Received: 28 April 2022 | Accepted: 19 June 2022
DOI: 10.1111/gcb.16386

Global Change Biology WILEY

RESEARCH ARTICLE

Cerrado deforestation threatens regional climate and water availability for agriculture and ecosystems

Ariane A. Rodrigues[1] | Marcia N. Macedo[2,3] | Divino V. Silvério[3,4] | Leandro Maracahipes[3,5] | Michael T. Coe[2,3] | Paulo M. Brando[2,3,6] | Julia Z. Shimbo[3] | Raoni Rajão[7] | Britaldo Soares-Filho[8] | Mercedes M. C. Bustamante[1]

[1]Department of Ecology, University of Brasília, Brasília, Distrito Federal, Brazil
[2]Woodwell Climate Research Center, Falmouth, Massachusetts, USA
[3]Amazon Environmental Research Institute, Brasília, Distrito Federal, Brazil
[4]Federal Rural University of the Amazon, Capitão Poço, Pará, Brazil
[5]Institute of Biology, State University of Campinas, Campinas, São Paulo, Brazil
[6]Department of Earth System Science, University of California-Irvine, Irvine, California, USA
[7]Department of Production Engineering, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil
[8]Center for Remote Sensing, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil

Correspondence
Ariane A. Rodrigues, Department of Ecology, University of Brasília, 70910-900 Brasília, Distrito Federal, Brazil.
Email: arianerodrigues@gmail.com

Funding information
Conselho Nacional de Desenvolvimento Científico e Tecnológico, Grant/Award Number: 141988/2020-7, Nexus-Cerrado 441463/2017-7 and PELD-Tang 441703/2016-0; Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Grant/Award Number: 001; Fundação de Amparo à Pesquisa do Estado de São Paulo, Grant/Award Number: 2020/06085-1; National Science Foundation, Grant/Award Number: DEB 1457602 and INFEWS 1739724

Abstract

The Brazilian Cerrado is one of the most biodiverse savannas in the world, yet 46% of its original cover has been cleared to make way for crops and pastures. These extensive land-use transitions (LUTs) are expected to influence regional climate by reducing evapotranspiration (ET), increasing land surface temperature (LST), and ultimately reducing precipitation. Here, we quantify the impacts of LUTs on ET and LST in the Cerrado by combining MODIS satellite data with annual land use and land cover maps from 2006 to 2019. We performed regression analyses to quantify the effects of six common LUTs on ET and LST across the entire gradient of Cerrado landscapes. 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. Global climate changes from increased atmospheric greenhouse gas concentrations will only exacerbate these effects. Considering potential future scenarios, we found that abandoning deforestation control policies 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.

KEYWORDS
conservation, ecosystem services, Forest Code, restoration, savanna, soybean expansion

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 (ET; 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 1000 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 (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; A. A. Souza et al., 2020; 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. Although legal, such large-scale deforestation is far from sustainable—resulting in massive biodiversity losses and greenhouse gas emissions of ~3.2 GtCO_2e (Russo et al., 2018). Even where protection exists, law enforcement is weak: an estimated 15% (1 Mha) of all Cerrado deforestation occurring from 2009 to 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, 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 (LUTs) 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 LUT alter ET and LST in the Cerrado?; (2) What is the cumulative effect of all historic LUTs on the present-day regional climate of the Cerrado?; and (3) How might future LUTs in the Cerrado further alter local and regional climate (ET and LST)?

2 | METHODS

2.1 | Study area

Our analysis focuses on the Brazilian Cerrado biome (Figure 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 year^{-1} (Assad & Evangelista, 1994; Sano et al., 2019), with the lowest rainfall occurring in the northeast (i.e., bordering the semiarid Caatinga) and increasing toward 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., 2008). The annual mean air temperature ranges from 18 to 27°C, and the relative humidity ranges from 60% to 90% (Silva et al., 2008; Figure 2).

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 to 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 to present (C. M. Souza et al., 2020). 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 (Appendix S1). To control for the strong climate gradient across the Cerrado (Figure 2), we generated 2°×2° grid cells (Appendix S2) and fitted regressions for each resulting climate region before summarizing the data for the entire biome.

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

FIGURE 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.

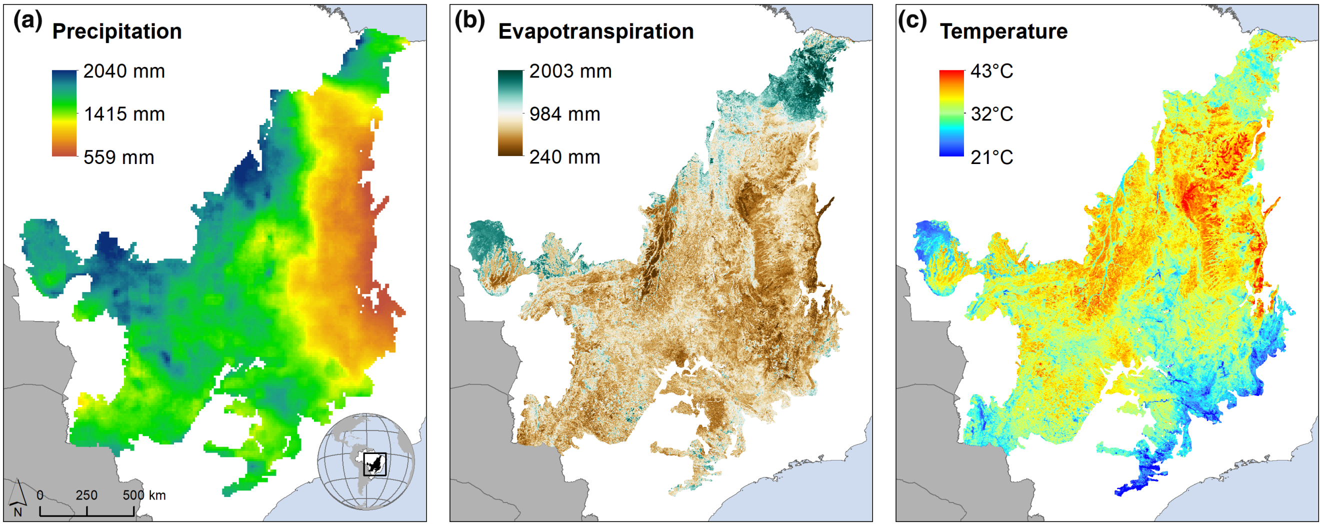

FIGURE 2 Maps depicting the average annual (a) precipitation, (b) evapotranspiration, and (c) land surface temperature across the Brazilian Cerrado. Climate variables were calculated for our study period (2006–2019) based on Global Precipitation Measurement data (Huffman et al., 2019) and MODIS-derived products MOD16A2 Version 6 (Wan et al., 2015) and MOD11A2 Version 6 (Running et al., 2017).

($p<.05$), 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 (Appendix 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).

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 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.

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 ($p>.05$) 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:

