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Carina Barbosa Colman

STRATEGIES FOR A SUSTAINABLE LAND USE IN THE BRAZILIAN CERRADO

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Tese apresentada para obtenção do grau de Doutor no Programa de Pós-Graduação em Tecnologias Ambientais da Fundação Universidade Federal de Mato Grosso do Sul, área de concentração: *Saneamento Ambiental e Recursos Hídricos*.

Orientador: Prof. Dr. Paulo Tarso Sanches de Oliveira

Aprovada em: 21/02/2022

Banca Examinadora

Dr. Paulo Tarso Sanches de Oliveira
Presidente

Prof. Dr. Divino Vicente Silvério
UFRA

Prof. Dr. Fabio de Oliveira Roque
INBIO/UFMS

Prof. Dr. Jamil Alexandre Ayach Anache
FAENG/UFMS

Prof. Dr. José Marcato Junior
FAENG/UFMS

Campo Grande, MS
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DEDICATÓRIA

A Jesus Cristo, Senhor das nossas vidas e
ao amor da minha vida, Isaack.

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ABSTRACT

Colman, C. B. (2021). **Strategies for a sustainable land use in the Brazilian Cerrado.** Doctoral Thesis, Faculty of Engineering, Architecture and Urbanism, and Geography, Federal University of Mato Grosso do Sul, Campo Grande, MS. Brazil.

Land use and land cover changes have intensified in the Brazilian Cerrado in the last years. However, the directions of the loss of native vegetation, conservation strategies and the advance of agricultural frontiers are yet poorly investigated. The objective of this thesis is to provide a guidance for the use of the soil, aiming at a sustainable and efficient use in the biome that grows the most in agricultural production in the country. The evaluation of vegetation loss drivers showed that the distance to rivers, roads and cities, agricultural potential, permanent and annual agriculture and cattle raising lead to greater loss of native vegetation, while protected areas prevent this loss. It was found that the native vegetation loss model is capable of reproducing vegetation loss in the medium and long term. Furthermore, we have seen that vegetation losses occur mainly within large properties. Through the projection of production and conservation scenarios, it was found that the creation of protected areas protects native vegetation more than the increase in the legal reserve and that the elimination of the legal reserve would cause greater loss of vegetation than eliminating the areas protected. It was concluded that private properties are essential for efficient planning of land use and cover. The results of this doctoral thesis are important to guide the study of sustainable use and occupation of the Cerrado biome and help decision makers in territorial planning on how to arbitrate territorial demands aiming at the rational use of natural resources in the Cerrado.

Keywords: native vegetation, conservation, legal reserve, protection area, land use and land cover changes, scenarios, nexus, water erosion, agricultural expansion.

RESUMO

Colman, C. B. (2021). **Estratégias para um uso da terra sustentável no Cerrado brasileiro.** Tese de Doutorado, Faculdade de Engenharias, Arquitetura e Urbanismo, e Geografia, Universidade Federal de Mato Grosso do Sul, Campo Grande, MS. Brasil.

As mudanças do uso e cobertura do solo têm se intensificado no Cerrado brasileiro. Os rumos da perda de vegetação nativa, as estratégias de conservação e o avanço das fronteiras agrícolas são pouco conhecidos e devem ser investigados. É fundamental compreender a dinâmica do uso e cobertura do solo diante o aumento da demanda global por alimentos e a necessidade de conservação dos serviços ecossistêmicos. O objetivo desta tese é fornecer melhor orientação para o uso do solo, visando um uso sustentável e eficiente no bioma que mais cresce em produção agrícola no país. A avaliação dos *drivers* de perda de vegetação mostrou que a distância a rios, estradas e cidades, potencial agrícola, agricultura permanente e anual e pecuária levam à maiores perdas de vegetação nativa, enquanto áreas protegidas evitam essa perda. Verificou-se que o modelo de perda de vegetação nativa é capaz de reproduzir perdas de vegetação a médio e longo prazo. Além disso, vimos que as perdas de vegetação ocorrem, principalmente, dentro de grandes propriedades. Através da projeção de cenários de produção e conservação, verificou-se que a criação de áreas protegidas, protege mais a vegetação nativa do que o aumento da reserva legal e que a eliminação da reserva legal causaria maior perda de vegetação do que a eliminação das áreas protegidas. Concluiu-se que as propriedades privadas são essenciais para o planejamento eficiente do uso e cobertura do solo. Os resultados desta tese de doutorado são importantes para orientar o estudo de uso e ocupação sustentável do bioma Cerrado, criação de novos produtos e, auxiliar os tomadores de decisão no planejamento territorial em como arbitrar as demandas territoriais visando o uso racional dos recursos naturais do Cerrado.

