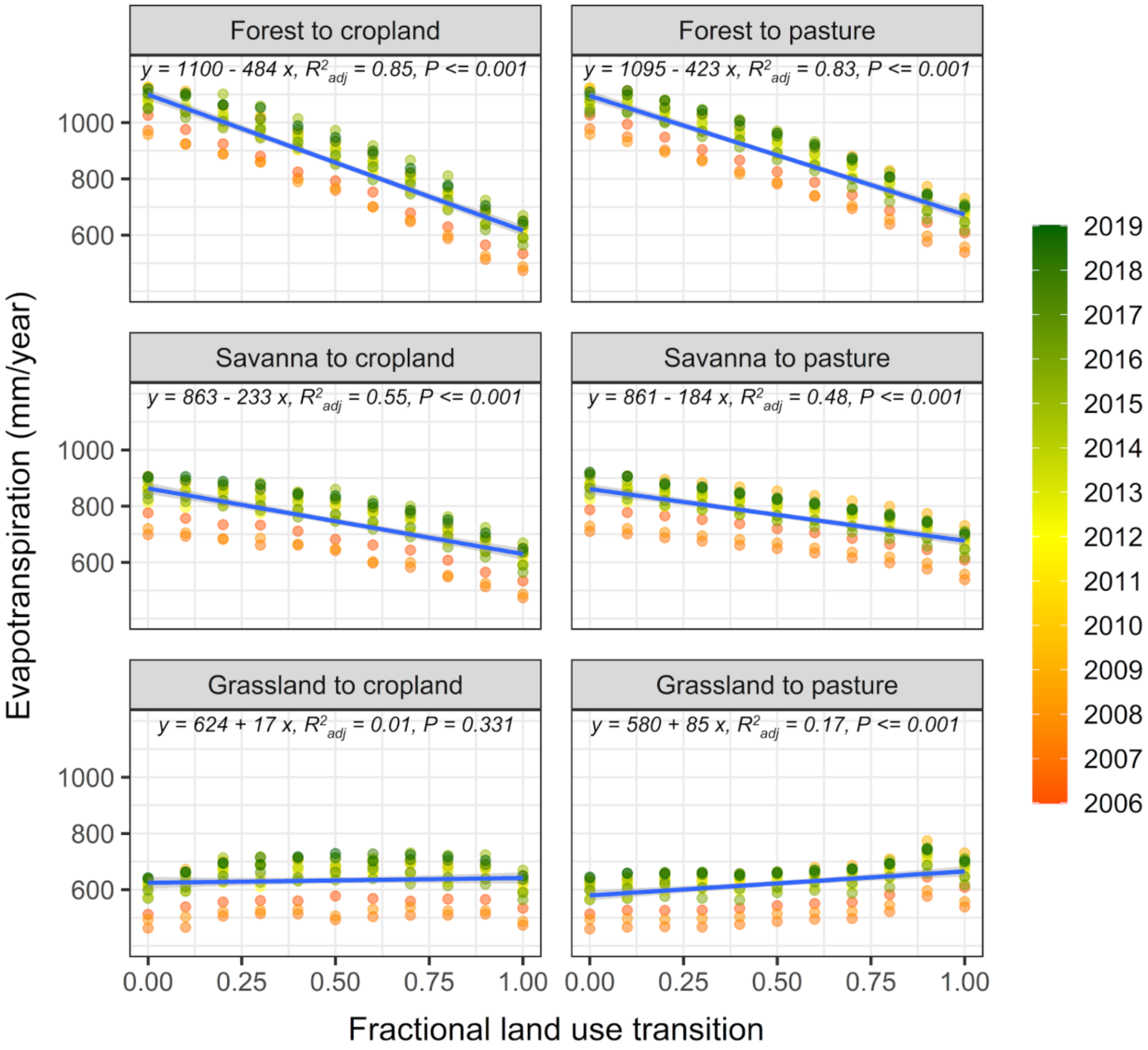


Figure 3.4. Change in average annual evapotranspiration (ET) as a function of fractional change in land use, estimated from 2006 to 2019 for the Cerrado biome.

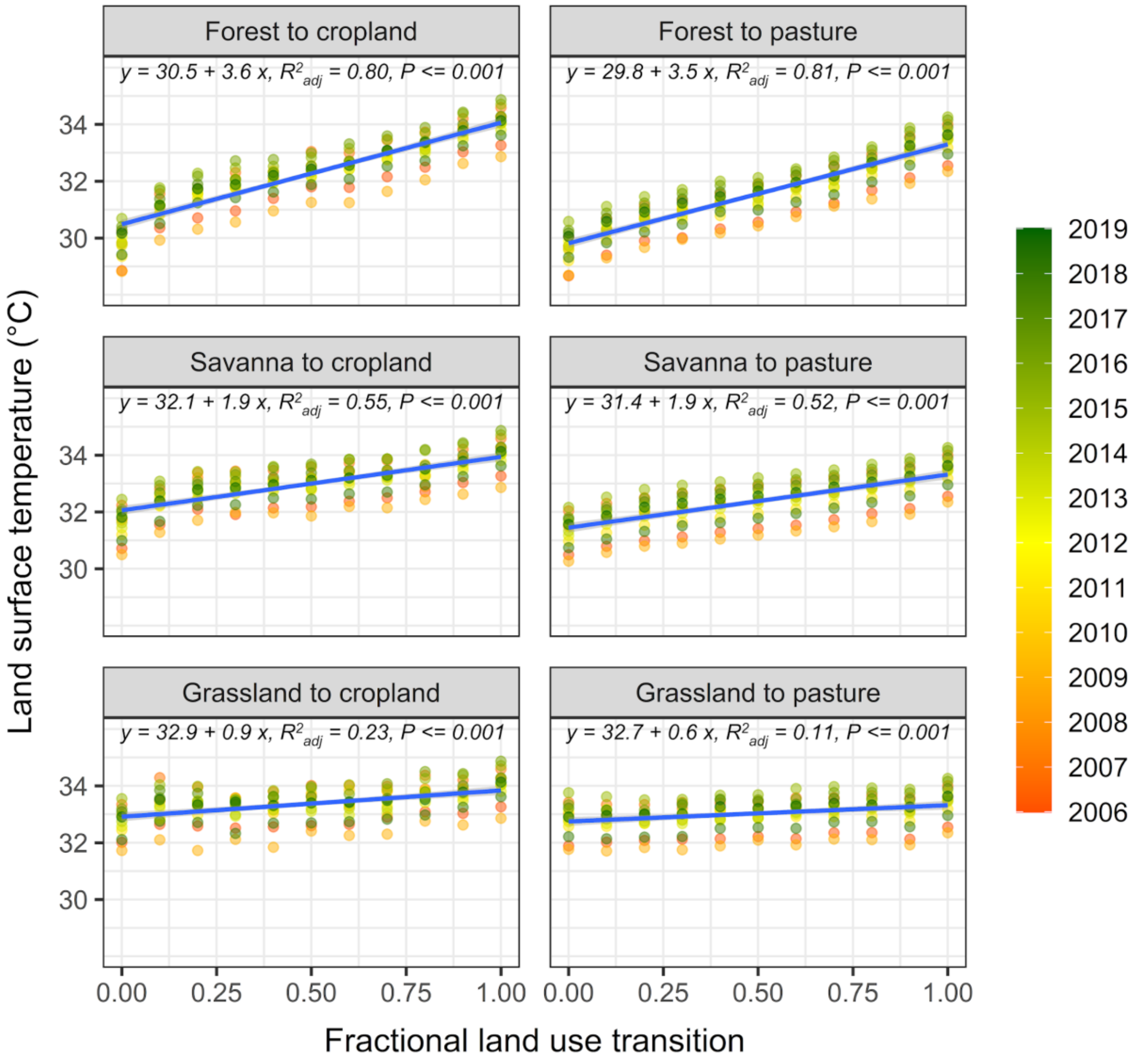


Figure 3.5. Change in average daytime land surface temperature (LST) as a function of fractional change in land use, estimated from 2006 to 2019 for the Cerrado biome.

3.3.2. *Cumulative effect of historic LUTs on Cerrado climate*

Our analysis of historic maps indicates that most (57%) of the Cerrado’s original vegetation was dominated by savanna formations (Figure 3.6). Of the 89.4 Mha of Cerrado cleared by 2019, 19% (17.4 Mha) were originally native grasslands, 61% (54.1 Mha) were savanna formations, and 20% (18 Mha) were forest formations. Although the absolute area of savanna loss was considerably higher than that of forest or grassland, deforestation affected a similar fraction of each class given their relative abundances in the original vegetation map. Based on the historic baseline (Figure 3.3), the majority of the Cerrado's native vegetation (55% of grasslands, 69% of savannas, and 82% of forests) was converted to pasture, while the balance in each category was converted to croplands. From 2006-2019, 5.8 Mha of native vegetation were cleared, pasture area declined by 2.9 Mha, and cropland area expanded by 7.5 Mha (Figure 3.6).

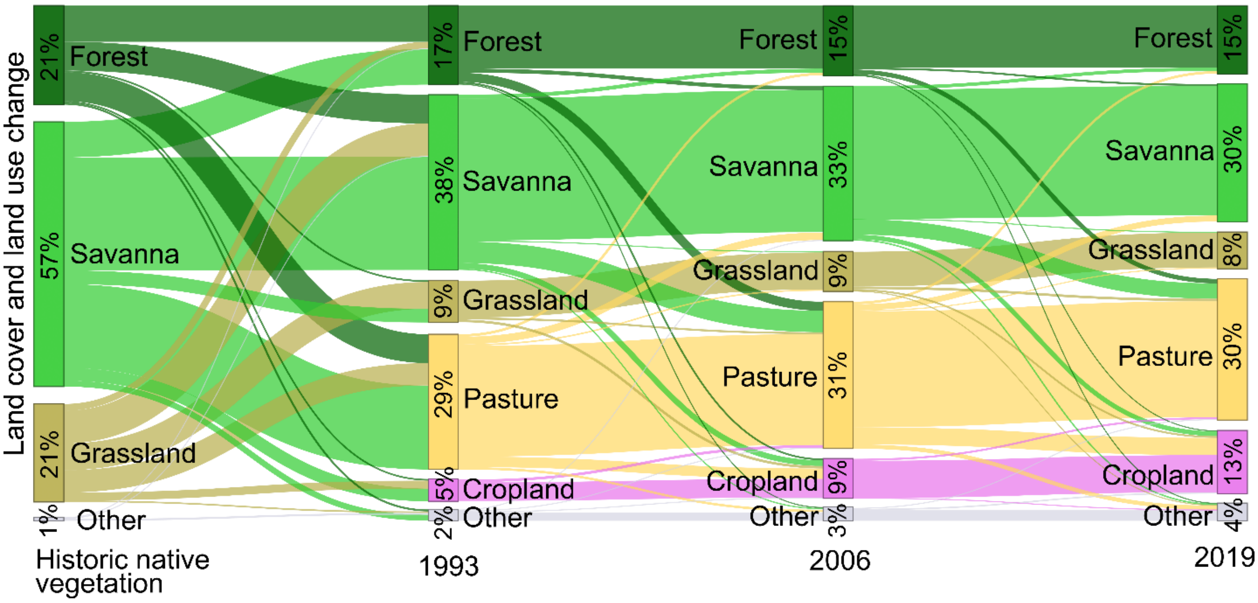


Figure 3.6. Brazilian Cerrado land cover and land use dynamics during three time-steps, showing transitions from: (1) original native vegetation to 1993; (2) 1993 to 2006; and (3) 2006 to 2019 (this study). The map of potential historic native vegetation came from MCTI (2021) and maps of land cover and land use in 1993, 2006, and 2019 came from MapBiomas (2020).

Cerrado vegetation recycles roughly two-thirds of annual precipitation (PPT) back to the atmosphere via evapotranspiration each year (ET = 980 mm and PPT = 1415 mm, considering annual averages from 2006-2019). Our results indicate that, if native vegetation had been preserved (i.e., considering the historic baseline, Figure 3.3), ET in 2019 would have been 10% higher (169 km^3) and average daytime LST would have been 0.9 ºC lower. Given the heterogeneity of LUTs and the natural climate gradient in this vast region (Figure 3.2), we identified hotspots of reduced ET and increased LST throughout the biome (Figure 3.7). Notable hotspots of warming occurred in western Bahia and northern Minas Gerais, where average annual temperatures are already high (33.9 ºC and 31.8 ºC, respectively). Intense drying was widespread in areas with relatively high ET, particularly in Tocantins, Mato Grosso (along the Cerrado-Amazon transition), and Maranhão (in the northern Cerrado).