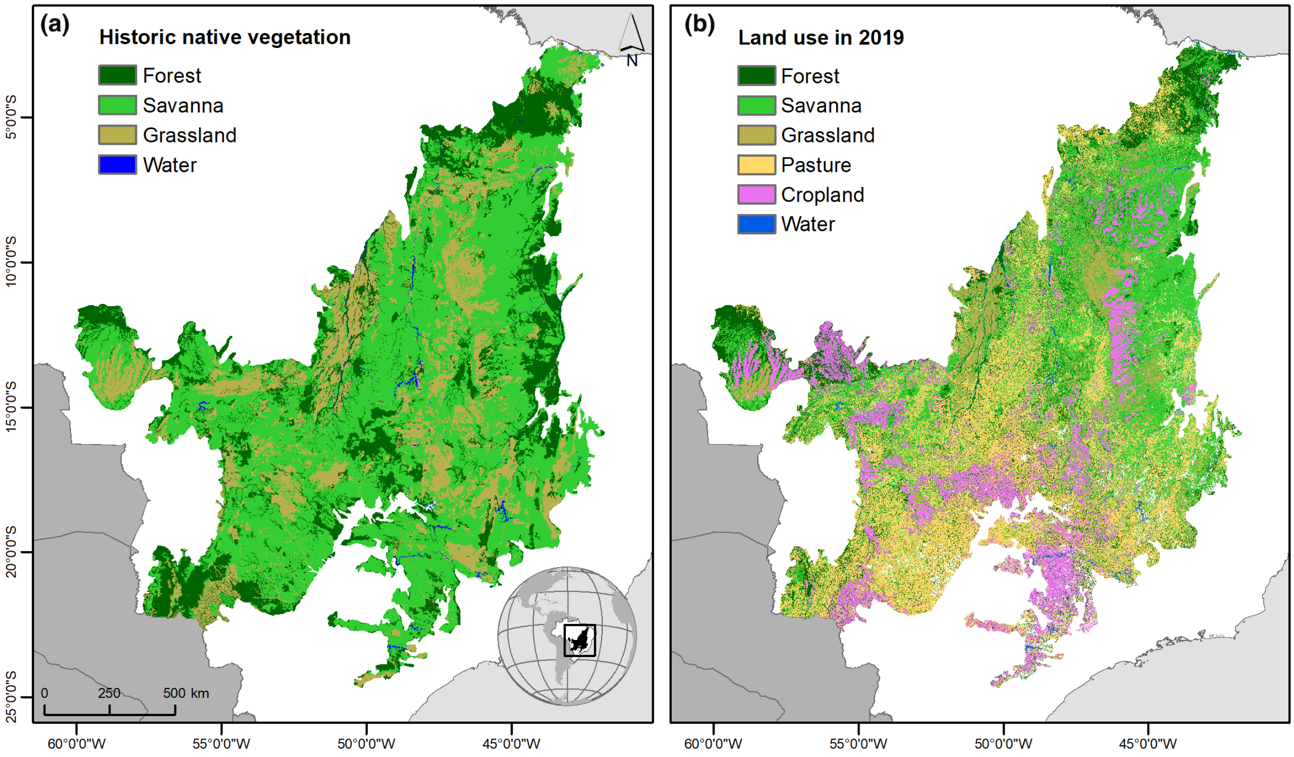

FIGURE 3 Maps of (a) presumptive native vegetation distribution prior to large-scale human occupation (historic baseline; adapted from Ministry of Science, Technology, and Innovations, 2021) and (b) 2019 land cover and land-use classes (MapBiomas, 2020) in the Cerrado.

(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 year^{-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% (Appendix 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 to 2014, capped at the 2004 peak of 1.8 Mha year^{-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 year^{-1} from 2012 to 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 to 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 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 $year^{-1}$ over the last 10 years (from 2009 to 2018; MapBiomas, 2021), we estimate that it would take ~10 years (from 2019 to 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 (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 Brazilian Foundation for Sustainable Development (2019) dataset, we estimated the vegetation debt in riparian APPs considering the sum of built areas, anthropic areas, and forestry in each municipality (Appendix S5).

3 | RESULTS

3.1 | LUT effects on ET and LST

Our analyses show that the transition from native Cerrado vegetation to cropland or pasture generally reduces ET and increases LST (Figures 4 and 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°C, 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 ($p > .05$). 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.

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 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), 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 to 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 6).

Cerrado vegetation recycles roughly two-thirds of annual precipitation (PPT) back to the atmosphere via ET each year (ET = 980 mm and PPT = 1415 mm, considering annual averages from 2006 to 2019). Our results indicate that, if native vegetation had been preserved (i.e., considering the historic baseline, Figure 3), ET in 2019 would have been 10% higher (169 km^3) and average daytime LST would have been 0.9°C lower. Given the heterogeneity of LUTs and the natural climate gradient in this vast region (Figure 2), we identified hotspots of reduced ET and increased LST throughout the biome (Figure 7). Notable hotspots of warming occurred in western Bahia and northern Minas Gerais, where average annual temperatures are already high (33.9 and 31.8°C, 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).

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

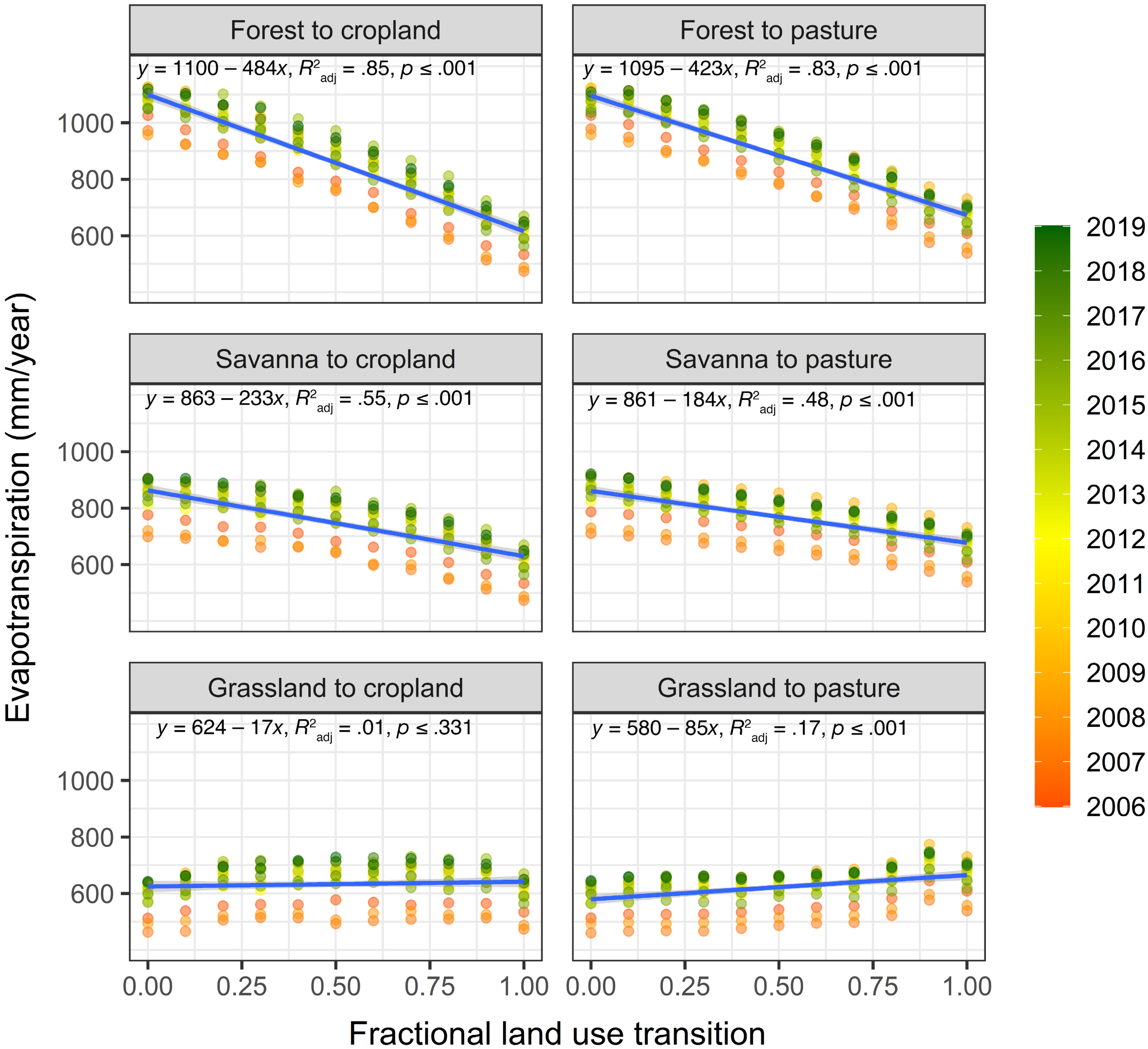

FIGURE 4 Change in average annual evapotranspiration as a function of fractional change in land use, estimated from 2006 to 2019 for the Cerrado biome.

in LST of 0.7°C in 2050 (Table 1), compared to the baseline from Rochedo et al. (2018). 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°C average increase in LST relative to 2018. 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 8).

The Cerrado Recovering scenario resulted in a mean annual ET increase of 4 mm (8 km^3) and average LST decrease of 0.04°C relative to 2018. 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 0.5 Mha of 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.