Palavras-chave: vegetação nativa, conservação, reserva legal, área de proteção, mudanças de uso e cobertura do solo, cenários, nexus, erosão hídrica, expansão agrícola.

SUMÁRIO

LISTA DE FIGURAS

LISTA DE TABELAS

ORGANIZATION OF THESIS

The Thesis is organized into **two** chapters. We start with a **General Introduction** gives *Background and Problem Statement* and the *Specific Objectives* of this research. **Chapter 1** evaluates the factors that influence the loss of native vegetation and projects the loss of native vegetation for the years 2050 and 2070, while **Chapter 2,** we designed scenarios on production and conservation, and we assess whether private properties protect Cerrado's native vegetation.

To date I have published the work relative to the **Chapter 2** of this thesis on internationally peer-reviewed scientific journal. **Chapter 2** of this thesis has been published as Colman, C.B., Guerra, A., Roque, F.O., Rosa, I.M.D., Oliveira, P.T.S. Identifying priority regions and territorial planning strategies for conserving native vegetation in the Cerrado (Brazil) under different scenarios of land use changes, Science of The Total Environment, 807, https://doi.org/10.1016/j.scitotenv.2021.150998. (Impact factor 2021: 9.963). **Chapter 1** is an article non-peer-reviewed preprint that has been submitted to Land Use Policy. For the work done in these Chapters, I was responsible for data collection and analysis as well as the manuscript composition.

GENERAL INTRODUCTION

1. Background and problem statement

The Brazilian Cerrado is considered the largest arable area in the world (EMBRAPA, 2021). In this biome are the Brazilian states that produced and exported the most grains in 2021, and new production records are expected for the year 2022 (IBGE, 2022; LSPA, 2022). This is mainly because of its favorable topographic conditions (flat and smooth undulating relief), soils suitable for agricultural mechanization and application of the technologies (Althoff and Rodrigues, 2019; Klink and Machado, 2005; Lapola et al., 2014). At the same time, the Cerrado has little more of its native vegetation (54%) and becomes a major attraction for caretakers of the environment (MapBiomas, 2020; Polizel et al., 2021; Rajão et al., 2020; Rattis et al., 2021). Simulating the trajectory and changes of land use is essential to guide future uses and conserve the environment (de Barros Ferraz et al., 2005; Guerra et al., 2020; Merten and Minella, 2013). In addition, knowing where native vegetation is concentrated, such as on public or private property, is essential to establish conservation and recovery strategies for protected areas (Azevedo et al., 2017; Stefanes et al., 2018). One of the main features for simulating the spatial dynamics of land use and land cover is through computer models (Rosa et al., 2013; Soares-Filho et al., 2016). Modeling techniques allow the assessment of land cover and land use changes in various scenarios. For example, scenarios that maintain the general rate of deforestation as it is today (business as usual) or scenarios that assume the implementation of additional government measures (Lapola et al., 2011; Soares-Filho et al., 2006).

Simulations of land use and land cover change have already been carried out in other biomes such as the Amazon and the Pantanal (Guerra et al., 2020; Rosa et al., 2013). Although there are studies that address the trajectory of use and coverage, or showed the importance of legal strategies for the conservation of native vegetation (Azevedo et al., 2017; Bergier, 2013; Pacheco et al., 2021; Soares-Filho et al., 2014), no study has investigated land use change trajectories in the Cerrado biome, and none has evaluated variables that explain the loss of native vegetation at the property scale. This type of modeling would allow us to build a spatial distribution, designed for territorial occupation studies. In a later stage of the assessment of the trajectory of change in land use and occupation, we can consider projections based on environmental legislation to investigate the expected trajectories of native vegetation for production and conservation scenarios.