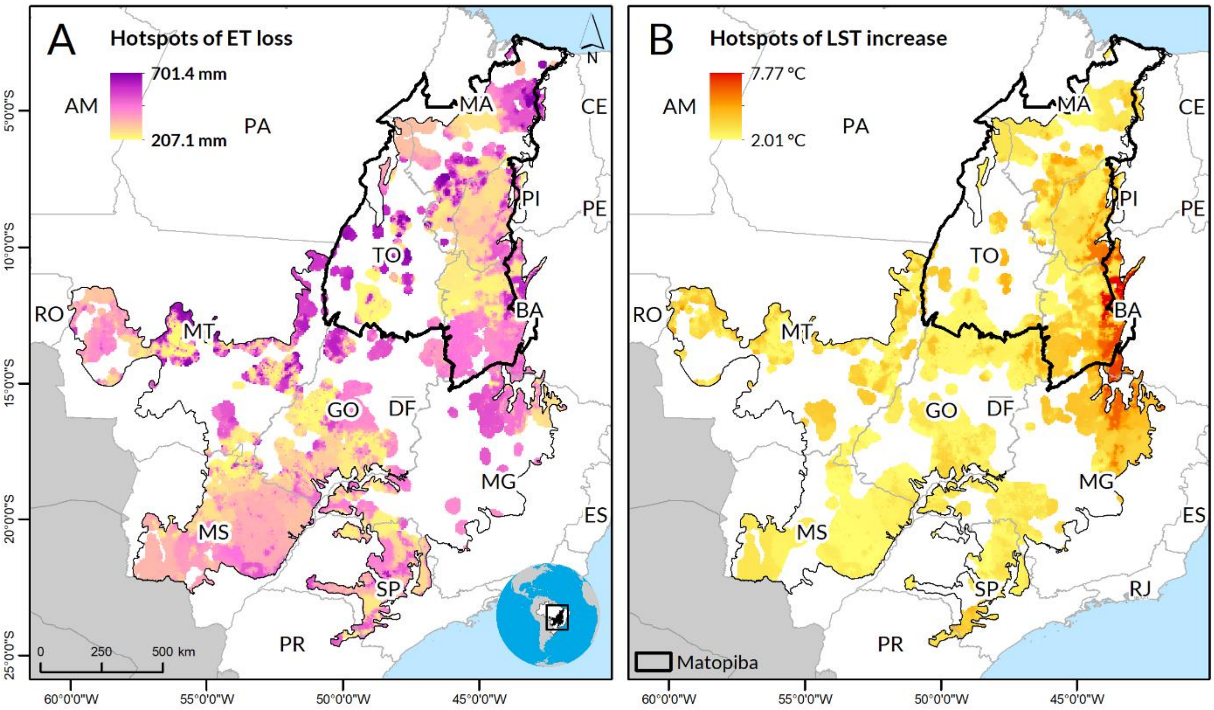


Figure 3.7. Hotspots of (a) drying (ET loss) and (b) warming (LST increase) associated with the spatial patterns of land use transitions since Cerrado conversion began. ET and LST changes were calculated for land use in 2019, compared to the baseline of historic native vegetation. Hotspots of ET loss and LST increase are derived from the spatial clustering of above-average values, varying from 207-700 mm and 2.0 -7.8 °C, respectively. Cerrado areas depicted as white include areas with no statistically significant differences, as well as coldspots and spatial outliers (Anselin, 1995). Labels indicate the Brazilian states of Bahia (BA), Distrito Federal

(DF), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso do Sul (MS), Mato Grosso (MT), Piauí (PI), São Paulo (SP), and Tocantins (TO).

3.3.3. Future scenarios of land-use and climate change in the Cerrado

Under the Cerrado Collapse scenario, our model indicated a projected decrease in annual ET of 84 mm (171 km^3) and a mean increase in LST of 0.7 ºC in 2050, compared to the baseline from Rochedo et al. (2018) (Table 1). In contrast, the Cerrado Struggling scenario would result in a projected decrease of 29 mm (59 km^3) in annual ET and a 0.3 ºC average increase in LST relative to 2019. Our findings indicate that the Matopiba region would be disproportionately affected, since it contains most (15 Mha) of the remaining vegetation that could be legally converted and coincides with existing hotspots of drying and warming (Figure 3.8).

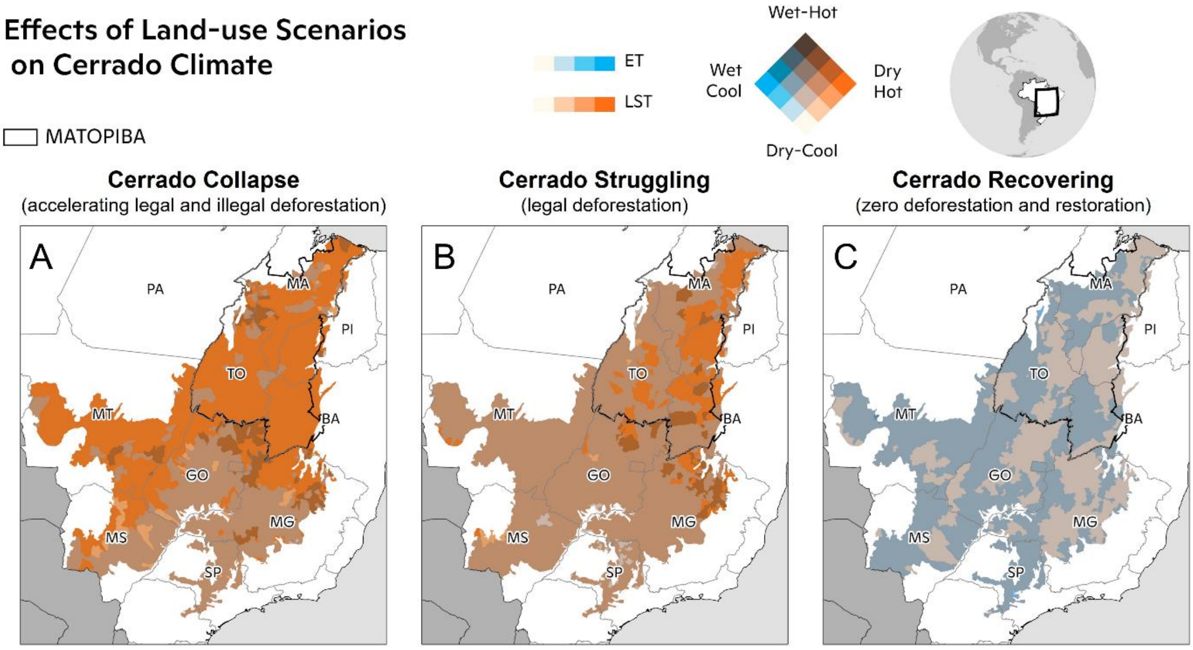


Figure 3.8. Change in evapotranspiration (ET) and land surface temperature (LST) under three contrasting scenarios of future land-use transitions in the Brazilian Cerrado. The Cerrado

Collapse scenario (a) assumes no deforestation control policies, resulting in 63.6 Mha of additional deforestation by 2050. The Cerrado Struggling scenario (b) assumes clearing the 28.4 Mha of native vegetation that exceed minimum conservation requirements. The Cerrado Recovering scenario (c) assumes no further deforestation, as well as restoration of 5.2 Mha of illegally cleared vegetation in riparian areas (APPs) and legal reserves (RLs). These scenarios were developed based on previously published data (Rajão et al., 2020; Rochedo et al., 2018).

The Cerrado Recovering scenario resulted in a mean annual ET increase of 4 mm (8 km^3) and average LST decrease of 0.04 ºC relative to 2019. These results account for the climate benefit of restoring 5.2 Mha of illegally cleared vegetation, but not for the avoided warming and drying resulting from protection of native vegetation (e.g., through zero deforestation policies) that would otherwise have been converted to crops and pasture. Moreover, our results indicate that the area of environmental debt requiring restoration may be considerably higher. Using high-resolution maps of riparian forest distribution (Brazilian Foundation for Sustainable Development, 2019), we found that the environmental debt in riparian APPs is over seven times higher than the area currently reflected in the CAR database (Rajão et al., 2020). Our results indicate that approximately 30% (3.6 Mha) of the 12 Mha of original riparian vegetation has been converted to anthropogenic land uses. The remaining 70% of riparian vegetation recycles 42 mm (85 km^3) of water to the atmosphere annually. Restoration of this 3.6 Mha area could increase ET by an additional 7 mm (14 km^3) per year.

3.4. Discussion

There is a significant body of literature on the relationship between deforestation and regional climate change in the Amazon biome (Davidson et al., 2012; Leite-Filho et al., 2021;

Maeda et al., 2021; Nobre et al., 1991; Silvério et al., 2015). By comparison, the impacts of large-scale clearing of the Cerrado on ET and LST are poorly understood. Earlier studies have quantified the climatic effects of Cerrado deforestation based on field observations (Anache et al., 2019; Nóbrega et al., 2017), remote sensing (Arantes et al., 2016; Loarie et al., 2011; Spera et al., 2016), and numerical modeling (Coe et al., 2011). While the results of these previous studies generally agree with our findings, none of them distinguish among the unique climatic signatures associated with specific LUTs in the Cerrado. Building on this past research, we separate the effects of specific LUTs, considering both the structural gradient of Cerrado vegetation (i.e., conversion of grasslands, savannas, and forests) and variations in their responses with local climate characteristics across the biome.

Although local climate and edaphic characteristics strongly influence the magnitude of land-use effects on climate, we observed remarkably consistent trends (i.e., increased LST and reduced ET) following conversion of forest and savanna formations to cropland and pasture. These patterns demonstrate that clearing vegetation types with woody biomass poses a critical risk to the region's climatic stability. Savannas (characterized by 50-70% woody cover) are the dominant vegetation type in the Cerrado, currently covering 60 Mha (30% of the biome in 2019; MapBiomas, 2020) and sustaining the bulk of the biome's ET fluxes (water recycling) and regional cooling (LST) functions. Savannas are also among the most threatened vegetation types, given the weak protection and high deforestation rates observed in the region today (0.9 Mha cleared in 2021; INPE, 2022). Recent data indicate that just 13% of savanna formations are within protected areas, compared with 38% of forest areas, 23% of grasslands, and 51% of wetlands in the biome (MapBiomas, 2021).

Our results show that conversion of grasslands caused notable increases in LST. This result indicates that the simplification of native grasslands (comprised of a diverse ensemble of native grasses and herbaceous plants, normally with sparse woody plants) to monocultures (croplands or planted pastures with exotic grasses) has a considerable impact on the regional energy balance. One potential explanation is that the higher plant diversity in native grasslands helps to modulate the LST response, given their varied phenological strategies to withstand a long, intense dry season (Lambers et al., 2020; Moraes et al., 2016). In contrast, croplands and pastures exhibit a more homogeneous seasonality, characterized by rapid, synchronized greening and senescence (Arantes et al., 2016), leading to rapid LST increases during the onset of the dry season in agricultural areas. Grassland-to-pasture transitions also caused an annual ET increase (15%) – consistent with the strong stomatal control and more conservative water use of native herbaceous vegetation, particularly compared to exotic grasses in cultivated pastures (Meirelles et al., 2011), such as the widespread species of the *Urochloa* genus (Ferraz & Felício, 2010). The combination of improved nutrition from fertilized pastures and *Urochloa* spp. capacity to extract water from deep soil layers (≥ 1.6 m) (Santos et al., 2004) could also contribute to a higher mean ET compared with native grasslands.

At regional scales, our results indicate that LUTs in the Cerrado have caused significant warming and drying. Comparing ET changes relative to the historic baseline (native vegetation existing prior to extensive land use changes), Arantes et al. (2016) found a regional effect of -1.5% ET reduction over the Cerrado in 2002 (using samples from the central Cerrado, primarily in Goiás state), while Spera et al. (2016) identified a -3% ET reduction over Matopiba in 2013. Here we expand on these approaches by dealing explicitly with vegetation heterogeneity and the strong climate gradient across this > 200-Mha region. Our approach reveals considerably more pronounced effects of land-use change (-10% annual ET reduction and +0.9 °C average LST increase in 2019) over the Cerrado, compared to the baseline of historic native vegetation. Our findings provide quantitative evidence of the importance of grasslands and savannas – the most common vegetation types in the tropics – for maintaining regional water and energy cycles (Figure 3.9).