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

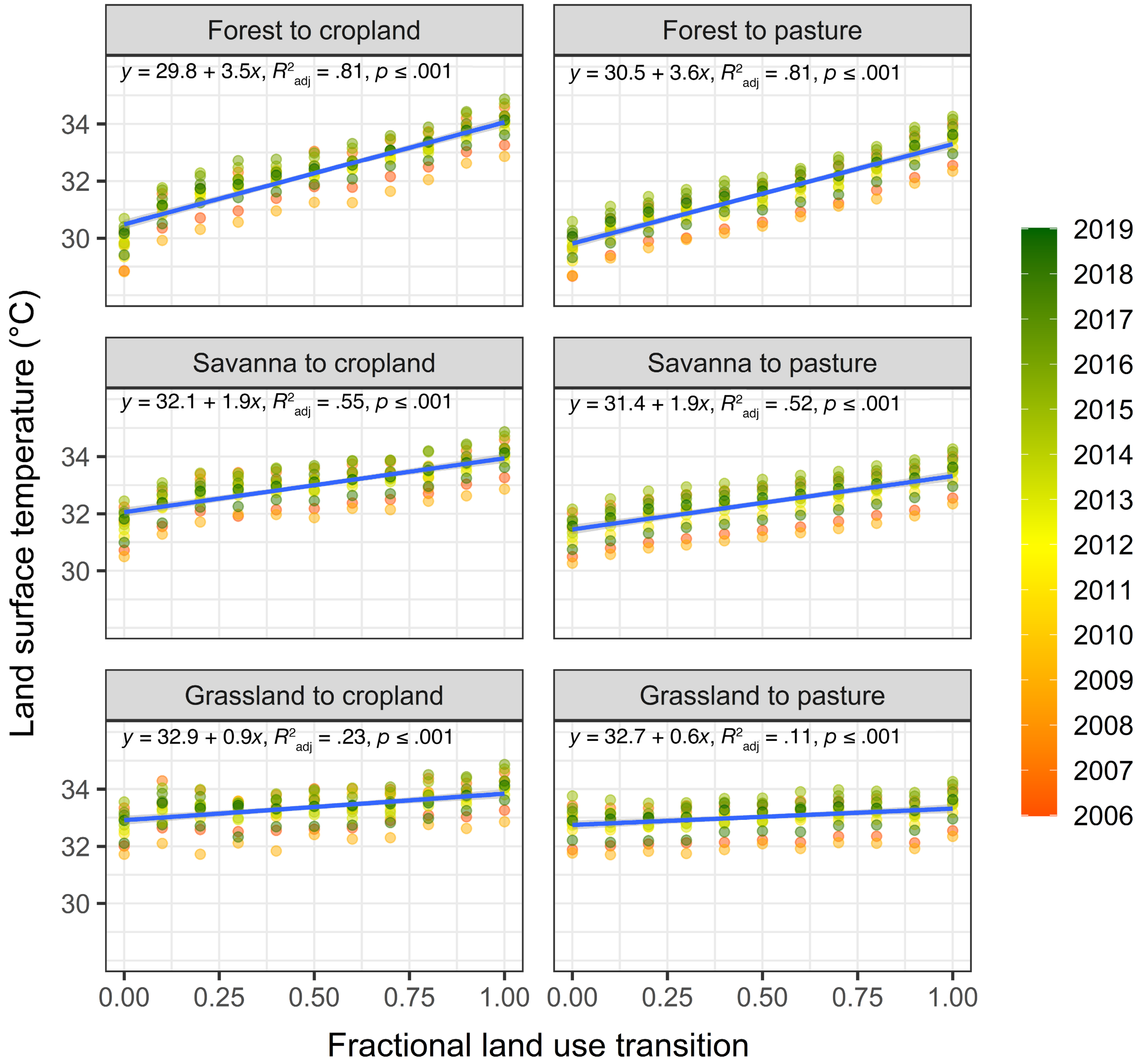

FIGURE 5 Change in average daytime land surface temperature as a function of fractional change in land use, estimated from 2006 to 2019 for the Cerrado biome.

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; National Institute for Space Research, 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

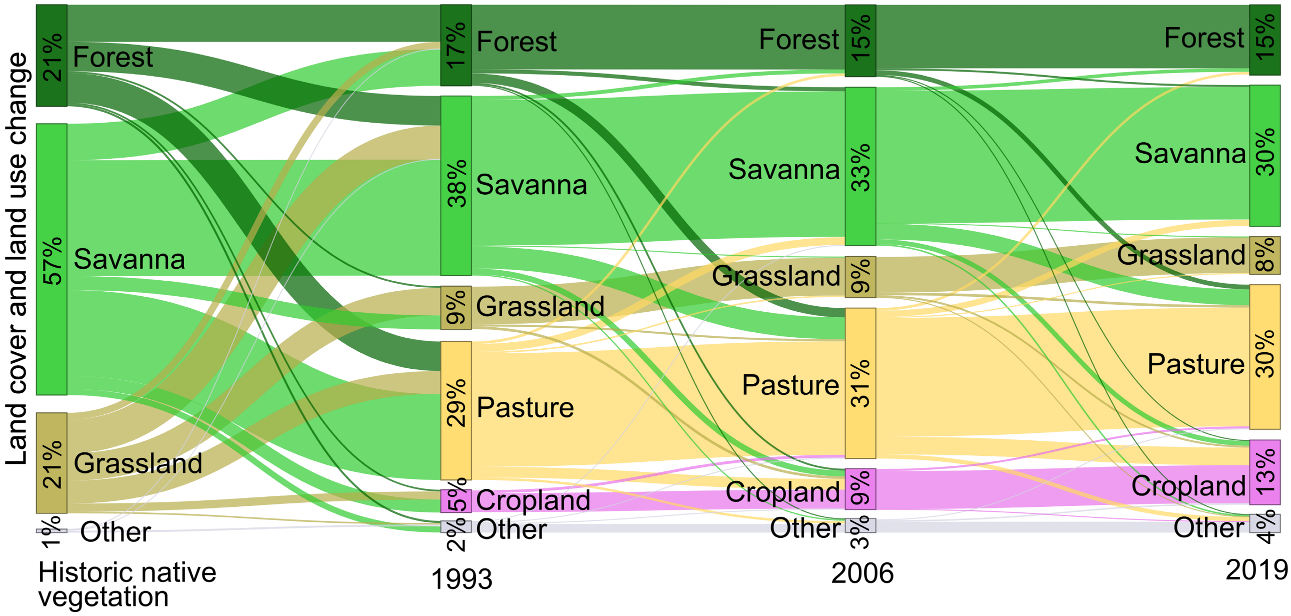

FIGURE 6 Brazilian Cerrado land cover and land-use dynamics during three time steps, showing transitions from: (1) original native vegetation to 1993; (2) 1993 to 2006; and (3) 2006 to 2019 (this study). The map of potential historic native vegetation came from Ministry of Science, Technology, and Innovations (2021) and maps of land cover and land use in 1993, 2006, and 2019 came from MapBiomas (2020).

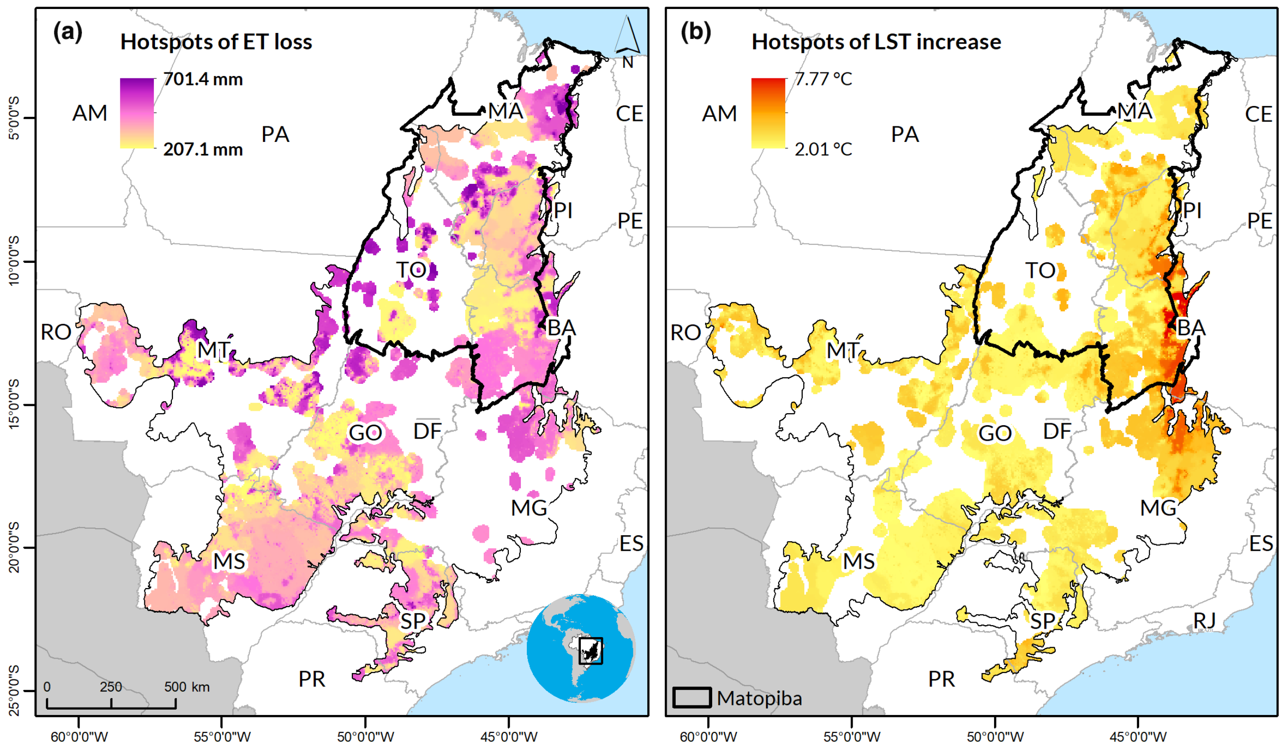

FIGURE 7 Hotspots of (a) drying (evapotranspiration [ET] loss) and (b) warming (land surface temperature [LST] increase) associated with the spatial patterns of land-use transitions since Cerrado conversion began. ET and LST changes were calculated for land use in 2019, compared to the baseline of historic native vegetation. Hotspots of ET loss and LST increase are derived from the spatial clustering of above-average values, varying from 207 to 701 mm and 2.0 to 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), Paraná (PR), São Paulo (SP), and Tocantins (TO).