Tools to support territorial planning, such as the Dinamica EGO model (Soares-Filho et al., 2013), simulate the patterns of change in the landscape in response to coupled human-ecological dynamics. In addition, software such as Qgis and Argis and advanced cellular automata model techniques support simulations of rural and urban areas (dos Santos et al., 2021; Okwuashi and Ndehedehe, 2021), and tools such as the annual mapping project of land use and land cover in Brazil (MapBiomas). The spatially-explicit model of deforestation that predicts the potential magnitude and spatial pattern of Amazon deforestation can also be applied to other biomes. This model developed by Rosa et al. (2013) it is probabilistic and quantifies uncertainty around predictions and parameters, shows the overall deforestation rate emerges “bottom up”, as the sum of local-scale deforestation driven by local processes, and that the deforestation is contagious, such that local deforestation rate increases through time if adjacent locations are deforested (Rosa et al., 2013). The first step of the modeling procedure is to identify the main drivers of deforestation in the Brazilian Cerrado. Some variables, although fundamental, were not considered in this model, such as: fire levels, climate changes, changes in legislation, construction of small hydroelectric plants.

In the Cerrado, there is a gap in studies that seek to project the trajectory of land use change, the behavior of land use, taking into account environmental legislation, especially because it takes time and space to store databases and simulate the projections. Due to the importance of one of the largest agricultural frontiers in Brazil and the world for water-food-energy security, an investigation of this biome is necessary. Within this context, we seek a better understanding of the dynamics of native vegetation in the Brazilian Cerrado, answering the following questions: what are the main causes of the loss of native vegetation in the Cerrado? How will the loss of native vegetation happen in the medium and long term? How does this loss happen at the ownership scale? Do Legal Reserves and Protected Areas also protect native Cerrado vegetation? Are private properties relevant to the protection of native vegetation?

2. Objectives

2.1 General objective

The main objective of this study is to evaluate the dynamics of native vegetation loss in the Brazilian Cerrado.

2.2 Specific objectives

i. To determine how the loss of native vegetation will happen in the medium and long term.
ii. To evaluate the effects of legal reserves and protected areas on the protection of native vegetation in the Brazilian Cerrado.

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CHAPTER 1

SIMULATING LAND USE CHANGE TRAJECTORIES OF THE CERRADO HOTSPOT REVEALS THE IMPORTANCE OF CONSIDERING PRIVATE PROPERTY SIZES FOR BIODIVERSITY CONSERVATION

Colman, C.B., Guerra, A., Roque, F.O., Rosa, I.M.D., Oliveira, P.T.S. Simulating land use change trajectories of the Cerrado Hotspot reveals the importance of considering private property sizes for biodiversity conservation, under Review in Land Use Policy, https://doi.org/10.31223/X5KP6V. (Impact factor 2021: 5.398)

Abstract

Simulating future land use changes can be an important tool to support decision-making, especially in areas that are experiencing rapid anthropogenic pressure, such as the Cerrado – Brazilian savanna. Here we used a spatially-explicit model to identify the main drivers of native vegetation loss in the Cerrado, and then projected this loss for 2050 and 2070. We also analyzed the role of property size in complex Brazilian environmental laws in determining different outcomes of these projections. Our results show that distance to rivers, roads and cities, agricultural potential, permanent and annual crop agriculture and cattle led to observed/historical loss of vegetation, while protected areas prevented such loss. Assuming full adoption of the current Forest Code, the Cerrado may lose 26.5 million ha (± 11.8 95% C.I.) of native vegetation by 2050 and 30.6 million ha (± 12.8 95% C.I.) by 2070, and this loss will occur mainly within large properties. In terms of reconciling conservation and agricultural production, we recommend that public policies focus primarily on large farms, such as protecting 30% of the area of properties larger than 2500 ha, which would avoid a loss of more than 4.1 million hectares of native vegetation, corresponding to 13% of the predicted loss by 2070.

Keywords: agrarian structure, agriculture, environmental law, farms, vegetation loss.