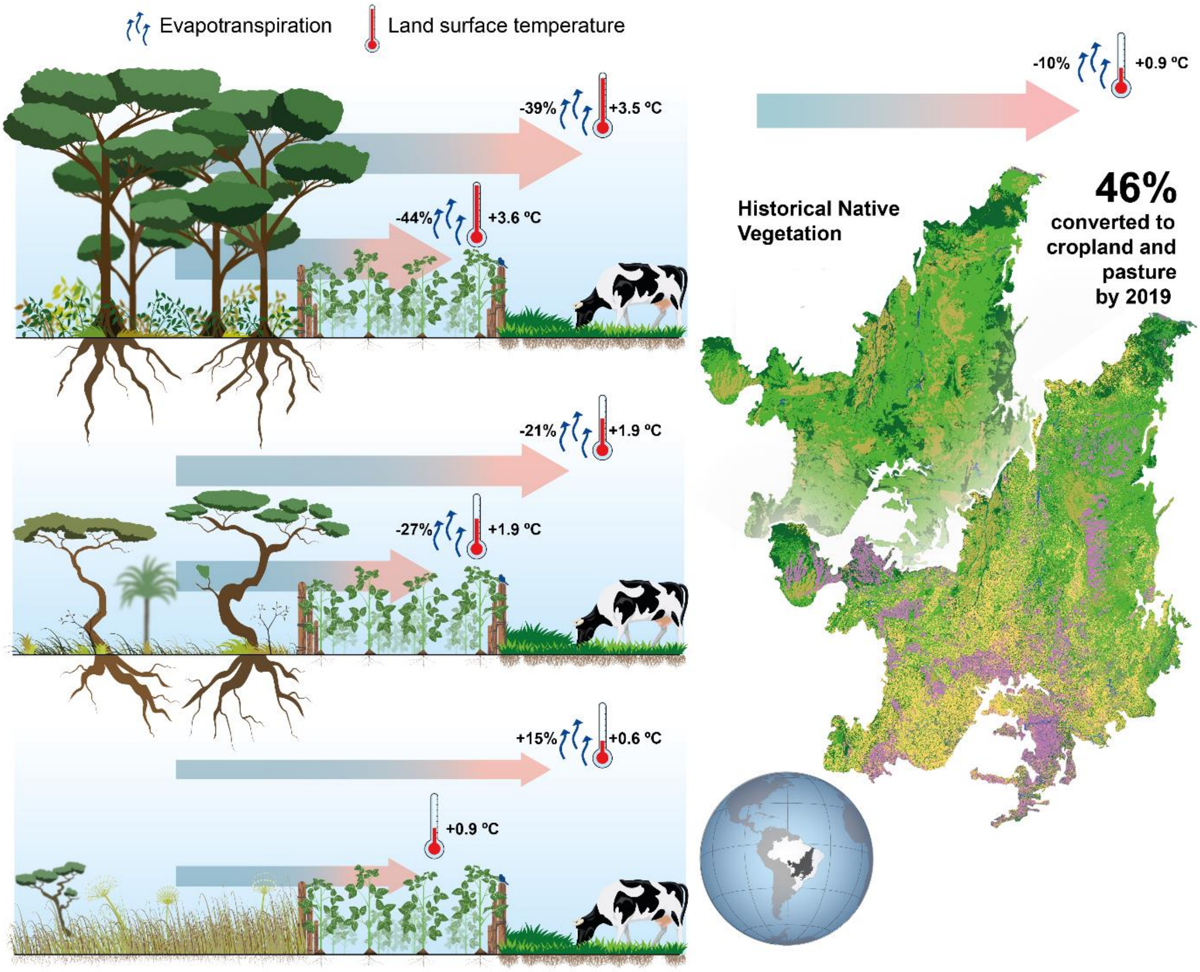


Figure 3.9. Synthesis of the observed impacts of land use transition on mean annual evapotranspiration (ET) and average land surface temperature (LST) in the Cerrado. At local scales (left panel), the conversion of forests and savannas to cropland or pasture reduced ET and increased LST. The conversion of grasslands to cropland or pasture also increased LST, albeit more moderately. In contrast, grassland-to-pasture conversion increased ET. At regional scale (right panel), we found that cumulative losses of native vegetation since large-scale human occupation began (i.e., historic baseline) have caused significant warming and drying.

Moreover, we show that these effects are not uniformly distributed in space, creating hotspots of change that could have drastic local consequences. For example, ET losses were concentrated in (primarily rainfed) soy-producing regions of Bahia, Mato Grosso, Maranhão and Tocantins. This is alarming, given that the changes reported here consider only the effect of land-use change, which will be greatly exacerbated by global climate changes due to increased atmospheric greenhouse gas concentrations. The last Intragovernmental Panel on Climate Change (IPCC) report projected hotter and dryer conditions for the reference regions covering most of the Cerrado (the Northeastern South America and South American Monsoon subregions; Arias et al., 2021). Together, these drivers of global change will likely amplify the effects of warming and drying (Hofmann et al., 2021; Marengo et al., 2022), intensifying the societal consequences of ongoing climate changes. Drier and warmer climate conditions have already reduced agricultural productivity over much of the Cerrado (Rattis et al., 2021), increasing conflicts over water use (Pousa et al., 2019; Santos et al., 2020b) and reducing hydropower production capacity (Cuartas et al., 2022). Climate changes have also increased fire frequency, contributing to reductions in the rate of vegetation recovery (Machida et al., 2021) and intensifying climate risks for vulnerable populations such as small landholders, Indigenous people, and traditional communities (Begotti & Peres, 2020; Intergovernmental Panel on Climate Change, 2018).

The environmental policies adopted today will determine the future climatic and hydrological stability of the Cerrado. Our results point to a range of potential outcomes. Recent weakening of environmental policies and enforcement has already increased deforestation across all biomes, and signs point to further backsliding on past commitments to (and successes in) reducing deforestation (Bustamante, 2020; Ferrante & Fearnside, 2019). Our Cerrado Collapse scenario suggests that continuing down this path of poor governance will cause a rapid increase in LST and reduction of ET in the region. Even our intermediate scenario, with zero illegal deforestation (Cerrado Struggling scenario), would cause severe warming and drying (-59 km^3 yearly ET reduction and +0.3 °C average LST increase).

Given that the region is already facing rainfall scarcity, drought-driven crop losses, and increased fire frequency, maintaining native vegetation could prove to be a win-win, supporting continued agricultural production while also conserving biodiversity. Cerrado vegetation can help protect soybean plantations against extreme heat and will play an increasingly important role in mitigating economic losses in the future (Flach et al., 2021). In this context, our Cerrado Recovering scenario suggests one practical pathway to avoid the intensification and begin reversing the large-scale climate transformations reported here. By adopting a zero-deforestation policy, as much as 63.6 Mha of vegetation clearing (from the worst-case scenario) could be avoided – preventing a further ET reduction of up to -171 km^3 annually, while avoiding a +0.7 ºC increase in average LST. Restoring the environmental debt would not only increase water recycling to the atmosphere and cool the land surface, but also greatly improve habitat connectivity for wildlife in this increasingly fragmented landscape (Carvalho et al., 2009; Rother et al., 2018).

Our results indicate that the Cerrado Recovering scenario would still be insufficient to counteract the large climatic transformation that has already happened, suggesting that this strategy needs to be augmented over the long term. Previous studies point to promising methods that could help address the challenge of restoring the Cerrado's mosaic of grasslands, savannas, and forests at relatively low cost (Raupp et al., 2020; Schmidt et al., 2019). Nevertheless, it can take decades for restored vegetation to establish and recover key attributes of mature vegetation, and the success of these efforts will depend on vegetation responses to global climate changes. Restoration can also be costly, considering that some systems have low potential for natural regeneration and may require additional investments (Cava et al., 2018). Given these challenges, we argue that avoiding additional Cerrado clearing remains the most cost-effective strategy and should be the top priority.

The conservation of Cerrado ecosystems is vital for the climate stability of a much larger region. The seasonal flooding of the Pantanal, one of the largest wetlands in the world, depends largely on river discharge from the Cerrado (Lima & Silva, 2007). Disruption of the Cerrado's hydroclimate can also affect the water supply of at least eight important Brazilian watersheds (Lima & Silva, 2005), increase the risk of forest fires along the Amazon-Cerrado agricultural frontier (Alencar et al., 2015), and compromise Brazil's ability to keep its emissions commitments (Rochedo et al., 2018; Silva Junior et al., 2020). This suite of interacting factors underscores the urgency of centering Cerrado conservation as a key strategy for mitigation and adaptation to climate changes.

Despite its critical role, the 105.6 Mha of remaining native vegetation in the Cerrado (MapBiomas, 2020) have been widely ignored in climate policy. A draft anti-deforestation proposal of the European Union, for example, concentrates exclusively on forest protection, ignoring protections for grasslands and savannas (Rankin, 2021), which cover most of the Cerrado biome. Our results provide clear evidence that the Cerrado sustains elevated ET, and that ongoing land-use changes are contributing to significantly warmer and drier conditions. We argue that international agreements and private sector initiatives aiming to eliminate deforestation from global supply chains must include protection of the Cerrado in their strategies. Failing to do so will engender environmental degradation that could prove catastrophic to climate stability and biodiversity, compromising the food, energy, and water security of the Cerrado, with cascading effects at regional and global scales.

3.5. *Supporting information*

S1. The relationship between land use transitions (LUT) and associated changes in annual evapotranspiration (ET) and average land surface temperature (LST) was calculated using linear regression models defined as:

$$ET_i = \beta_0 + \beta_1 LUT_i + \varepsilon_i$$

$$LST_i = \beta_0 + \beta_1 LUT_i + \varepsilon_i$$

where:

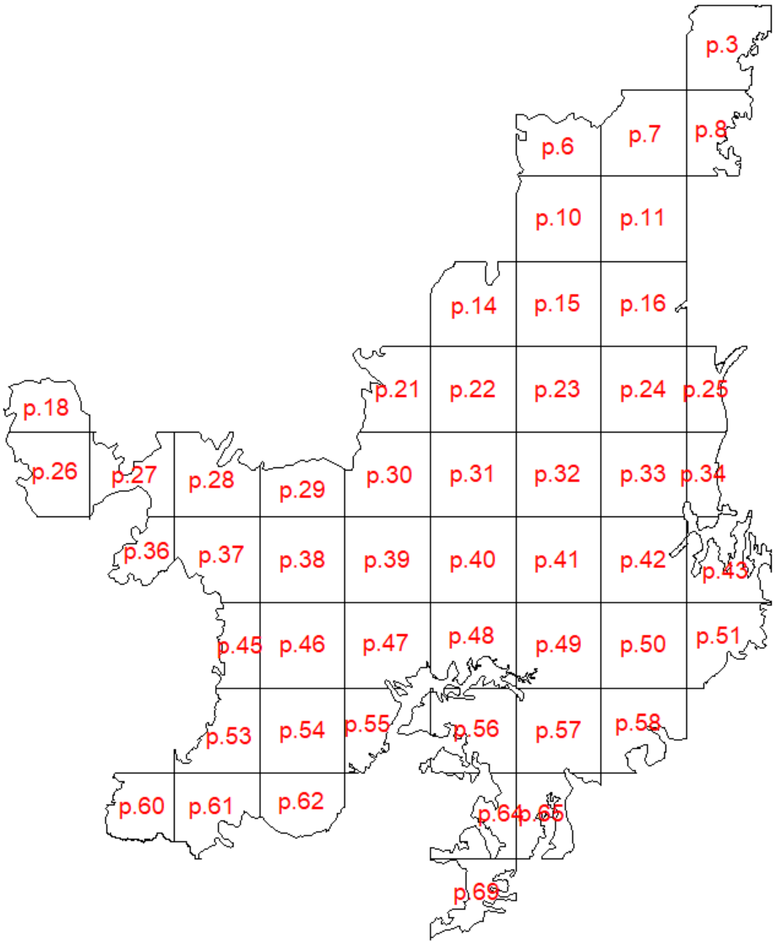
ET_i = Annual Evapotranspiration;

LST_i = Average Land Surface Temperature;

LUT_i = Fractional land-use change for each of the six transitions:

a) Forest to Cropland,
b) Forest to Pasture,
c) Savanna to Cropland,
d) Savanna to Pasture,
e) Grassland to Cropland,
f) Grassland to Pasture; and

ε_i = Error.