TABLE 1 Projected land-use changes under three future scenarios and their resulting impacts on annual evapotranspiration (ET) and average land surface temperature (LST). Values presented here reflect ET and LST changes at the end point of each scenario (after all the projected vegetation clearing or recovery), compared to the baseline

Scenario	Description	Vegetation change (Mha)	ET change ($km^3 year^{-1}$)	LST mean change (°C)
Cerrado Collapse[a]	Accelerating legal and illegal deforestation	−63.6	−170.6	+0.7
Cerrado Struggling[b]	Carrying out all legal deforestation	−28.4	−59.4	+0.3
Cerrado Recovering[b]	Achieving zero deforestation, with restoration of illegally deforested areas[c]	+5.2	+8.1	−0.04

[a]Projected changes relative to a 2012 baseline (Rochedo et al., 2018).

[b]Projected changes relative to a 2018 baseline (Rajão et al., 2020).

[c]Cerrado Recovery ET and LST changes refer only to the effects of restoration, without accounting for the effects of avoided deforestation.

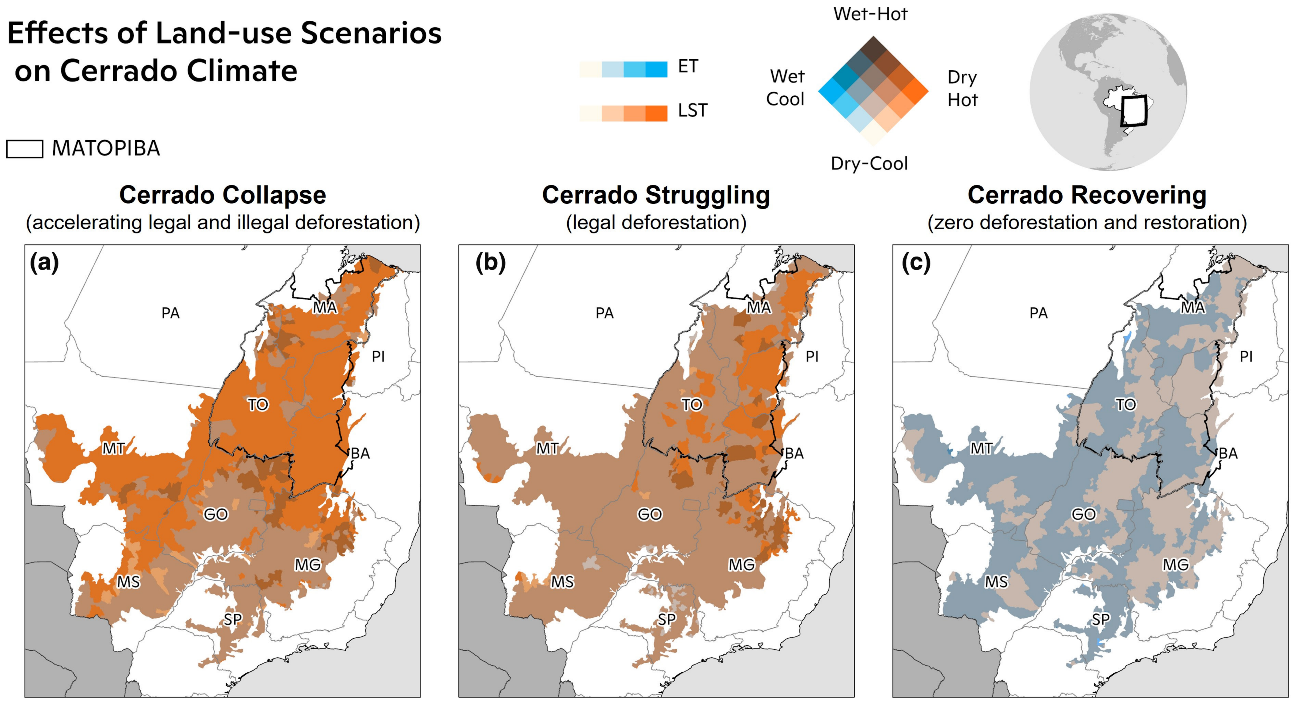

FIGURE 8 Change in evapotranspiration (ET) and land surface temperature (LST) under three contrasting scenarios of future land-use transitions in the Brazilian Cerrado. The Cerrado Collapse scenario (a) assumes no deforestation control policies, resulting in 63.6 Mha of additional deforestation by 2050. 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 (Areas of Permanent Protection) and Legal Reserves. These scenarios were developed based on previously published data (Rajão et al., 2020; Rochedo et al., 2018).

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

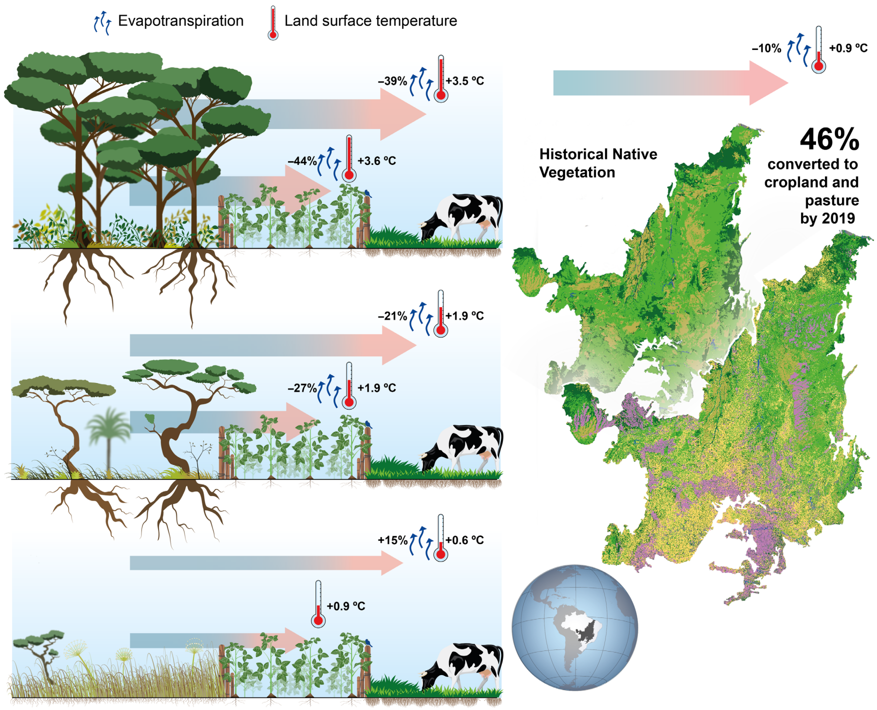

FIGURE 9 Synthesis of the observed impacts of land-use transition on mean annual evapotranspiration (ET) and average land surface temperature (LST) in the Cerrado. At local scales (left panel), the conversion of forests and savannas to cropland or pasture reduced ET and increased LST. The conversion 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.

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 9).

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., 2020) 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°C 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.