1. Introduction

Simulating land use change trajectories considering different legal scenarios has been a powerful approach to decision making (Brandão-Jr. et al. 2020), because it enables us to evaluate the costs and benefits of certain decisions (Sano et al. 2019). This is particularly relevant for regions that are undergoing rapid changes such as the biodiversity hotspots on the planet (Lambin and Meyfroidt 2011).

The Cerrado hotspot is the largest and most threatened tropical savanna in the world (Silva and Bates 2002) and has only 52% of native vegetation (Projeto MapBiomas 2019). Currently, the rate of deforestation in the Cerrado is higher than in the Brazilian Amazon (Brandão-Jr. et al. 2020), and the expansion of agriculture over the last 30 years was the main driver of these changes (Lapola et al. 2014). As Brazil is one of the largest producers and exporters of grains and meat (FAO 2010), the Cerrado has become one of the main agricultural areas in the world (Rausch et al. 2019). This is mainly because of its favorable topographic conditions (flat and smooth undulating relief), soils suitable for agricultural mechanization and low land prices (Klink and Machado 2005; Lapola et al. 2014).

In addition to being an important ecological and agricultural region for Brazil, the Cerrado is crucial for the country's water resource dynamics, as it comprises part of 10 out of the 12 major Brazilian hydrographic regions (Oliveira et al. 2014). Furthermore, the Cerrado provides important ecosystem services such as food and water provision, carbon storage, nutrient cycling and leisure and tourism services, which require high environmental costs for maintenance, owing to fragmentation, biodiversity loss, invasive species, soil erosion and degradation, water pollution and soil degradation (Klink and Machado 2005). Despite its importance, the Cerrado has only about 7% of formally protected areas (2.8% of Conservation Units and 4.3% of Indigenous Lands) compared to 24% in the Amazon (Ribeiro et al. 2016). About 90% of the biome is privately owned, where a large part of its remaining vegetation is concentrated (Soares-Filho et al. 2014). The size of properties is a proxy for financial and managerial success, for access to information and for compliance with environmental laws and, although some studies have already demonstrated this (Michalski et al. 2010; Godar et al. 2014; Stefanes et al. 2018), no study has been carried out simulating scenarios explicitly integrating the role of property size in determining future land use changes for the entire territory of the Cerrado.

The Cerrado is the Brazilian biome with the largest Legal Reserve deficit (minimum percentage of native vegetation required within private properties) and has around 4.2 million ha of native vegetation that needs to be recovered (Guidotti et al. 2017). Furthermore, 40% its native vegetation can be legally converted (Soares Filho et al. 2014). Following the current rate of loss, the ecosystem could disappear by 2030, according to estimates from Conservation International (Machado et al. 2004). Soares Filho et al. (2014) showed that by 2050 the Cerrado may lose 40.3 million ha of native vegetation, leaving only 32% of native vegetation. This massive conversion of land use could result in the extinction of about 1140 endemic species by 2050 (Strassburg et al. 2017).

These studies show the importance of assessing land cover and land use change (LCLUC) under multiple scenarios. There are studies that evaluate future land use scenarios for the Cerrado (Câmara et al. 2015; Sorretoni et al. 2018; 2019), however, to the best of our knowledge, there are no studies on scenarios of LCLUC that simultaneously aim to (1) understand which variables influence vegetation loss in the Cerrado and whether they change between periods, evaluating (2) which areas are most affected and how much will be lost at a property scale (the management unit of the Legal Reserve policy). The importance of the Cerrado for both biodiversity and the national economy has led to disagreement among decision makers, and scientific knowledge is essential to bring a balance to economic development and environmental conservation (Lemes et al. 2019). Model based scenarios can be a useful tool in providing information to the decision making of public and private power (Ferrier et al. 2016) and in reconciling agricultural production and conservation of the Cerrado. Here we used a spatially-explicit model to: i) identify the most important drivers of native vegetation loss in the Cerrado; and ii) generate projections of native vegetation loss for 2050 and 2070, considering the trend of recent years and assuming full implementation of the Native Vegetation Protection Law (NVPL), and considering the implications of simulations on the property scale.