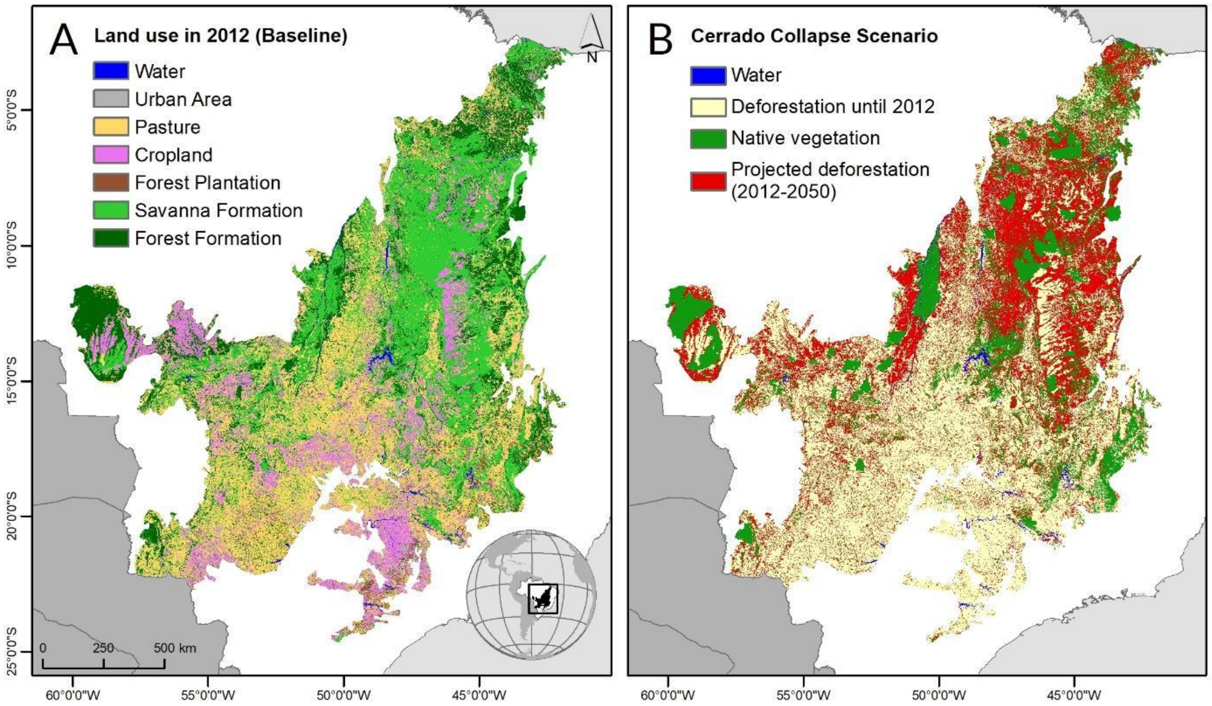
S2. Division of the Cerrado in equal 2 × 2 ° grids used to derive local regression models, excluding grids with small areas.

S3. Correspondence between cerrado native vegetation classes from the historic native vegetation map (i.e., vegetation that potentially existed in Brazil prior to large-scale land-use changes; Ministry of Science Technology and Innovations, 2021) with the classes used in the 2019 land use and land cover map from the Collection 5 of the MapBiomas project (MapBiomas, 2020).

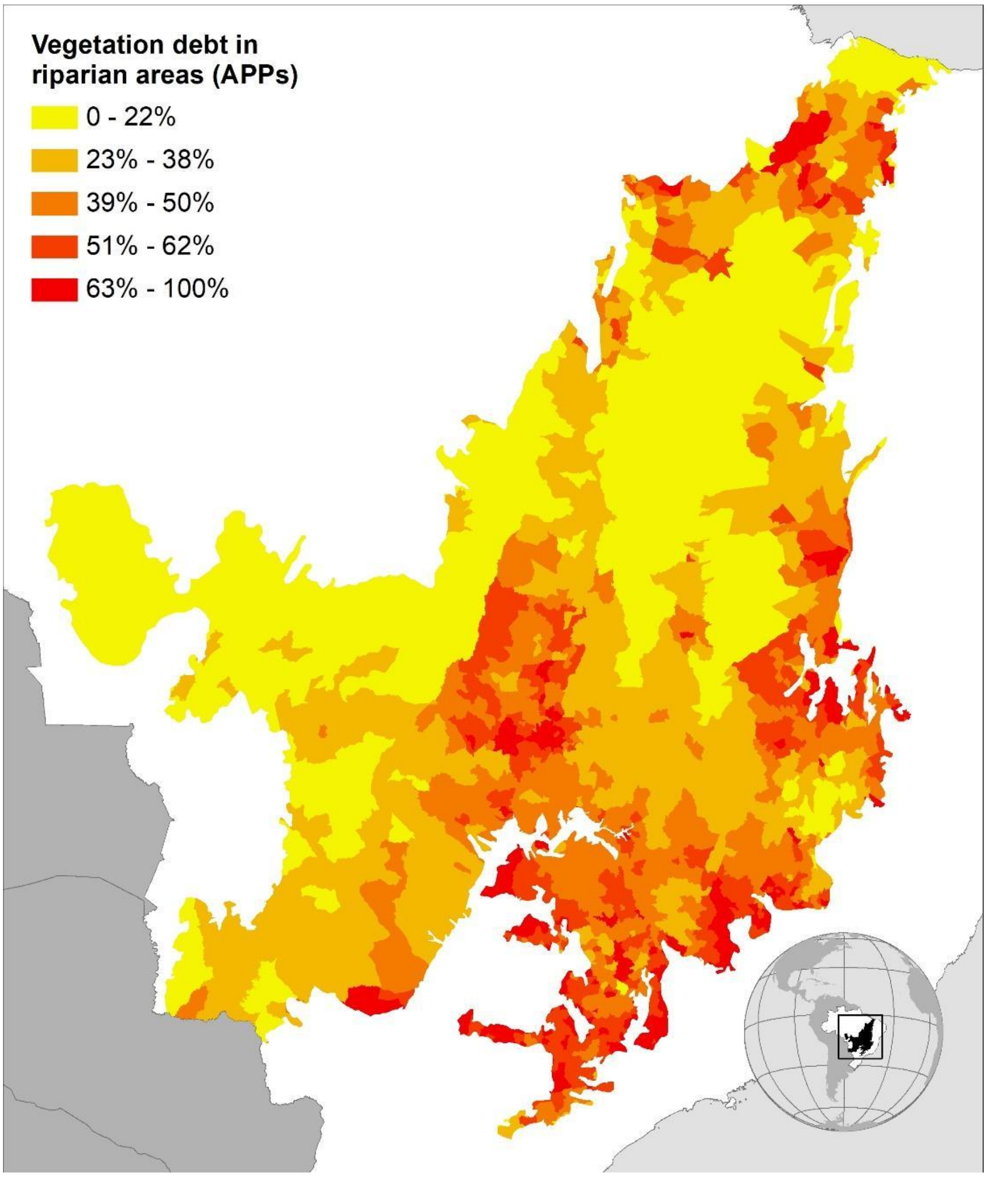
Class from the historic native vegetation map	Acronym	Corresponding MapBiomas v.5 class

Continental Water Body	A	River, Lake and Ocean
Open Ombrophilous Alluvial Forest	Aa	Forest Formation
Open Ombrophilous Lowland Forest	Ab	Forest Formation
Rocky Outcrop	Ar	Rocky Outcrop
Open Ombrophilous Submontane Forest	As	Forest Formation
Deciduous Seasonal Alluvial Forest	Ca	Forest Formation
Deciduous Seasonal Lowland Forest	Cb	Forest Formation
Deciduous Seasonal Montane Forest	Cm	Forest Formation
Deciduous Seasonal Submontane Forest	Cs	Forest Formation
Dense Ombrophilous Alluvial Forest	Da	Forest Formation
Dense Ombrophilous Lowland Forest	Db	Forest Formation
Dunes	Dn	Beach and Dune
Dense Ombrophilous Submontane Forest	Ds	Forest Formation
Woody-Grass Steppe	Eg	Grassland Formation
Semi-deciduous Seasonal Alluvial Forest	Fa	Forest Formation
Semi-deciduous Seasonal Lowland Forest	Fb	Forest Formation
Semi-deciduous Seasonal Montane Forest	Fm	Forest Formation
Semi-deciduous Seasonal Submontane Forest	Fs	Forest Formation
Mixed Ombrophilous Alluvial Forest	Ma	Forest Formation
Mixed Ombrophilous High Montane Forest	Ml	Forest Formation
Mixed Ombrophilous Montane Forest	Mm	Forest Formation
Contact Ombrophilous Forest/Seasonal Forest (Montane)	ONm	Forest Formation
Contact Ombrophilous Forest/Seasonal Forest (Submontane)	ONs	Forest Formation
Contact Ombrophilous Forest/Seasonal Forest (Ecotone, Submontane)	ONts	Forest Formation
Areas of Pioneer Formations (First Occupation Edaphic System)	P	Grassland Formation
Pioneer Formation with fluvial and/or lacustrine influence	Pa	Grassland Formation
Pioneer Formation with fluviomarine influence	Pf	Mangrove
Pioneer Formation with marine influence (Restinga)	Pm	Grassland Formation
Montane Vegetation Refuge	Rm	Grassland Formation
Savanna (Cerrado)	S	Savanna Formation
Shrub Savanna	Sa	Savanna Formation
Woody Savanna	Sd	Forest Formation
Woody-Grass Savanna	Sg	Grassland Formation
Contact Savanna/Mixed Ombrophilous Forest (High Montane)	SMl	Forest Formation
Contact Savanna/Mixed Ombrophilous Forest (Montane)	SMm	Forest Formation
Contact Savanna/Seasonal Forest (Lowland)	SNb	Savanna Formation
Contact Savanna/Seasonal Forest (Montane)	SNm	Savanna Formation
Contact Savanna/Seasonal Forest (Submontane)	SNs	Savanna Formation
Contact Savanna/Seasonal Forest (Ecotone, Montane)	SNtm	Savanna Formation
Contact Savanna/Seasonal Forest (Ecotone, Submontane)	SNts	Savanna Formation
Contact Savanna/Ombrophilous Forest (Submontane)	SOs	Forest Formation
Contact Savanna/Ombrophilous Forest (Ecotone, Submontane)	SOts	Forest Formation

Park Savanna	Sp	Grassland Formation
Contact Savanna/Savanna-Steppe (Lowland)	STb	Savanna Formation
Contact Savanna/Savanna-Steppe/Seasonal Forest (Montane)	STNm	Savanna Formation
Contact Savanna/Savanna-Steppe/Seasonal Forest (Submontane)	STNs	Savanna Formation
Contact Savanna/Savanna-Steppe/Seasonal Forest (Ecotone, Montane)	STNtm	Savanna Formation
Contact Savanna/Savanna-Steppe/Seasonal Forest (Ecotone, Submontane)	STNts	Savanna Formation
Contact Savanna/Savanna-Steppe (Submontane)	STs	Savanna Formation
Contact Savanna/Savanna-Steppe (Ecotone, Montane)	STtm	Savanna Formation
Contact Savanna/Savanna-Steppe (Ecotone, Submontane)	STts	Savanna Formation
Savanna-Steppe	T	Savanna Formation
Shrub Savanna-Steppe	Ta	Savanna Formation
Woody Savanna-Steppe	Td	Forest Formation
Woody-Grass Savanna-Steppe	Tg	Grassland Formation
Contact Savanna-Steppe/Seasonal Forest (Montane)	TNm	Savanna Formation
Contact Savanna-Steppe/Seasonal Forest (Submontane)	TNs	Savanna Formation
Contact Savanna-Steppe/Seasonal Forest (Ecotone, Montane)	TNtm	Savanna Formation
Contact Savanna-Steppe/Seasonal Forest (Ecotone, Submontane)	TNts	Savanna Formation
Park Savanna-Steppe	Tp	Grassland Formation



S4. Projected deforestation from (a) 2012 (baseline) until (b) 2050 under a scenario of accelerating legal and illegal deforestation (Cerrado Collapse scenario), resulting in additional 63.6 Mha of native vegetation being converted to cropland and pasture by 2050. The dataset was originally developed by Rochedo et al. (2018), assuming the abandonment of current deforestation control policies so that projected future annual rates of vegetation clearing resemble the inverse trend between 2004 and 2014 (capped at the 2004 peak of 1.8 Mha yr^{-1}).