AUTHOR CONTRIBUTIONS

Ariane A. Rodrigues designed the research, curated and analyzed the data, provided data visualizations, designed and implemented future scenarios, drafted the original manuscript, and managed revisions. Marcia N. Macedo assisted with research design, data analysis, overall project management, and manuscript preparation. Divino V. Silvério assisted with research design, data analysis, data visualization, coding and method development, and manuscript preparation. Leandro Maracahipes contributed to data analysis, data visualization, and manuscript preparation. Michael T. Coe and Paulo M. Brando helped develop the methodological approach, provided valuable input on data analyses, and contributed to project funding. Julia Z. Shimbo assisted with data acquisition and interpretation and provided guidance on land-use classification and Cerrado LUTs. Raoni Rajão and Britaldo Soares-Filho provided data on environmental debts and surpluses and contributed to future scenarios modeling. Mercedes M. C. Bustamante contributed to research design, helped secure project funding, coordinated and supervised project implementation. All authors contributed to manuscript editing and writing.

ACKNOWLEDGMENTS

This study was supported by grants from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq projects: Nexus-Cerrado #441463/2017-7; PELD-Tang #441703/2016-0) and the National Science Foundation (INFEWS #1739724; DEB #1457602). A.A.R. received support from the CNPq (grant #141988/2020-7) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES grant #001); L.M. received support from the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP grant #2020/06085-1). We are grateful to colleagues at the Amazon Environmental Research Institute (IPAM), the Max Planck Institute for Biogeochemistry, the Woodwell Climate Research Center (Woodwell), and the Ecosystems Laboratory at the University of Brasília for their helpful input on earlier versions of this manuscript. Special thanks to Carl Churchill and Gregory Fiske from Woodwell for help designing the maps in Figures 1 and 8, and for thoughtful comments and suggestions on all maps and visualizations in this manuscript. Thanks also to Raoni Rebouças of Sepia Studio for help designing the illustration in Figure 9.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data supporting our findings came from published sources cited in the reference list. ET and LST data are openly available in the Google Earth Engine repository. The digital annual maps of land cover and land use are available in the MapBiomas platform at https://mapbiomas.org/. Data on environmental debts and surpluses used for scenarios modeling are available at https://csr.ufmg.br/radiografia_do_car/. High-resolution data on land use in riparian areas are available at http://geo.fbds.org.br/. Projections for 2012–2050 land-use changes were used under license for this study and are available upon reasonable request, with permission of the authors and publishers of the original study (Rochedo et al., 2018). Derived data from this study are available online in Dryad Digital Repository at https://doi.org/10.5061/dryad.4f4qrfjfx. Correspondence and requests for materials should be addressed to the corresponding author.

ORCID

Ariane A. Rodrigues https://orcid.org/0000-0003-2542-2288
Marcia N. Macedo https://orcid.org/0000-0001-8102-5901
Divino V. Silvério https://orcid.org/0000-0003-1642-9496
Leandro Maracahipes https://orcid.org/0000-0002-6148-3291
Michael T. Coe https://orcid.org/0000-0002-7470-0697
Paulo M. Brando https://orcid.org/0000-0001-8952-7025
Julia Z. Shimbo https://orcid.org/0000-0001-6432-0351
Raoni Rajão https://orcid.org/0000-0002-1133-4837
Britaldo Soares-Filho https://orcid.org/0000-0002-7703-946X
Mercedes M. C. Bustamante https://orcid.org/0000-0003-1008-452X

REFERENCES

Alencar, A., Shimbo, J. Z., Lenti, F., Marques, C. B., Zimbres, B., Rosa, M., Arruda, V., Castro, I., Ribeiro, J. F. M., Varela, V., Alencar, I., Piontekowski, V., Ribeiro, V., Bustamante, M. M. C., Sano, E. E., & Barroso, M. (2020). Mapping three decades of changes in the Brazilian savanna native vegetation using landsat data processed in the google earth engine platform. *Remote Sensing*, *12*(6), 924. https://doi.org/10.3390/rs12060924

Alencar, A. A., Brando, P. M., Asner, G. P., & Putz, F. E. (2015). Landscape fragmentation, severe drought, and the new Amazon forest fire regime. *Ecological Applications*, *25*(6), 1493–1505. https://doi.org/10.1890/14-1528.1

Anache, J. A. A., Wendland, E., Rosalem, L. M. P., Youlton, C., & Oliveira, P. T. S. (2019). Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado. *Hydrology and Earth System Sciences*, *23*(3), 1263–1279. https://doi.org/10.5194/hess-23-1263-2019

Anselin, L. (1995). Local indicators of spatial association-LISA. *Geographical Analysis*, *27*(2), 93–115. https://doi.org/10.1111/j.1538-4632.1995.tb00338.x

Arantes, A. E., Ferreira, L. G., & Coe, M. T. (2016). The seasonal carbon and water balances of the Cerrado environment of Brazil: Past, present, and future influences of land cover and land use. *ISPRS Journal of Photogrammetry and Remote Sensing*, *117*, 66–78. https://doi.org/10.1016/j.isprsjprs.2016.02.008

Arias, P. A., Bellouin, N., Coppola, E., Jones, R. G., Krinner, G., Marotzke, J., Naik, V., Palmer, M. D., Plattner, G. K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P. W., Trewin, B., Rao, K. A., Adhikary, B., Allan, R. P., Armour, K., … Zickfeld, K. (2021). Technical summary. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

Assad, E. D., & Evangelista, B. A. (1994). Análise frequencial da precipitação pluviométrica. In E. D. Assad (Ed.), *Chuva nos Cerrados: Análise e Espacialização* (pp. 25–42). EMBRAPA—CPAC/SPI.

Begotti, R. A., & Peres, C. A. (2020). Rapidly escalating threats to the biodiversity and ethnocultural capital of Brazilian Indigenous Lands. *Land Use Policy*, *96*(March), 104694. https://doi.org/10.1016/j.landusepol.2020.104694

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Bourlière, F., & Hadley, M. (1970). The ecology of tropical savannas. *Annual Review of Ecology and Systematics*, *1*(1), 125–152. https://doi.org/10.1146/annurev.es.01.110170.001013

Brazilian Foundation for Sustainable Development. (2019). *Mapeamento em Alta Resolução dos Biomas Brasileiros*. Fundação Brasileira para o Desenvolvimento Sustentável. http://geo.fbds.org.br/

Brazilian Institute of Geography and Statistics. (2004). *Mapa de Biomas do Brasil—1:5.000.000*. Instituto Brasileiro de Geografia e Estatística. https://www.ibge.gov.br/geociencias/cartas-e-mapas/informacoes-ambientais/15842-biomas.html?edicao=16060&t=acesso-ao-produto

Brazilian Institute of Geography and Statistics. (2012). *Manual Técnico da Vegetação Brasileira* (2nd ed., Issue 1). Instituto Brasileiro de Geografia e Estatística. https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=263011

Brazilian Institute of Geography and Statistics. (2017). *Mapa de Vegetação do Brasil*. Instituto Brasileiro de Geografia e Estatística. http://www.ibge.gov.br/geociencias/informacoes-ambientais/vegetacao/22453-cartas-1-250-000.html?=&t=acesso-ao-produto

Bustamante, M. (2020). Tropical forests and climate change mitigation: The decisive role of environmental governance. *Georgetown Journal of International Affairs*, 18–21. https://gjia.georgetown.edu/2020/03/20/tropical-forests-climate-change-mitigation-role-of-environmental-governance/

Carvalho, F. M. V., de Marco, P., & Ferreira, L. G. (2009). The Cerrado into-pieces: Habitat fragmentation as a function of landscape use in the savannas of central Brazil. *Biological Conservation*, *142*(7), 1392–1403. https://doi.org/10.1016/j.biocon.2009.01.031

Cava, M. G. B., Pilon, N. A. L., Ribeiro, M. C., & Durigan, G. (2018). Abandoned pastures cannot spontaneously recover the attributes of old-growth savannas. *Journal of Applied Ecology*, *55*(3), 1164–1172. https://doi.org/10.1111/1365-2664.13046

Coe, M. T., Brando, P. M., Deegan, L. A., Macedo, M. N., Neill, C., & Silvério, D. (2017). The forests of the Amazon and Cerrado moderate regional climate and are the key to the future. *Tropical Conservation Science*, *10*, 194008291772067. https://doi.org/10.1177/1940082917720671

Coe, M. T., Latrubesse, E. M., Ferreira, M. E., & Amsler, M. L. (2011). The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. *Biogeochemistry*, *105*(1), 119–131. https://doi.org/10.1007/s10533-011-9582-2

Cohn, A. S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., & Thompson, S. (2019). Forest loss in Brazil increases maximum temperatures within 50 km. *Environmental Research Letters*, *14*(8), 084047. https://doi.org/10.1088/1748-9326/ab31fb

Convention on Biological Diversity. (2010). Strategic plan for biodiversity 2011–2020 and the Aichi Targets. In *Decisions adopted by the conference of the parties to the convention on biological diversity at its tenth meeting*. Secretariat of the Convention on Biological Diversity. https://www.cbd.int/sp/