2. Methods

2.1 Study Area

The Cerrado, also known as the Brazilian Savanna, covers an area of 2 million km2 of Brazilian territory (about 24% of the total area), including the Distrito Federal and part of ten states (Fig. 1). The biome has been classified as one of the 25 global biodiversity hotspots (Myers et al. 2000) and it is one of the most important biomes in Brazil, surrounded by four other biomes: The Amazon, Caatinga, Pantanal and Atlantic Forest.

According to the Köppen climate classification system (Peel et al. 2007), the predominant climate groups of the Cerrado are: Aw - equatorial, dry winter (83% of the Cerrado); Cwb - dry winter, warm temperate, hot summer (8% of the Cerrado); Cfa - humid, hot temperate, hot summer (5% of the Cerrado); Cwa - dry winter, warm temperate, hot summer (4% of the Cerrado). The average annual rainfall of the Cerrado is approximately 1500 mm, with lower values (close to 700 mm) in the Northeast region, in the transition zone between the Cerrado and Caatinga biomes. The highest average annual precipitation (greater than 2000 mm) is in the Northwest, in the transition area between the Cerrado and the Amazon Forest. The rainy season is from October to March, and the dry season is from April to September (Oliveira et al. 2014).

The predominant soil types, classified according to the FAO Soil Classification (FAO 2014) are: Ferralsols (~41%), Arenosols (~23%), Acrisols (~12%) and Plinthosols (~10%). In general, they are weather resistant and very acidic soils, with little organic matter and nutrients, especially nitrogen and phosphorus (Klink and Machado 2005). The most common anthropogenic use is pasture (~30%), mainly for producing meat and agriculture (~9%) with the predominance of annual crops of soybean (90%), cotton (7%) and corn (3%) (Rudorff et al. 2015). The recent expansion of agricultural production occupies approximately 50% (~1 million km^2) of the Cerrado area and in recent years the expansion has occurred mainly towards the northern and more preserved region of the biome, known as MATOPIBA (states of Maranhão, Tocantins, Piauí and Bahia) (Zu Ermgassen et al. 2020).

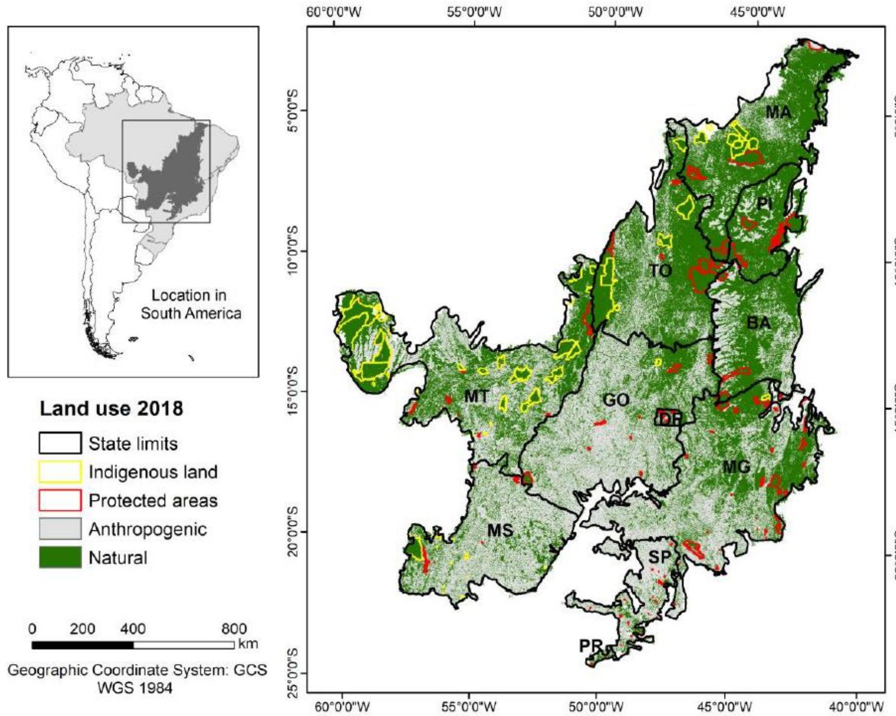

Fig 1. Study area. States included in the Cerrado hotspot: Bahia (BA), Maranhão (MA), Tocantins (TO), Piauí (PI), Mato Grosso do Sul (MS), Mato Grosso (MT), Goiás (GO), Distrito Federal (DF), Minas Gerais (MG), São Paulo (SP), and Paraná (PR). The areas highlighted in yellow are indigenous land and the areas highlighted in red are protected areas.