S5. Percentage of Cerrado’s native vegetation inside riparian Areas of Permanent Preservation (APP) that was converted to other land uses (built areas, anthropic areas, and forestry) by 2013, aggregated by municipality (Brazilian Foundation for Sustainable Development, 2019).

4. CHAPTER – How can we increase crop production without deforestation? Dynamics of pasture and cropland expansion in the Cerrado and lessons learned

4.1. Introduction

Agriculture currently occupies 37% (4,800 Mha) of the world's available land (excluding Antarctica and inland waters), with one-third of it being used for cropland and the remaining area for pastures (FAO, 2023). To meet the food demand of the growing population and rising per capita income, it will be necessary to increase crop production by 18% and livestock and fish production by 16% until 2031 (OECD & FAO, 2022). In Latin America, crop and beef production is projected to grow by 13% and 11%, respectively, mainly from yield improvement. However, an additional 6.2 Mha of land would have to be incorporated into crop production and 1.8 Mha into pasture (OECD & FAO, 2022).

Meeting the increasing global food demand while also striving to create a world free of hunger (United Nations Sustainable Development Goal 2) and reducing greenhouse gases emissions to keep global warming under 2 °C (Paris Agreement) is an even more challenging task. Crop yield needs to increase by 24% with a 5% (80 Mha) decline in crop area, and animal productivity needs to increase by 31% in 2030. However, the projected increase in crop yield and animal productivity over the next decade is only 10% and 5%, respectively. (OECD & FAO, 2022). Productivity improvements would have to come from technologies and management practices more efficient in the use of resources and less carbon intensive, including precision agriculture and new crop varieties (OECD & FAO, 2022). While there is optimism that technology and energy improvements will keep productivity levels high and help us adapt to a changing climate, there are limits to climate-resistant technologies (Moscona & Sastry, 2023), and locally appropriate solutions must also be considered.

Another aspect often overlooked in global analysis is the unequal distribution of impacts from increased food demand. While the rates of deforestation for food production have decreased globally, they are still high in the tropics, affecting the world’s most biodiverse areas, including the Brazilian Cerrado (Kong et al., 2021; Winkler et al., 2021). The region has been under high deforestation pressure to meet the growing demand for commodities in the international market.

Brazil is one of the top producers of soy, corn, coffee, and beef and a significant proportion of this production comes from the Cerrado. In fact, half of the internationally traded volume of soy and beef from Brazil comes from the Cerrado (Trase, 2017, 2020). The boom in Brazil's agriculture has resulted in the conversion of 2.5 times more area of native vegetation in the Cerrado than in the Amazon, even though the Cerrado is only half the size of the Amazon (Zalles et al., 2019). Agriculture is the main driver of deforestation, leading to the loss of 50% of the Cerrado original native vegetation cover (MapBiomas, 2023).

The loss of vegetation and the expansion of cropland and pasture have cascading effects on the ecosystem that affect the WEF Nexus in the Cerrado. As explained in Chapter 3, when natural vegetation formations such as forests, savannas, and grasslands are replaced by cropland and pasture, it significantly impacts the energy balance and water cycle at both local and regional scales. These changes can further interact with the changing climate, resulting in reduced water availability during the dry period, increased wildfire risks, delayed onset of the rainy season, and ultimately affecting agriculture yields and profitability.

Despite the high traded volume of commodities, there's a large portion of farmland in the Cerrado region that remains underutilized. It has been well-established that agriculture expansion over cleared areas could meet projected food demand, without further deforestation (Rausch et al., 2019; Rudorff et al., 2015, 2018; Strassburg et al., 2014, 2017). To achieve this, cropland would have to expand over the vast extension of pastures in the Cerrado. Pasture is the largest land use in the biome, taking up approximately one-quarter of the area (51 Mha) (MapBiomas, 2023), which makes it the main direct driver of deforestation. Most properties develop extensive cattle ranching with low levels of mechanization, fertilizers, and water inputs (Ferraz & Felício, 2010; Oliveira et al., 2004), resulting in low average livestock density (Arantes et al., 2018; Brito et al., 2018; Veloso et al., 2020). This low-input system decreases production costs and has helped Brazil to become the top beef exporter in the world, trading over \$5.4 billion yr^{-1} (zu Ermgassen et al., 2020).

The stocking rates in the Cerrado have gradually increased, reaching 1.1 animal unit ha^{-1} in 2021 (Lapig-UFG, 2021), well below the carrying capacity of 2.4 - 2.5 animal unit ha^{-1}, achievable on average in Brazil (Strassburg et al., 2014). Over a quarter (14 Mha) of pastures show low vigor, which can be a sign of severe degradation (MapBiomas, 2023; Santos et al., 2022). Pasture intensification and restoration offer an opportunity for cropland expansion and ecological restoration in ecosystems with high value for biodiversity conservation and ecosystem services provision (Schüler & Bustamante, 2022). In fact, considering the extensive area and low productivity, cattle ranching has been indicated as Brazil's top opportunity for interventions aimed at balancing production and environmental goals (Bustamante et al., 2012).

Expansion of agriculture over pasture has already happened in areas where land is scarce, mostly in the southern portion of the Cerrado, which led to a decoupling trend between production and deforestation in the late 2000's (Macedo et al., 2012). Currently, croplands occupy 26 million hectares (13%) of the almost 200 million hectares of the biome (MapBiomas, 2023). Soybeans account for 74% of the farmland area, followed by sugar cane at 12%, and other crops such as coffee, cotton, citrus, and rice, which make up the remaining 14% (MapBiomas, 2023).

In the early 2000's, the area under commodity row crops almost doubled in Brazil (from 26 Mha in 2000 to 46 Mha in 2014), mostly replacing pasture areas (79% of the expansion)

(Zalles et al., 2019). However, productivity and land use improvements have not delivered the expected land-sparing effect, since deforestation rates remain high and have recently increased. Between 2018-2022, deforestation levels in the Cerrado increased significantly from 730,000 ha to 1.1 Mha (INPE, 2023). During the first 10 months of 2023, deforestation in the Cerrado continued to increase, surpassing last year's rate by 53% – comparing the same 10-month period (INPE, 2023). Almost all (93%) of the increase in Cerrado deforestation occurred in the states of Maranhão, Tocantins, Piauí, and Bahia (INPE, 2023), the new Brazilian agricultural frontier referred to as Matopiba.

Assessing the processes involved in agriculture-driven deforestation requires careful consideration of complex feedbacks and interactions from land systems (Meyfroidt et al., 2022; Pendrill et al., 2022). Although the cropland area experienced a boom between 2000 and 2014, expanding over already cleared pastures (Zalles et al., 2019), the area of pasture in Brazil has remained relatively stable since 2002 (Parente et al., 2019). These numbers may suggest that cropland is displacing pasture into native vegetation, potentially causing indirect deforestation, but further investigation is needed to confirm these relationships. Agricultural intensification could spare land for nature, but there is also the possibility of increased deforestation from rebound effect, when increased profitability leads to further expansion of farming areas (Lambin & Meyfroidt, 2011).

Deforestation is caused by several direct and indirect drivers, such as unclear or contested land tenure, land speculation, poor land management, market-driven crop booms and busts, and low land suitability (Pendrill et al., 2022). Therefore, to understand the potential for promoting better use of already cleared areas, it is important to examine various land use dynamics at different scales (Meyfroidt et al., 2022). In this study, we investigated the potential for cropland expansion without new deforestation in the Cerrado, by assessing the spatial and temporal dynamics of land use transition over the past 35 years. Specifically, we focused on four key types of land transitions: (a) pasture expansion over native vegetation (native vegetation to pasture), (b) direct conversion of native vegetation to cropland (native vegetation to cropland), (c) cropland expansion over pasture (pasture to cropland), and (d) pasture abandonment (pasture to native vegetation).

4.2. Material and Methods

Land use and land cover change data were obtained from MapBiomas project version 7.0 (2022) annual maps, with 84.3% overall accuracy. MapBiomas project has produced 30-m pixel resolution annual land use and land cover maps for Brazil from 1985 until nowadays. Their methods rely on Landsat imagery and machine learning algorithms to perform pixel-by-pixel classification, implemented on the Google Earth Engine platform (Souza et al., 2020b). We calculated yearly transitions and respective areas from biome and state limits obtained from the Brazilian Institute of Geography and Statistics (IBGE, 2004, 2021) using the MapBiomas toolkit. We then summed the areas, year by year from 1985-2021, for the four targeted transitions: (a) pasture expansion over native vegetation, (b) direct conversion of native vegetation to cropland, (c) cropland expansion over pasture, and (d) pasture abandonment. Native vegetation class was created by joining the level 1 MapBiomas classes of forest formations and natural non-forest formations, while cropland and pasture came from level 2 MapBiomas classes. These three classes, native vegetation, cropland, and pasture, correspond to 90% of the area in the Cerrado (MapBiomas, 2023).

We used Google Earth Engine platform to calculate the age of current cropland areas, by adding up the years of consecutive cropland classification for each pixel, looking backwards from 2021 (the base year) and stopping the count when another class appeared in the series. We also assessed the persistence of pasture areas before conversion to cropland, as the number of consecutive years of pasture classification for each pixel, using the Google Earth Engine platform. Finally, we calculated the Spearman correlation between the time series of land transition data using R version 4.2.2 (R Core Team, 2022) and RStudio (Posit Team, 2023).

Crop suitability was quantified using the data produced by Rudorff et al. (2015), considering risk for growing soybeans – according to the crop calendar. Risk was calculated from the combination of soil characteristics and the long-term pattern of weather for the region, classified into a 4-level rank of crop suitability: high (climate risk < 20%), moderate (climate risk > 20% and < 30%), low (climate risk > 30% and < 40%) and unsuitable. The map also includes slope and altitude restrictions. Slope restriction applies to areas with slope > 12%, hindering agriculture mechanization. Considering that soy in Brazil grows better in highlands, altitude parameters affect producer's interest in the land. Altitude restrictions were based on the minimal altitude soy, maize and cotton were grown in different regions throughout the Cerrado, during the 2013-2014 harvest. Combining these indicators, Rudorff et al. (2015) created a rank with 13 levels of crop suitability (Figure 4.1). Two of these classes concentrated 92.5% of the area of soy, maize, and cotton (first crop) fields for the 2013-2014 harvest: high and moderate climate and soil crop suitability, without slope or altitude restrictions. As these areas are more appealing for commercial crop activity, our analyses of suitable areas for cropland expansion over pastures and native vegetation considered only these two classes. We updated Rudorff et al. (2015) map with MapBiomas v7 land use and land cover map for 2020 (MapBiomas, 2022; Souza et al., 2020b), masking out pixels that were not classified as native vegetation or pasture in the 2020 map. We also updated the distribution of crop suitability categories according to the land use and land cover classes as in 2020.