Critical Ecosystem Partnership Fund. (2018). *Ecosystem profile: Cerrado biodiversity hotspot full report*. Supernova. https://www.cepf.net/our-work/biodiversity-hotspots/cerrado

Cuartas, L. A., Cunha, A. P. M. D. A., Alves, J. A., Parra, L. M. P., Deusdará-Leal, K., Costa, L. C. O., Molina, R. D., Amore, D., Broedel, E., Seluchi, M. E., Cunningham, C., Alvalá, R. C. D. S., & Marengo, J. A. (2022). Recent hydrological droughts in Brazil and their impact on hydropower generation. *Water*, *14*(4). https://doi.org/10.3390/w14040601

Davidson, E. A., Araújo, A. C., Artaxo, P., Balch, J. K., Brown, I. F., Bustamante, M. M. C., Coe, M. T., DeFries, R. S., Keller, M., Longo, M., Munger, J. W., Schroeder, W., Soares-Filho, B. S., Souza, C. M., & Wofsy, S. C. (2012). The Amazon basin in transition. *Nature*, *481*(7381), 321–328. https://doi.org/10.1038/nature10717

Davin, E. L., & Noblet-Ducoudré, N. (2010). Climatic impact of global-scale deforestation: Radiative versus nonradiative processes. *Journal of Climate*, *23*(1), 97–112. https://doi.org/10.1175/2009JCLI3102.1

Embrapa Territorial. (2020). *GeoMatopiba: Inteligência Territorial Estratégica para o Matopiba*. www.embrapa.br/geomatopiba

Ferrante, L., & Fearnside, P. M. (2019). Brazil's new president and 'ruralists' threaten Amazonia's environment, traditional peoples and the global climate. *Environmental Conservation*, *46*(4), 261–263. https://doi.org/10.1017/S0376892919000213

Ferraz, J. B. S., & Felício, P. E. (2010). Production systems—An example from Brazil. *Meat Science*, *84*(2), 238–243. https://doi.org/10.1016/j.meatsci.2009.06.006

Flach, R., Abrahão, G., Bryant, B., Scarabello, M., Soterroni, A. C., Ramos, F. M., Valin, H., Obersteiner, M., & Cohn, A. S. (2021). Conserving the Cerrado and Amazon biomes of Brazil protects the soy economy from damaging warming. *World Development*, *146*, 105582. https://doi.org/10.1016/j.worlddev.2021.105582

Gasparri, N. I., Kuemmerle, T., Meyfroidt, P., le Polain de Waroux, Y., & Kreft, H. (2016). The emerging soybean production frontier in Southern Africa: Conservation challenges and the role of south-south telecouplings. *Conservation letters*, *9*(1), 21–31. https://doi.org/10.1111/conl.12173

Grace, J., Jose, J. S., Meir, P., Miranda, H. S., & Montes, R. A. (2006). Productivity and carbon fluxes of tropical savannas. *Journal of Biogeography*, *33*(3), 387–400. https://doi.org/10.1111/j.1365-2699.2005.01448.x

Guidotti, V., Freitas, F. L. M., Sparovek, G., Pinto, L. F. G., Hamamura, C., Carvalho, T., & Cerignoni, F. (2017). Números detalhados do Novo Código Florestal e suas implicações para os PRAs. *Sustentabilidade Em Debate*, *5*, 1–10. https://doi.org/10.13140/RG.2.2.23229.87526

Hofmann, G. S., Cardoso, M. F., Alves, R. J., Weber, E. J., Barbosa, A. A., Toledo, P. M., Pontual, F. B., Salles, L. O., Hasenack, H., Cordeiro, J. L. P., Aquino, F. E., & Oliveira, L. F. B. (2021). The Brazilian Cerrado is becoming hotter and drier. *Global Change Biology*, *27*(17), 4060–4073. https://doi.org/10.1111/gcb.15712

Huffman, G. J., Stocker, E. F., Bolvin, D. T., Nelkin, E. J., & Tan, J. (2019). *GPM IMERG final precipitation L3 1 month 0.1 degree x 0.1 degree V06 (no. 6)*. Goddard Earth Sciences Data and Information Services Center (GES DISC). https://doi.org/10.5067/GPM/IMERG/3B-MONTH/06

Intergovernmental Panel on Climate Change. (2018). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. Y. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change* (pp. 3–24). https://www.ipcc.ch/sr15/

Joly, C. A., Scarano, F. R., Seixas, C. S., Metzger, J. P., Ometto, J. P., Bustamante, M. M. C., Padgurschi, M. C. G., Pires, A. P. F., Castro, P. F. D., Gadda, T., Toledo, P., & Padgurschi, M. C. G. (2019). *1º Diagnóstico Brasileiro de Biodiversidade e Serviços Ecossistêmicos*. Editora Cubo. https://doi.org/10.4322/978-85-60064-88-5

Keys, P. W., Wang-Erlandsson, L., & Gordon, L. J. (2018). Megacity precipitationsheds reveal tele-connected water security challenges. *PLoS One*, *13*(3), e0194311. https://doi.org/10.1371/journal.pone.0194311

Klink, C. A., & Machado, R. B. (2005). Conservation of the Brazilian Cerrado. *Conservation Biology*, *19*(3), 707–713. https://doi.org/10.1111/j.1523-1739.2005.00702.x

Lahsen, M., Bustamante, M. M. C., & Dalla-Nora, E. L. (2016). Undervaluing and overexploiting the Brazilian Cerrado at our peril. *Environment: Science and Policy for Sustainable Development*, *58*(6), 4–15. https://doi.org/10.1080/00139157.2016.1229537

Lambers, H., de Britto Costa, P., Oliveira, R. S., & Silveira, F. A. O. (2020). Towards more sustainable cropping systems: Lessons from native Cerrado species. *Theoretical and Experimental Plant Physiology*, *32*(3), 175–194. https://doi.org/10.1007/s40626-020-00180-z

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(9), 3465–3472. https://doi.org/10.1073/pnas.1100480108

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications*, *12*(1), 2591. https://doi.org/10.1038/s41467-021-22840-7

Lima, J. E. F. W., & Silva, E. M. (2005). Estimativa da superficial do Cerrado brasileiro. In A. Scariot, J. C. Souza-Silva, & J. M. Felfili (Eds.), *Cerrado: Ecologia, Biodiversidade e Conservação* (1st ed., pp. 61–72). Ministério do Meio Ambiente. https://doi.org/10.1590/S0100-69162006000300003

Lima, J. E. F. W., & Silva, E. M. (2007). Estimativa da contribuição hídrica superficial do Cerrado para as grandes regiões hidrográficas brasileiras. *Simpósio Brasileiro de Recursos Hídricos*, *XVII*, 1–13.

Lima, M., Silva Junior, C. A., Rausch, L., Gibbs, H. K., & Johann, J. A. (2019). Demystifying sustainable soy in Brazil. *Land Use Policy*, *82*, 349–352. https://doi.org/10.1016/j.landusepol.2018.12.016

Loarie, S. R., Lobell, D. B., Asner, G. P., Mu, Q., & Field, C. B. (2011). Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Climate Change*, *1*(2), 105–109. https://doi.org/10.1038/nclimate1067

Machida, W. S., Gomes, L., Moser, P., Castro, I. B., Miranda, S. C., da Silva-Júnior, M. C., & Bustamante, M. M. C. (2021). Long term post-fire recovery of woody plants in savannas of central Brazil. *Forest Ecology and Management*, *493*, 119255. https://doi.org/10.1016/j.foreco.2021.119255

Maeda, E. E., Abera, T. A., Siljander, M., Aragão, L. E. O. C., Moura, Y. M., & Heiskanen, J. (2021). Large-scale commodity agriculture exacerbates the climatic impacts of Amazonian deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(7). https://doi.org/10.1073/pnas.2023787118

MapBiomas. (2020). *Collection 5.0 of the annual series of land use and land cover maps of Brazil*. Brazilian annual land use and land cover mapping project. http://mapbiomas.org

MapBiomas. (2021). *Collection 6.0 of the annual series of land use and land cover maps of Brazil*. Brazilian annual land use and land cover mapping project. http://mapbiomas.org

Marengo, J. A., Jimenez, J. C., Espinoza, J. C., Cunha, A. P., & Aragão, L. E. O. (2022). Increased climate pressure on the agricultural frontier in the Eastern Amazonia–Cerrado transition zone. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-021-04241-4

Meirelles, M. L., Franco, A. C., Farias, S. E. M., & Bracho, R. (2011). Evapotranspiration and plant-atmospheric coupling in a *Brachiaria brizantha* pasture in the Brazilian savannah region. *Grass and Forage Science*, *66*(2), 206–213. https://doi.org/10.1111/j.1365-2494.2010.00777.x

Ministry of Science, Technology, and Innovations. (2021). *Fourth national communication of Brazil to the United Nations framework Convention on Climate Change*. Ministry of Science, Technology and Innovations. https://unfccc.int/documents/267657

Miralles, D. G., de Jeu, R. A. M., Gash, J. H., Holmes, T. R. H., & Dolman, A. J. (2011). Magnitude and variability of land evaporation and its components at the global scale. *Hydrology and Earth System Sciences*, *15*(3), 967–981. https://doi.org/10.5194/hess-15-967-2011

Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., & Gascon, C. (2011). Global biodiversity conservation: The critical role of hotspots. In F. E. Zachos & J. C. Habel (Eds.), *Biodiversity hotspots: Distribution and protection of conservation priority areas* (1st ed., pp. 3–22). Springer.