2.2 Land-cover change model

To identify the variables (or drivers) that mainly cause vegetation loss in the Cerrado, we used a spatially-explicit model (Rosa et al. 2013; 2015; Guerra et al. 2020). This model has already been successfully applied and validated in other Brazilian biomes (Rosa et al. 2013; Guerra et al. 2020) and it predicts the loss of vegetation at the scale of properties taking into account different legal requirements. This model is purely data-driven and based on the probability that a cell will be converted from native vegetation for anthropogenic use over time (for more details, see Rosa et al. 2013; Guerra et al. 2020). This probability is determined as a function of the multiple drivers that can lead to such change (see Appendix for more details). The process is divided into two steps: the first that identifies the variables that predict vegetation loss, and their effect (direction and magnitude), and the second that projects the loss over time.

The variables included in the model were identified as possible predictors of Cerrado vegetation loss based on a literature review (Table A1). We used the rural properties of the "Cadastro Ambiental Rural" (CAR; Rural Environmental Registry), and the Legal Reserve (LR) values as a scale for calculating the loss of vegetation according to the Native Vegetation Protection Law - NVPL (Brazil, # 12,651, of 2012), which establishes 20% of the legal reserve for Cerrado areas and 35, 50 and 80% for the Legal Amazon (see Soares-Filho et al. 2014; Brancalion et al. 2016).

There were two types of variables, namely statistic variables that do not vary within a short period of time (e.g. distance to roads, cities and rivers, protected areas, dry season length, elevation, agricultural potential and property size) (Fig. A1) and dynamic variables which are those that vary over time (e.g. cattle, permanent and annual crop agriculture) (Fig. A2). All data were converted to the same resolution (1 km x 1 km) and projected onto the same geographic projection (WGS 1984 UTM).

We then calibrated the model for four time periods (2008-2010, 2010-2012, 2012-2014 and 2014-2016) attributed to different rates of vegetation loss (Fig. A3), thus leading to potential differences in projected rates (that can be derived from the model). After that, we performed a model ensemble by averaging the projections from the four periods, obtaining the rate of vegetation loss every two years from 2016 to 2070. To assess the goodness-of-fit of the models, we computed the area under the receiver operating characteristic (or AUC) values for each period of each analyzed area (Table A2).

2.3 Properties

We used the January 2020 CAR database, which had 892,127 properties registered from the Cerrado, of which 83% of registered properties are considered small, 12% are medium and 5% are large properties. The area of large properties covers 56% of the Cerrado area (CAR 2020). To assess how much vegetation will be lost in small, medium and large properties we used the classification by Michalski et al. (2010) that considers five classes: C1 ($1 \leq 150$ ha), C2 ($150 \leq 400$ ha), C3 ($400 \leq 1000$ ha), C4 ($1000 \leq 2500$ ha) and C5 (> 2500 ha). The classification is also adopted by Stefanes et al. (2018) in the Cerrado of Mato Grosso do Sul. We consider C1 as small properties, C2 and C3 as medium, and C4 and C5 as large properties.

3. Results

3.1 Drivers

The variables identified as important to explain the loss of vegetation in the Cerrado were different between the periods analyzed (2008-2010, 2010-2012, 2012-2014 and 2014-2016). Protected areas (including Indigenous lands) indicate a positive impact in all periods, showing a lower probability of native vegetation loss inside these areas. The distance to rivers explained the vegetation loss in three periods (2008-2010, 2010-2012, and 2012-2014), while distance to cities explained only two periods (2008-2010 and 2014-2016), and distance to roads only explained 2010-2012 (Table 1). In all periods analyzed, the greater distance from rivers led to greater loss of native vegetation while the opposite occurred for roads and cities.