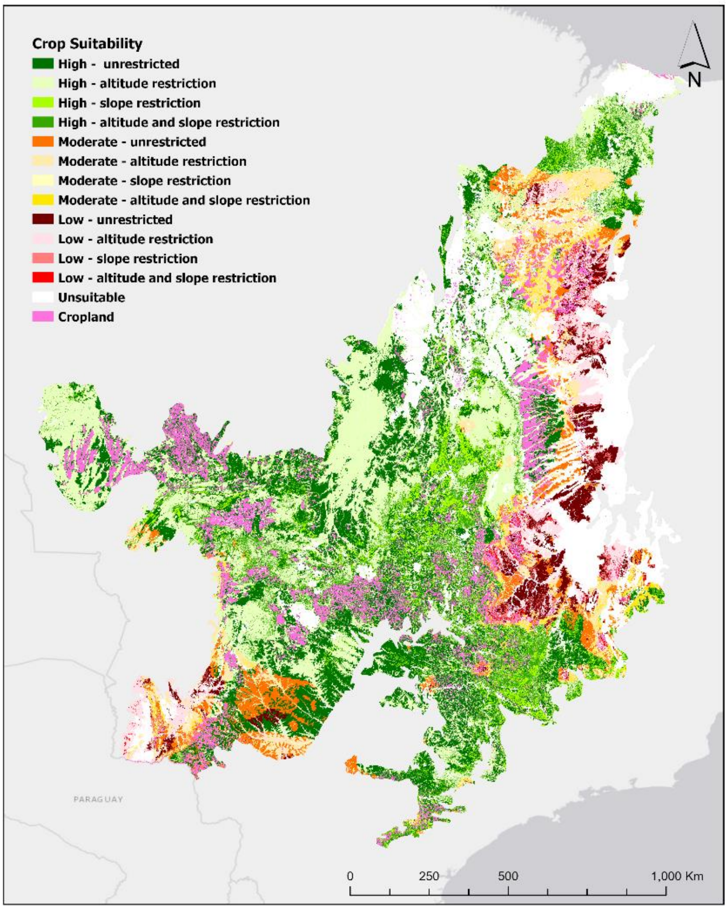


Figure 4.1. Crop suitability throughout the Cerrado, divided into 13 levels, calculated from the risk of growing soy in different climate and soil conditions, with slope and altitude restrictions (Rudorff et al., 2015). The map also depicts cropland areas already established in 2014. Areas with high and moderate crop suitability without altitude and slope restrictions concentrated 92.5% of the planted area of soy, maize, and cotton (first crop) in 2013-2014.

4.3. Results

Considering the whole studied period, from 1985-2021, 18.8 Mha of native vegetation was converted to pasture, and 3.4 Mha was directly converted to cropland. The conversion of pasture to cropland totaled 5.9 Mha, while a larger area of pasture (8.9 Mha) showed signs of abandonment and native species regrowth (Figure 4.2). Pasture-to-cropland transition and native vegetation-to-cropland transition were positively correlated (ρ = 0.48, Figure 4.3). There was a negative correlation between native vegetation-to-pasture transition and the opposite trajectory, pasture-to-native vegetation transition (ρ = -0.38).

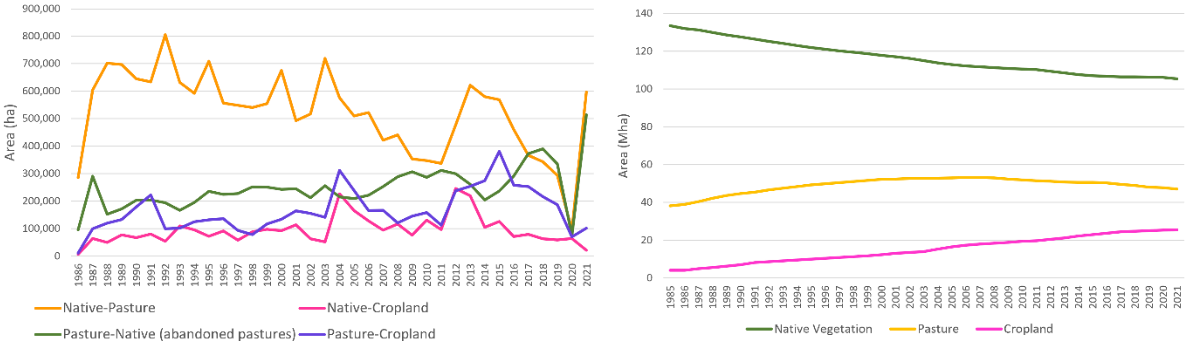
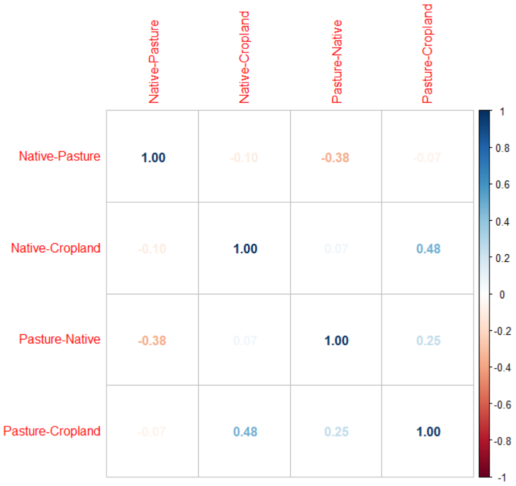


Figure 4.2. Land use transition dynamics: (a) transition from native vegetation to cropland, native vegetation to pasture, pasture to cropland, and pasture to native vegetation, from 1985 - 2021 and (b) yearly land cover and land use area in Cerrado for the same period (calculated from MapBiomas, 2022).



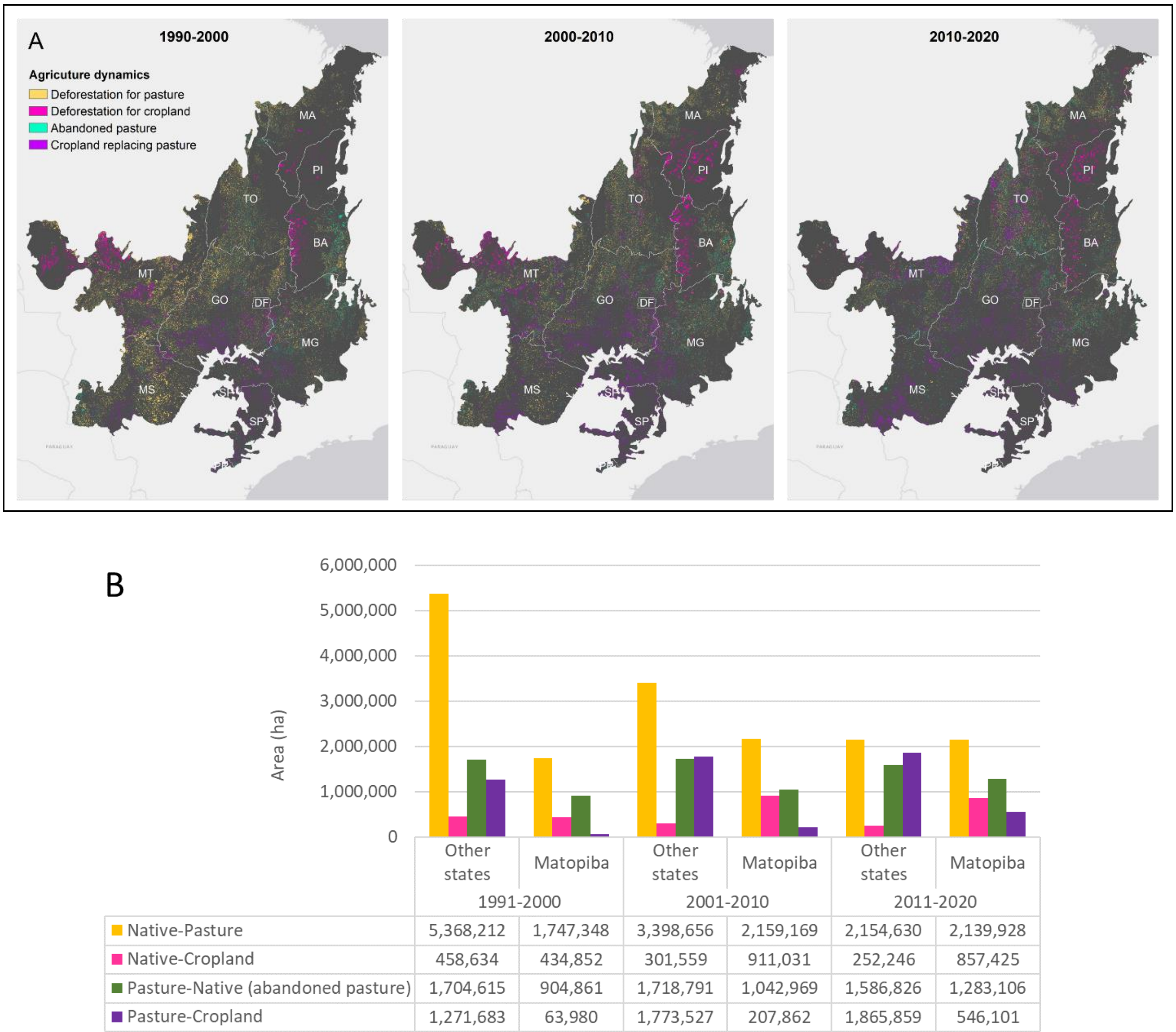
	Native-Pasture	Native-Cropland	Pasture-Native	Pasture-Cropland
Native-Pasture	1.00	-0.10	-0.38	-0.07
Native-Cropland	-0.10	1.00	0.07	0.48
Pasture-Native	-0.38	0.07	1.00	0.25
Pasture-Cropland	-0.07	0.48	0.25	1.00

Figure 4.3. Spearman Correlation coefficient between the four observed land use and land cover transitions (native vegetation to cropland, native vegetation to pasture, pasture to cropland, and pasture to native vegetation).

Over the last three decades (1990-2000, 2000-2010, 2010-2020), pasture expansion over native vegetation has gradually reduced (Figure 4.4), but it is still the prevailing land use transition, driving the loss of 414,000 ha yr^{-1} of cerrado vegetation between 2010-2020. The rate of pasture abandonment has increased over time, representing over two-thirds (278,000 ha yr^{-1}) of new pasture conversions in the last decade (2010-2020).

Direct conversion from native vegetation to cropland has increased in the last three decades, amounting to 113,000 ha yr^{-1} in 2011-2020, mainly in the Matopiba region. Between 2010-2020, the rate of native vegetation transition to agricultural uses (pasture and cropland) in Matopiba exceeded that of other states. During this period, direct conversion of native vegetation to cropland caused 40% of all the native vegetation loss in Matopiba, against 10% in other states. The Matopiba region experienced a considerable increase of 39% in cropland expansion into native vegetation between 2000-2010 and kept similar rates over the last decade (2010-2020).

The rate of cropland expansion over pasture almost doubled from 124,000 ha yr^{-1} in 1990-2000 to 224,000 ha yr^{-1} in 2010-2020, advancing from southern Cerrado, where it was concentrated in the 1990s, to the northern Cerrado, reaching areas in Tocantins by 2020. Even though the rate at which cropland replaced pasture increased over time, it is still smaller than the rate at which pasture areas are expanding over native vegetation (414,000 ha yr^{-1}) and being abandoned (278,000 ha yr^{-1}), in the last decade (2010-2020). In Matopiba region, the area of cropland expansion over pasture more than doubled in the last two decades (from 2000-2010 to 2010-2020), but it is still five times lower than the area of native vegetation converted to pasture and cropland, in the last decade (2011-2020).



	1991-2000		2001-2010		2011-2020	
	Other states	Matopiba	Other states	Matopiba	Other states	Matopiba
Native-Pasture	5,368,212	1,747,348	3,398,656	2,159,169	2,154,630	2,139,928
Native-Cropland	458,634	434,852	301,559	911,031	252,246	857,425
Pasture-Native (abandoned pasture)	1,704,615	904,861	1,718,791	1,042,969	1,586,826	1,283,106
Pasture-Cropland	1,271,683	63,980	1,773,527	207,862	1,865,859	546,101

Figure 4.4. A) Spatial dynamics of agriculture expansion in the last three decades (1990-2000, 2000-2010, 2010-2020), encompassing four land use transitions. State name acronyms: Bahia (BA), Distrito Federal (DF), Goiás (GO), Maranhão (MA), Minas Gerais (MG), Mato Grosso (MT), Mato Grosso do Sul (MS), Paraná (PR), Piauí (PI), São Paulo (SP) and Tocantins (TO). B) Bar chart showing the land use transitions over the three observed periods (1990-2000, 2000-2010, and 2010-2020), highlighting the differences between Matopiba states and other Cerrado states.