Moraes, M. G., Carvalho, M. A. M., Franco, A. C., Pollock, C. J., & Figueiredo-Ribeiro, R. C. L. (2016). Fire and drought: Soluble carbohydrate storage and survival mechanisms in herbaceous plants from the Cerrado. *Bioscience*, *66*(2), 107–117. https://doi.org/10.1093/biosci/biv178

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853–858. https://doi.org/10.1038/35002501

National Institute for Space Research. (2022). *Programa de Monitoramento da Amazônia e Demais Biomas (PRODES)—Bioma Cerrado*. Instituto Nacional de Pesquisas Espaciais—Coordenação Geral de Observação da Terra. http://terrabrasilis.dpi.inpe.br/

Neves, D. M., Dexter, K. G., Pennington, R. T., Bueno, M. L., & Oliveira Filho, A. T. (2015). Environmental and historical controls of floristic composition across the South American Dry Diagonal. *Journal of Biogeography*, *42*(8), 1566–1576. https://doi.org/10.1111/jbi.12529

Nobre, C. A., Sellers, P. J., & Shukla, J. (1991). Amazonian deforestation and regional climate change. *Journal of Climate*, *4*(10), 957–988. https://doi.org/10.1175/1520-0442(1991)004<0957:ADARCC>2.0.CO;2

Nóbrega, R. L. B., Guzha, A. C., Torres, G. N., Kovacs, K., Lamparter, G., Amorim, R. S. S., Couto, E., & Gerold, G. (2017). Effects of conversion of native cerrado vegetation to pasture on soil hydro-physical properties, evapotranspiration and streamflow on the Amazonian agricultural frontier. *PLoS One*, *12*(6), e0179414. https://doi.org/10.1371/journal.pone.0179414

Oliveira, R. S., Bezerra, L., Davidson, E. A., Pinto, F., Klink, C. A., Nepstad, D. C., & Moreira, A. (2005). Deep root function in soil water dynamics in Cerrado savannas of central Brazil. *Functional Ecology*, *19*(4), 574–581. https://doi.org/10.1111/j.1365-2435.2005.01003.x

Organisation for Economic Co-operation and Development, & Food and Agriculture Organization. (2019). *OECD-FAO agricultural outlook 2019–2028*. OECD Publishing, Food and Agriculture Organization of the United Nations. https://doi.org/10.1787/agr_outlook-2019-en

Organisation for Economic Co-operation and Development, & Food and Agriculture Organization. (2021). *OECD-FAO agricultural outlook 2021–2030*. OECD Publishing. https://doi.org/10.1787/19428846-en

Pennington, R. T., Lehmann, C. E. R., & Rowland, L. M. (2018). Tropical savannas and dry forests. *Current Biology*, *28*(9), R541–R545. https://doi.org/10.1016/j.cub.2018.03.014

Pousa, R., Costa, M. H., Pimenta, F. M., Fontes, V. C., Brito, V. F. A., & Castro, M. (2019). Climate change and intense irrigation growth in Western Bahia, Brazil: The urgent need for hydroclimatic monitoring. *Water*, *11*(5), 933. https://doi.org/10.3390/w11050933

Rajão, R., Soares-Filho, B., Nunes, F., Börner, J., Machado, L., Assis, D., Oliveira, A., Pinto, L., Ribeiro, V., Rausch, L., Gibbs, H., & Figueira, D. (2020). The rotten apples of Brazil's agribusiness. *Science*, *369*(6501), 246–248. https://doi.org/10.1126/science.aba6646

Rankin, J. (2021, September 14). *Leaked EU anti-deforestation law omits fragile grasslands and wetlands*. The Guardian. https://www.theguardian.com/environment/2021/sep/14/leaked-eu-anti-deforestation-law-omits-fragile-grasslands-and-wetlands

Rattis, L., Brando, P. M., Macedo, M. N., Spera, S. A., Castanho, A. D. A., Marques, E. Q., Costa, N. Q., Silverio, D., & Coe, M. T. (2021). Climatic limit for agriculture in Brazil. *Nature Climate Change*, *11*(12), 1098–1104. https://doi.org/10.1038/s41558-021-01214-3

Raupp, P. P., Ferreira, M. C., Alves, M., Campos-Filho, E. M., Sartorelli, P. A. R., Consolaro, H. N., & Vieira, D. L. M. (2020). Direct seeding reduces the costs of tree planting for forest and savanna restoration. *Ecological Engineering*, *148*, 105788. https://doi.org/10.1016/j.ecoleng.2020.105788

Rausch, L. L., Gibbs, H. K., Schelly, I., Brandão, A., Morton, D. C., Filho, A. C., Strassburg, B., Walker, N., Noojipady, P., Barreto, P., & Meyer, D. (2019). Soy expansion in Brazil's Cerrado. *Conservation Letters*, *12*(6). https://doi.org/10.1111/conl.12671

Rezende, C. L., Scarano, F. R., Assad, E. D., Joly, C. A., Metzger, J. P., Strassburg, B. B. N., Tabarelli, M., Fonseca, G. A., & Mittermeier, R. A. (2018). From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. *Perspectives in Ecology and Conservation*, *16*(4), 208–214. https://doi.org/10.1016/j.pecon.2018.10.002

Ribeiro, J. F., & Walter, B. M. T. (1998). Fitofisionomias do bioma Cerrado. In S. M. Sano & S. P. Almeida (Eds.), *Cerrado: Ambiente e flora* (pp. 87–166). Embrapa Centro de Pesquisa Agropecuária dos Cerrados.

Rochedo, P. R. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A. F. P., Koberle, A., Davis, J. L., Rajão, R., & Rathmann, R. (2018). The threat of political bargaining to climate mitigation in Brazil. *Nature Climate Change*, *8*(8), 695–698. https://doi.org/10.1038/s41558-018-0213-y

Rother, D. C., Vidal, C. Y., Fagundes, I. C., Metran da Silva, M., Gandolfi, S., Rodrigues, R. R., Nave, A. G., Viani, R. A. G., & Brancalion, P. H. S. (2018). How legal-oriented restoration programs enhance landscape connectivity? Insights from the Brazilian Atlantic Forest. *Tropical Conservation Science*, *11*, 194008291878507. https://doi.org/10.1177/1940082918785076

Rudorff, B., Risso, J., Aguiar, D., Gonçalves, F., Salgado, M., Perrut, J., Oliveira, L., Virtuoso, M., Montibeller, B., Baldi, C., Rabaça, G., de Paula, H., Gerente, J., Almeida, M., Bernardo, R., Cúrcio, S., Lopes, V., & Chagas, V. (2015). Análise Geoespacial da Dinâmica das Culturas Anuais no Bioma Cerrado: 2000 a 2014. In *Agrosatélite*. Agrosatélite Geotecnologia Aplicada Ltda. https://agrosatelite.com.br/cases#cases

Ruhoff, A. L., Paz, A. R., Aragao, L. E. O. C., Mu, Q., Malhi, Y., Collischonn, W., Rocha, H. R., & Running, S. W. (2013). Assessment of the MODIS global evapotranspiration algorithm using eddy covariance measurements and hydrological modelling in the Rio Grande basin. *Hydrological Sciences Journal*, *58*(8), 1658–1676. https://doi.org/10.1080/02626667.2013.837578

Running, S., Mu, Q., & Zhao, M. (2017). *MOD16A2 MODIS/terra net evapotranspiration 8-day L4 global 500 m SIN grid V006 (no. 006)*. NASA EOSDIS land processes DAAC. https://doi.org/10.5067/MODIS/MOD16A2.006

Russo, G., Alencar, A., Ribeiro, V., Amorim, C., Shimbo, J., Lenti, F., & Castro, I. (2018). *Cerrado: The Brazilian savanna's contribution to GHG emissions and to climate solutions* (Issue December). Instituto de Pesquisa Ambiental da Amazônia (IPAM). https://ipam.org.br/wp-content/uploads/2018/12/Policy-Brief-Cerrado-COP24-en-1.pdf

Salazar, A., Baldi, G., Hirota, M., Syktus, J., & McAlpine, C. (2015). Land use and land cover change impacts on the regional climate of non-Amazonian South America: A review. *Global and Planetary Change*, *128*, 103–119. https://doi.org/10.1016/j.gloplacha.2015.02.009

Sano, E. E., Rodrigues, A. A., Martins, E. S., Bettiol, G. M., Bustamante, M. M. C., Bezerra, A. S., Couto, A. F., Vasconcelos, V., Schüler, J., & Bolfe, E. L. (2019). Cerrado ecoregions: A spatial framework to assess and prioritize Brazilian savanna environmental diversity for conservation. *Journal of Environmental Management*, *232*, 818–828. https://doi.org/10.1016/j.jenvman.2018.11.108

Santos, A. B., Costa, M. H., Mantovani, E. C., Boninsenha, I., & Castro, M. (2020). A remote sensing diagnosis of water use and water stress in a region with intense irrigation growth in Brazil. *Remote Sensing*, *12*(22), 3725. https://doi.org/10.3390/rs12223725

Santos, A. J. B., Quesada, C. A., Silva, G. T., Maia, J. F., Miranda, H. S., Miranda, A. C., & Lloyd, J. (2004). High rates of net ecosystem carbon assimilation by *Brachiara* pasture in the Brazilian Cerrado. *Global Change Biology*, *10*(5), 877–885. https://doi.org/10.1111/j.1529-8817.2003.00777.x

Schmidt, I. B., Ferreira, M. C., Sampaio, A. B., Walter, B. M. T., Vieira, D. L. M., & Holl, K. D. (2019). Tailoring restoration interventions to the grassland-savanna-forest complex in central Brazil. *Restoration Ecology*, *27*(5), 942–948. https://doi.org/10.1111/rec.12981

Silva, F. A. M., Assad, E. D., & Evangelista, B. A. (2008). Caracterização Climática do Bioma Cerrado. In S. M. Sano, S. P. Almeida, & J. F. Ribeiro (Eds.), *Cerrado: Ecologia e Flora* (pp. 70–88). Embrapa Informação Tecnológica.

Silva Junior, C. A., Teodoro, P. E., Delgado, R. C., Teodoro, L. P. R., Lima, M., Pantaleão, A. A., Baio, F. H. R., Azevedo, G. B., Azevedo, G. T. O. S., Capristo-Silva, G. F., Arvor, D., & Facco, C. U. (2020). Persistent fire foci in all biomes undermine the Paris Agreement in Brazil. *Scientific Reports*, *10*(1), 16246. https://doi.org/10.1038/s41598-020-72571-w

Silvério, D., Brando, P. M., Macedo, M. N., Beck, P. S. A., Bustamante, M., & Coe, M. T. (2015). Agricultural expansion dominates climate changes in southeastern Amazonia: The overlooked non-GHG forcing. *Environmental Research Letters*, *10*(10), 104015. https://doi.org/10.1088/1748-9326/10/10/104015

Soares-Filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., & Alencar, A. (2014). Cracking Brazil's forest code. *Science*, *344*(April), 363–364. https://doi.org/10.1126/science.124663

Soares-Filho, B., Rajão, R., Merry, F., Rodrigues, H., Davis, J., Lima, L., Macedo, M., Coe, M., Carneiro, A., & Santiago, L. (2016). Brazil's market for trading forest certificates. *PLoS One*, *11*(4), e0152311. https://doi.org/10.1371/journal.pone.0152311

Soares-Filho, B. S., Cerqueira, G. C., & Pennachin, C. L. (2002). Dinamica—A stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecological Modelling*, *154*(3), 217–235. https://doi.org/10.1016/S0304-3800(02)00059-5

Solbrig, O. T. (1996). The diversity of the savanna ecosystem. In O. T. Solbrig, E. Medina, & J. F. Silva (Eds.), *Biodiversity and savana ecosystem processes: A global perspective* (Vol. *121*). Springer. https://doi.org/10.1007/978-3-642-78969-4

Souza, A. A., Galvão, L. S., Korting, T. S., & Prieto, J. D. (2020). Dynamics of savanna clearing and land degradation in the newest agricultural frontier in Brazil. *GIScience & Remote Sensing*, *57*(7), 965–984. https://doi.org/10.1080/15481603.2020.1835080

Souza, C. M., Shimbo, J. Z., Rosa, M. R., Parente, L. L., Alencar, A. A., Rudorff, B. F. T., Hasenack, H., Matsumoto, M., Ferreira, L. G., Souza-Filho, P. W. M., Oliveira, S. W., Rocha, W. F., Fonseca, A., Marques, C. B., Diniz, C. G., Costa, D., Monteiro, D., Rosa, E. R., Vélez-Martin, E., … Azevedo, T. (2020). Reconstructing three decades of land use and land cover changes in Brazilian biomes with landsat archive and earth engine. *Remote Sensing*, *12*(17), 2735. https://doi.org/10.3390/rs12172735

Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., & Mustard, J. F. (2016). Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology*, *22*(10), 3405–3413. https://doi.org/10.1111/gcb.13298

Spera, S. A., Winter, J. M., & Partridge, T. F. (2020). Brazilian maize yields negatively affected by climate after land clearing. *Nature Sustainability*, *3*(10), 845–852. https://doi.org/10.1038/s41893-020-0560-3

Spracklen, D., Arnold, S. R., & Taylor, C. M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, *489*(7415), 282–285. https://doi.org/10.1038/nature11390

Strassburg, B. B. N., Brooks, T., Feltran-Barbieri, R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A. E., Oliveira Filho, F. J. B., Scaramuzza, C. A. M., Scarano, F. R., Soares-Filho, B., & Balmford, A. (2017). Moment of truth for the Cerrado hotspot. *Nature Ecology & Evolution*, *1*(4), 0099. https://doi.org/10.1038/s41559-017-0099

Strassburg, B. B. N., Latawiec, A. E., Barioni, L. G., Nobre, C. A., Silva, V. P., Valentim, J. F., Vianna, M., & Assad, E. D. (2014). When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, *28*, 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001

Trase. (2021). *Transparency for sustainable trade*. Stockholm Environment Institute. www.trase.earth

Vieira, R. R. S., Ribeiro, B. R., Resende, F. M., Brum, F. T., Machado, N., Sales, L. P., Macedo, L., Soares-Filho, B., & Loyola, R. (2018). Compliance to Brazil's forest code will not protect biodiversity and ecosystem services. *Diversity and Distributions*, *24*(4), 434–438. https://doi.org/10.1111/ddi.12700

Wan, Z., Hook, S., & Hulley, G. (2015). *MOD11A2 MODIS/terra land surface temperature/emissivity 8-day L3 global 1 km SIN grid V006 (no. 006)*. NASA EOSDIS land processes DAAC. https://doi.org/10.5067/MODIS/MOD11A2.006

Winckler, J., Reick, C. H., Luyssaert, S., Cescatti, A., Stoy, P. C., Lejeune, Q., Raddatz, T., Chlond, A., Heidkamp, M., & Pongratz, J. (2019). Different response of surface temperature and air temperature to deforestation in climate models. *Earth System Dynamics*, *10*(3), 473–484. https://doi.org/10.5194/esd-10-473-2019

Zalles, V., Hansen, M. C., Potapov, P., Stehman, S., Tyukavina, A., Pickens, A., Song, X.-P., Adusei, B., Okpa, C., Aguilar, R., John, N., & Chavez, S. (2019). Near doubling of Brazil's intensive row crop area since 2000. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(2), 428–435. https://doi.org/10.1073/pnas.1810301115

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Rodrigues, A. A., Macedo, M. N., Silvério, D. V., Maracahipes, L., Coe, M. T., Brando, P. M., Shimbo, J. Z., Rajão, R., Soares-Filho, B., & Bustamante, M. M. C. (2022). Cerrado deforestation threatens regional climate and water availability for agriculture and ecosystems. *Global Change Biology*, *00*, 1–16. https://doi.org/10.1111/gcb.16386