The land dynamics among Cerrado states from 1985-2021 have considerably different profiles (Figure 4.5). Pasture expansion over native vegetation is the primary process driving native vegetation loss, but direct conversion of native vegetation to cropland corresponds to 91% of native vegetation transitions in Piauí. Matopiba states sustained low rates of cropland expansion over pasture and high rates of direct native vegetation conversion to cropland during the two last decades (2000-2010, 2010-2020). In Tocantins, however, direct conversion of native vegetation to crops rarely happens, as 94% of all native vegetation conversions resulted in the creation of pastures. Bahia is under strong land use dynamics of deforestation for agricultural uses and pasture abandonment, with high rates of direct conversion of native vegetation to cropland. While in Maranhão and Tocantins, there was an increase in pasture abandonment, in Goiás, Mato Grosso, Mato Grosso do Sul, and Minas Gerais, there was a considerable decrease in this transition. In the last decade, cropland expansion over pasture surpassed pasture expansion over native vegetation in Goiás, while in São Paulo and Paraná, it has been the main land use dynamics throughout the entire time series. Recently, São Paulo experienced an increase in direct conversion of native vegetation to cropland, from 2006 until 2018.

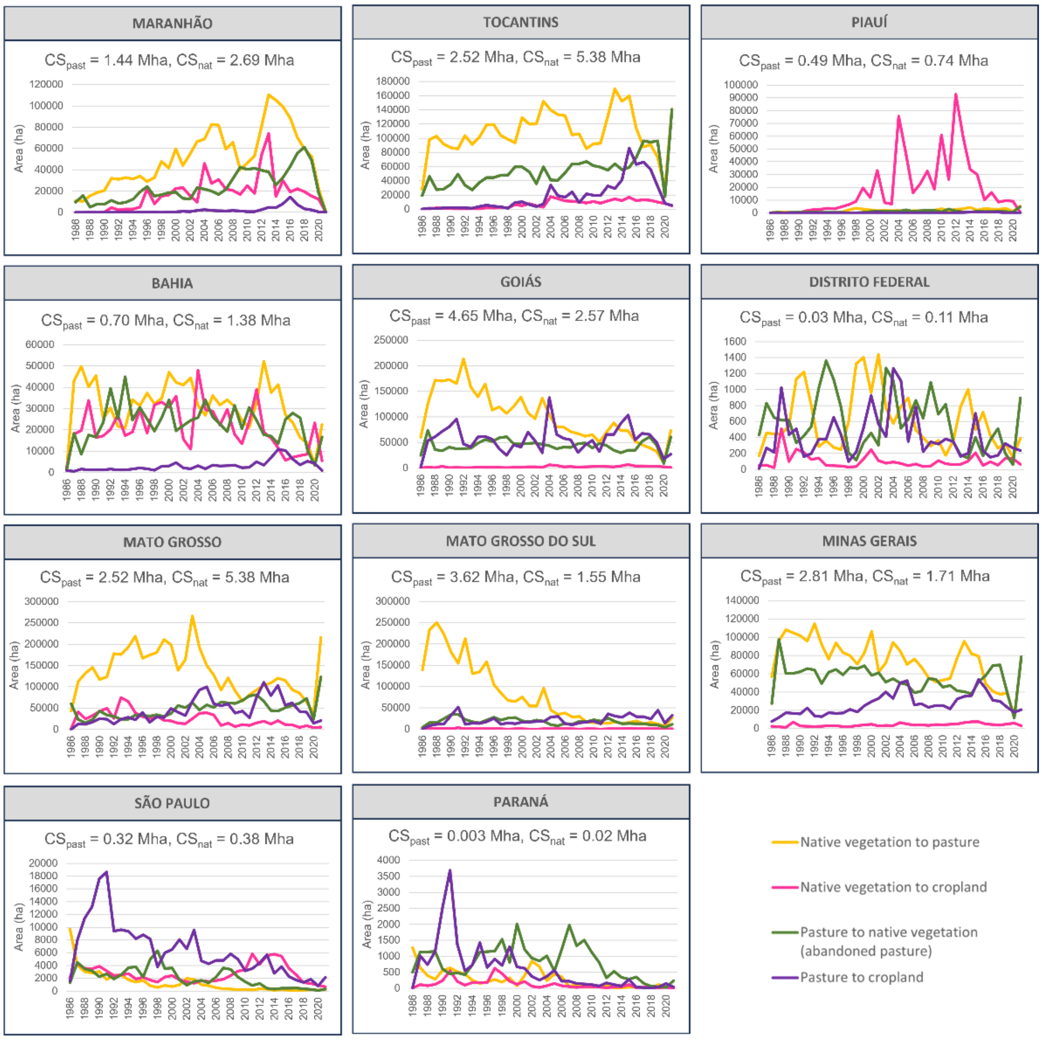


Figure 4.5. Land use and land cover transitions in Cerrado by state, yearly data from 1985 until 2021, considering the four main types of transitions – native vegetation to cropland, native vegetation to pasture, pasture to cropland, and pasture to native vegetation – and the remaining area with crop suitability over pasture (CS$_{\text{past}}$) and over native vegetation (CS$_{\text{nat}}$) within each state in 2020. Crop suitability here considers high and average soil and climatic suitability, without slope or altitude restrictions, to grow soybeans (Rudorff et al., 2015) and land use and land cover data were calculated from MapBiomas project, version 7.0 (2022).

There is an area of 38 Mha with moderate to high crop suitability in the Cerrado, 48% over pasture and the remainder over native vegetation (Figure 4.6). Goiás (4.6 Mha), Mato Grosso do Sul (3.6 Mha), Minas Gerais (2.8 Mha) and Mato Grosso (2.5 Mha) together hold

76% of the area with moderate-high crop suitability over pasture. The largest area with moderate-high crop suitability over native vegetation is in Mato Grosso (5.4 Mha), followed by Tocantins (3.2 Mha), Maranhão (2.7 Mha) and Goiás (2.6 Mha). Together, these states account for 70% of the area with a high potential for commercial soy production over native vegetation.

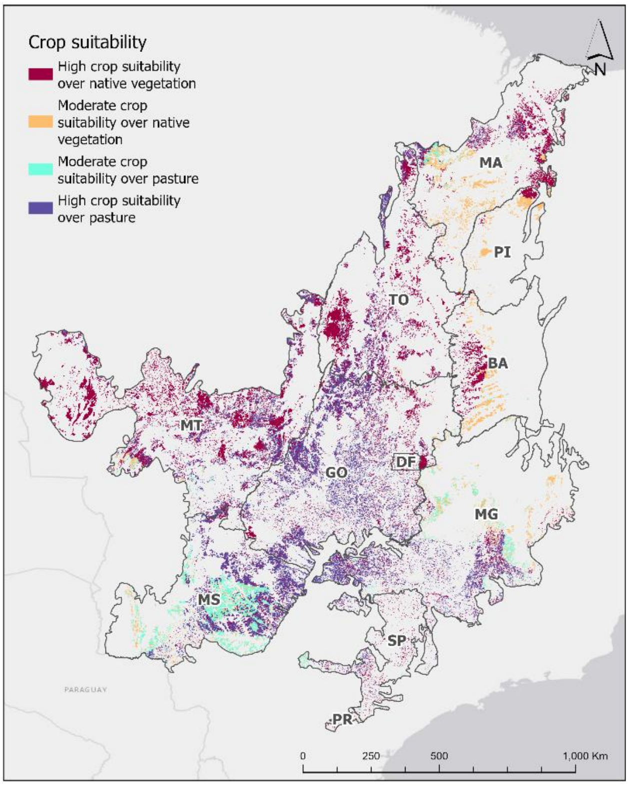


Figure 4.6. Moderate-High soil and climatic suitability, without slope or altitude restrictions, to grow soybeans in the Cerrado (Rudorff et al. 2015), over areas of pasture and native vegetation (calculated from MapBiomas 2022).

The cropland age map indicates a pattern of cropland expansion trajectory around the borders of old and consolidated areas (Figure 4.7). Current cropland areas have a mean age of 20 yr, and 27% were established in the last 10 years. Average crop age is lower in Tocantins (10 yr), Piauí (13 yr) and Maranhão (15 yr). New crop production zones were developed in these states, far from the old-consolidated areas. Although Bahia is part of Matopiba new agriculture frontier, the average cropland age in this state is higher (20 yr). In the last decade, new cropland areas were also created in states with old agricultural land use and a low fraction of remaining native vegetation. New croplands (1-10 yr) represent at least 20% of the total cropland area in São Paulo (21%), Bahia (23%), Goiás (26%), Minas Gerais (31%) and Mato Grosso do Sul (36%). In absolute values, croplands with 1-10 yr occupy large areas of Goiás (1.3 Mha), Mato Grosso (1.1 Mha) and Minas Gerais (1.1 Mha).

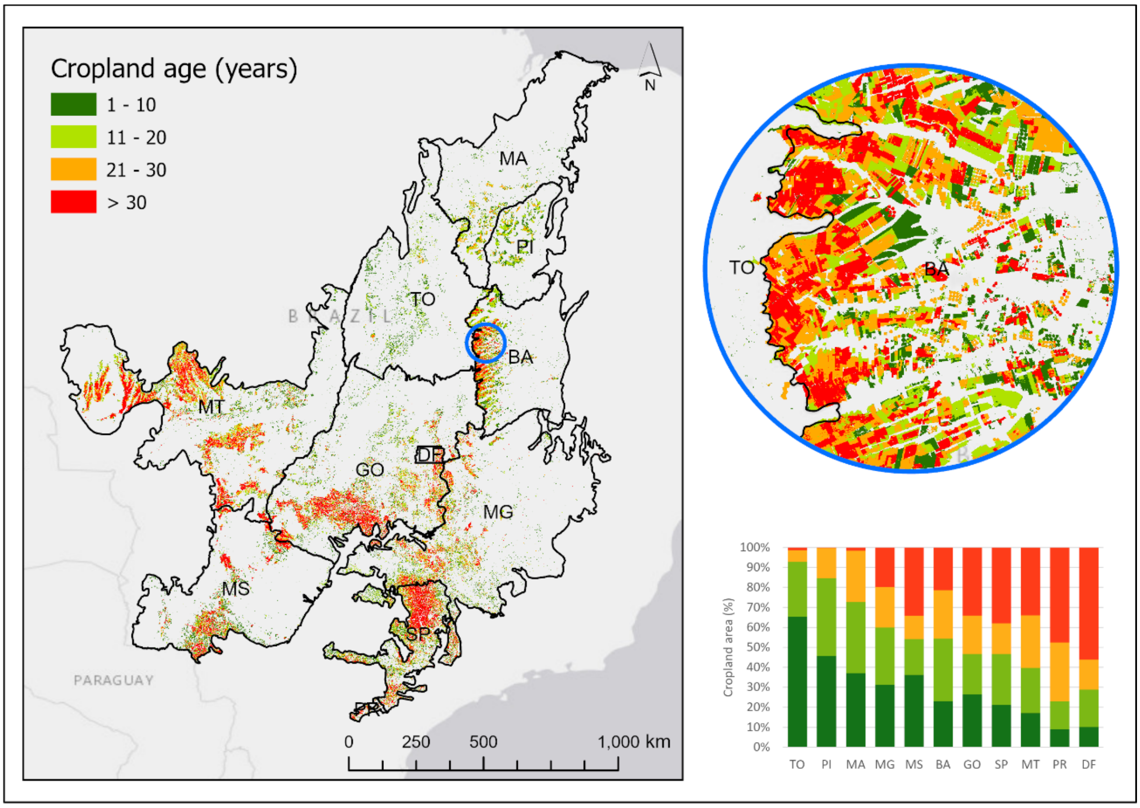


Figure 4.7. Distribution of current croplands throughout the Cerrado, classified by the age (in years) since their establishment. The inset map displays a detailed view of cropland areas in Bahia, showing that new cropland farms have been created in areas adjacent to old, consolidated farms. The bar chart indicates the proportional area of cropland according to cropland age by state, signaling regional differences.

Of the current 27 Mha of cropland in the Cerrado (MapBiomas 2022), 28% (7.5 Mha) was established over pastures. A considerable area of croplands replaced newly created pastures: almost one fifth (1.4 Mha) of these pastures became cropland within 5 years from their establishment, one-quarter (2 Mha) became cropland within 7 years, and 35% (2.6 Mha) within 10 years (Fog. 7). A larger proportion of cropland replacing new pastures (< 5 years) was observed in Piauí (82%), Maranhão (48%) and Bahia (47%) (Figure 4.8).

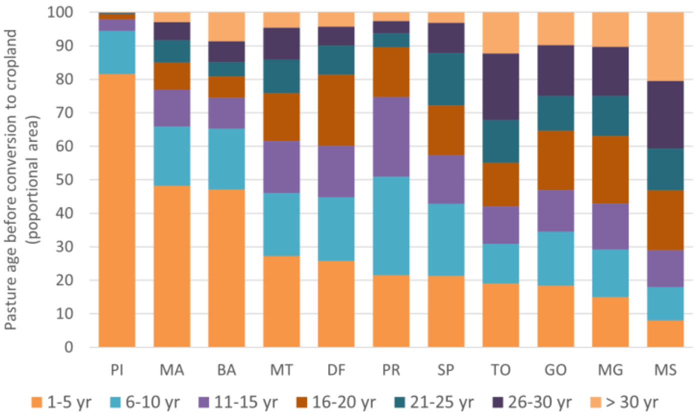


Figure 4.8. The bar chart shows how many years since its establishment it took for pastures to become croplands in each of the Cerrado states. The assessment was based on all cropland areas in 2021, created from pasture replacement.

4.4. Discussion

There was a 33% decrease in the conversion of native vegetation to agricultural uses from 1990-2000 to 2010-2020, but the dominant process of land transition in the Cerrado is still the expansion cropland and pasture over native vegetation, resulting in the loss of 527,000 hectares yr^{-1} of cerrado vegetation in the past decade (2020-2020). Additionally, our findings indicate that there is a coupled process of cropland expansion over pasture in Midwestern and Southeastern Cerrado states and cropland expansion over native vegetation ($\rho = 0.48$) in

Matopiba, but at a lower rate. Although this trend was observed in previous studies (Polizel et al., 2021; Zalles et al., 2019), we identified the temporal variation of these transitions throughout the Cerrado and assessed the spatial patterns at biome and state level, with an integrated analysis of the main land use transitions in the biome.

The correlation between cropland expansion over pasture and pasture expansion over native vegetation was weak ($\rho = 0.25$), requiring further investigation to confirm the deforestation displacement effect. However, our results indicate the ongoing advancement of pasture over native vegetation in the last decade (414,000 ha yr^{-1}, in 2011-2020) was almost twice the size of the area of cropland replacing pasture (224,000 yr^{-1}, in 2011-2020). Land use displacement involves direct and indirect mechanisms operating across multiple scales (from local to international). Even though direct displacement may be hard to confirm, soybean expansion may indirectly affect deforestation by increasing land prices and pushing landowners to open more areas to either sell or increase production (Richards, 2015). The presence of soybeans was one of the factors driving pasture expansion over native vegetation in Mato Grosso (Picoli et al., 2020). Further investigation on the effects of land use transitions on land prices could help reveal the regional land dynamics displacement from other Cerrado estates to Matopiba.

Pasture advancement over native vegetation is slowing down (-40%, from 1990-2000 to 2010-2020), but direct native vegetation conversion to cropland is increasing (+24%, from 1990-2000 to 2010-2020). In the future, the conversion of pasture to crops might be the main process supporting agriculture expansion in the Cerrado, but the future scenario is uncertain. The assessed land use patterns are not linear. We observed patterns of booms and busts that respond to different social, economic and environmental conditions, like variations in soybean profit margins (Zalles et al., 2019), public policies and deforestation-free trade agreements (Picoli et al., 2020), droughts and increased temperatures (Silva et al., 2023). At state-level, land transition profiles indicated that even intensively cultivated areas such as the Cerrado of São Paulo can experience an upsurge in the rates of agriculture expansion over native vegetation.

Regarding land suitability, there are equal opportunities for cropland expansion over pasture or native vegetation. Currently, there are 18 Mha of land suitable for cropland production over pastures mostly concentrated in long-established agricultural states with large pasture extensions, such as Goiás, Mato Grosso do Sul and Minas Gerais. These areas require targeted policies to drive crop production towards pastures in parallel with pasture intensification (Santos et al., 2020b; Veloso et al., 2020). Land suitable for cropland production over native vegetation adds up to 20 Mha, distributed largely across Mato Grosso, Tocantins, Maranhão and Bahia. Additional strategies to protect native vegetation in these states need to be put in place to avert agriculture-driven deforestation. Although Piauí has been a recent frontier of soy expansion, areas with high crop suitability in the state are exhausted, both over pasture and native vegetation. This means current cropland expansion in Piauí is under high climate risk (Rattis et al., 2021), and as climate change intensifies, there is a risk of increased land conversion pressure in old-established agriculture areas outside Matopiba, less subject to intense climate variability, in Mato Grosso, Goiás, Mato Grosso do Sul, Minas Gerais. Therefore, developing effective policies to drive agriculture over already opened areas and avoid pasture expansion over native vegetation will have to consider the possibility of displacement within the Cerrado.

Over the 37-year series, abandoned pasture was the second largest transition category, amounting to 8.9 Mha. The high proportion of abandoned land suggests poor land management and can also be linked to land speculation (Miranda et al., 2019; Richards, 2015). When the class pasture is identified as native vegetation by MapBiomas, it indicates that the gradual process of pasture abandonment and encroachment is at an advanced stage. There are great opportunities to promote sustainable intensification in pastures by maintaining silvopastoral systems with native species (Silva et al., 2021b; Vieira et al., 2022). Many of these previous pasture sites, however, may have low ecological value and low diversity compared to ecosystems covered by native vegetation (Cava et al., 2018), so they cannot be considered restored areas without going through a more detailed investigation. Moreover, in most cases, the transition from pasture to native vegetation class does not imply land use change. Only 20% of Brazilian pastures remained stable between 1985 and 2017, and most pasture areas work as land reserves to be used for production once there are better opportunities (Parente et al., 2019). In Brazil, unused land kept only for speculative purposes can be dispossessed for redistribution under agrarian reform policies. So, converting the land into low-productive pastures is an inexpensive way of securing property rights (Sparovek et al., 2019).

The dynamics of land use also reveal a significant area of pastures being used as temporary activity before conversion to agriculture. Our results indicate that 19% of cropland expansion over pasture replaced recently created pastures, under 5 yr, which raises a warning because the land is converted before it can become productive. This is a common practice in Piauí, Maranhão and Bahia. Converting the area to pasture before selling or renting to agriculture can also be a strategy used to reclaim disputed land, with unclear land-tenure rights. In Brazil, 17% of the area is considered unregistered, i.e., it does not fall under any category of land use from official databases (Sparovek et al., 2019). Land insecurity is higher for local and traditional communities and indigenous peoples, impacted by land, water, food system and governance exclusion (Lopes et al., 2021).

4.5. Concluding remarks

In synthesis, there is potential for cropland expansion over 18 Mha of pastures, mostly over Goiás, Mato Grosso do Sul, Minas Gerais and Mato Grosso. To achieve the land-sparing effect, other direct and indirect drivers of agricultural deforestation also must be addressed. The main indirect effect to target is the likely displacement of pasture expansion over native vegetation, when cropland advances over pastures. Pasture abandonment is also a widespread process that needs to be targeted to promoting better land use. Direct native vegetation conversion to cropland is an increasing process in Maranhão, Piauí and Bahia, driving increased rates of deforestation in Cerrado. Specific policies and trading agreements should be developed for this region, involving higher protection levels for the remaining native vegetation. Strategies must address regional and local differences in land dynamics. Matopiba is often referred to as a unified group, but there are marked differences in land transitions occurring in Piaui and Tocantins, for example. Speculative pasture expansion over native vegetation to keep land reserved and resolve disputed land tenure needs to be properly measured and monitored. Land use disputes can be potentially reduced by the recognition of all collective and traditional land rights.

The most successful examples of deforestation reduction in Brazil have been achieved from combined strategies of protected areas creation, recognition of traditional lands rights, incentive policies, command and control policies, and trade agreements (Nepstad et al., 2014; Soares-Filho & Rajão, 2018). That may help explain why intensification alone has not been able to spare land for nature. Since there is enough open land for agricultural expansion, policies to effectively coerce croplands to these areas need to include reinforced protection of all biomes, in order to avoid displacement.

From a global perspective, it is also important to consider that, although the country has a challenging task ahead, meeting increased global food demand will hardly be achieved only from increases in agricultural production. Multiple solutions will have to be put in place globally to feed the world with low carbon emissions, including reducing waste in production and consumption, adopting plant-based diets, increasing production in areas already opened, and, at the same time, improving the distribution of food to regions where there is deficient nutrient consumption (Clark et al., 2020).

5. CONCLUDING REMARKS

This dissertation investigated how cropland and pasture expansion over native cerrado vegetation affected land surface temperature and water recycling at local and regional scales. Our findings showed that the effects of agriculture expansion varied according to local climate conditions and the type of vegetation being converted (grassland, savanna, or forest). On a regional scale, the overall effect was a reduction in annual evapotranspiration and an increase in average land surface temperature. We observed these transitions from the perspective of the WEF Nexus (Chapter 1) and discussed how the current focus on agricultural production, mediated by changes in temperature and evapotranspiration, may affect Cerrado ecosystems. The possible repercussions include increased fire frequency, reduced water availability, reduced hydropower production, and reduced vegetation recovery rates. Deforestation for pasture and cropland also intensifies the dryer and warmer conditions of global climate change, which in turn can have negative feedback on agricultural production, reducing yields and profitability. To break this cycle, agriculture and pasture must be developed without further deforestation. Additionally, regeneration initiatives need to be augmented to counterbalance the intensive transformation the Cerrado has been through over the last 50 years.

We then investigated opportunities and constraints for cropland and pasture expansion in the Cerrado, without further deforestation, analyzing regional and local spatial-temporal patterns of land use transitions. Although there are opportunities to increase agriculture production without new deforestation, the necessary policies, and mechanisms to promote these changes still need to be implemented. The conversion of native vegetation to pastures and croplands is rapidly advancing in the Cerrado, and several factors need to be addressed to reverse this trend. These include avoiding potential deforestation displacement, preventing pasture expansion driven by land speculation, securing land collective and traditional land rights over disputed land, and creating mechanisms to curb the direct conversion of native vegetation to croplands in the Matopiba region. Other measures such as increased protection of areas with high crop suitability over native vegetation, avoiding pasture abandonment, promoting intensification and better use of pastures, recovering abandoned and degraded pastures, and promoting the expansion of cropland over pastures must be put in place. Without these measures, the projected increases in the international demand for agricultural commodities will continue to exert pressure for the conversion of this highly threatened biome, affecting water, food, and energy security.

The WEF Nexus approach underpins our discussions about the impacts of replacing cerrado vegetation by cropland and pasture. Brazil's development model, which focus on export-oriented commodities, caused a vast transformation in the Cerrado, leading to changes in the energy balance and water cycle at regional scale. Our research reveals the connection between the main land use transitions in the biome (from forest, savanna and grassland vegetation to cropland and pasture), highlighting the connectedness between biotic and abiotic ecosystems components, through energy flows and water cycling. These are underlying mechanisms explaining why WEF Nexus components depend on each other, and why the social-environmental consequences of native vegetation clearing are also connected, affecting water distribution, hydroelectric energy generation, and agriculture production.

We also discussed the direct and indirect mechanisms involved in clearing the Cerrado, beyond the goal of increasing agriculture production. Our research found that many areas of pasture are underutilized and going through encroachment, cycles of cropland expansion are correlated to increased clearing of native vegetation, and deforestation for pasture is often an intermediate land occupation – possibly related to land speculation. All these indirect mechanisms through which agriculture contributes to deforestation also affect the WEF Nexus security. Therefore, integrated solutions must consider the synergies between water, energy, and food – along with the underlying biodiversity and ecosystem services that sustain these resources – and address the direct and indirect drivers of deforestation.

Throughout this dissertation, we emphasized the importance of considering the integrated WEF Nexus in social-environmental analysis. We also highlighted the dire consequences of not taking immediate and urgent action to reverse the conversion of native vegetation to cropland and pasture. In addition, we identified various points of intervention in the system. Our research is intended to contribute to the ongoing discussion of this topic, and we recognize that it is far from complete. On the contrary, our work raises new questions that can be explored through further analysis. For instance, future research could investigate the ways in which land prices mediate spillover and displacement effects of cropland replacing pastures, the differences between pastures with increasing presence of native species and native vegetation regeneration over pastures, sizes and connectivity of pasture patches with higher interest for cropland expansion or cerrado regeneration, and possible effects of native vegetation and pasture transitions on rainfall.

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