Agriculture and cattle explained native vegetation loss in only one or two periods, whereby the agricultural potential influenced the vegetation loss in 2008-2010 and 2010-2012, and the annual crop agriculture influenced the loss in 2010-2012 and 2012-2014. Permanent agriculture and cattle explained the loss of vegetation in only one period (2012-2014). On the other hand, dry season length and elevation did not explain the loss of vegetation in the Cerrado in any of the periods observed (Table 1).

Table 1. Mean of the single variable models for Cerrado.

Variables	**2008-2010**	**2010-2012**	**2012-2014**	**2014-2016**
Land Cover	3.77	2.71	2.45	2.55
Distance to roads	0	-4E-06	0	0
Distance to cities	9E-06	0	0	-8E-06
Dry season length	0	0	0	0
Elevation	0	0	0	0
Agricultural Potential	2.25E-04	-5.8E-05	0	0
Distance to Rivers	7.8E-05	7.9E-05	3E-05	0
Cattle	0	0	1.64E-03	0
Permanent Agriculture	0	0	1E-06	0
Annual Crop Agriculture	0	2.2E-05	-8.1E-05	0
Protected Areas	-1.73	-1.38	-1.45	-1.08

3.2 Projections

According to our projections, the Cerrado may lose 26.1% (± 11.6% 95% C.I.) of the area of native vegetation according to the Legal Reserve limits (excluding the protected area and indigenous land) by 2050 and 30.2% (± 12.6% 95% C.I.) by 2070. This corresponds to 26.5 million ha (± 11.8 95% C.I.) loss of native vegetation by 2050 and 30.6 million ha (± 12.8 95% C.I.) by 2070. The conversion values of native vegetation varied between the periods analyzed, in which 2008-2010 showed the lowest loss and 2012-2014 the highest loss (Fig. A4).

The loss of vegetation in the Cerrado by 2070 will occur mainly in large properties (C4 and C5), adding up to more than 7 million hectares, especially in the MATOPIBA region (Fig. 2). For states that do not include MATOPIBA and Mato Grosso do Sul and Mato Grosso, vegetation loss will occur mainly in medium-sized properties (between 150 and 1000 ha - C2 and C3).

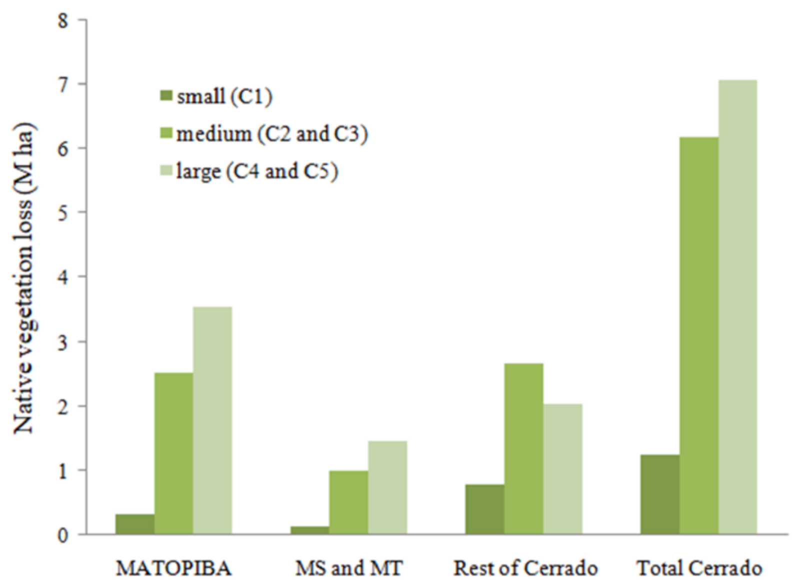

Fig 2. Native vegetation loss per property size in the Cerrado by 2070.

We spatialized the projected native vegetation losses in the Cerrado for 2050 and 2070 (Fig. 3 a,b). The states with the greatest expected vegetation loss by 2070 are Minas Gerais (22.0%), Tocantins (18.0%), Goiás (14.6%), Mato Grosso (10.6%) and Maranhão (10.4%) (Fig. 3b,d). We generated an animation showing the evolution of the probability of loss of vegetation from 2016 to 2070 (available at http://bit.ly/38u2zl2).

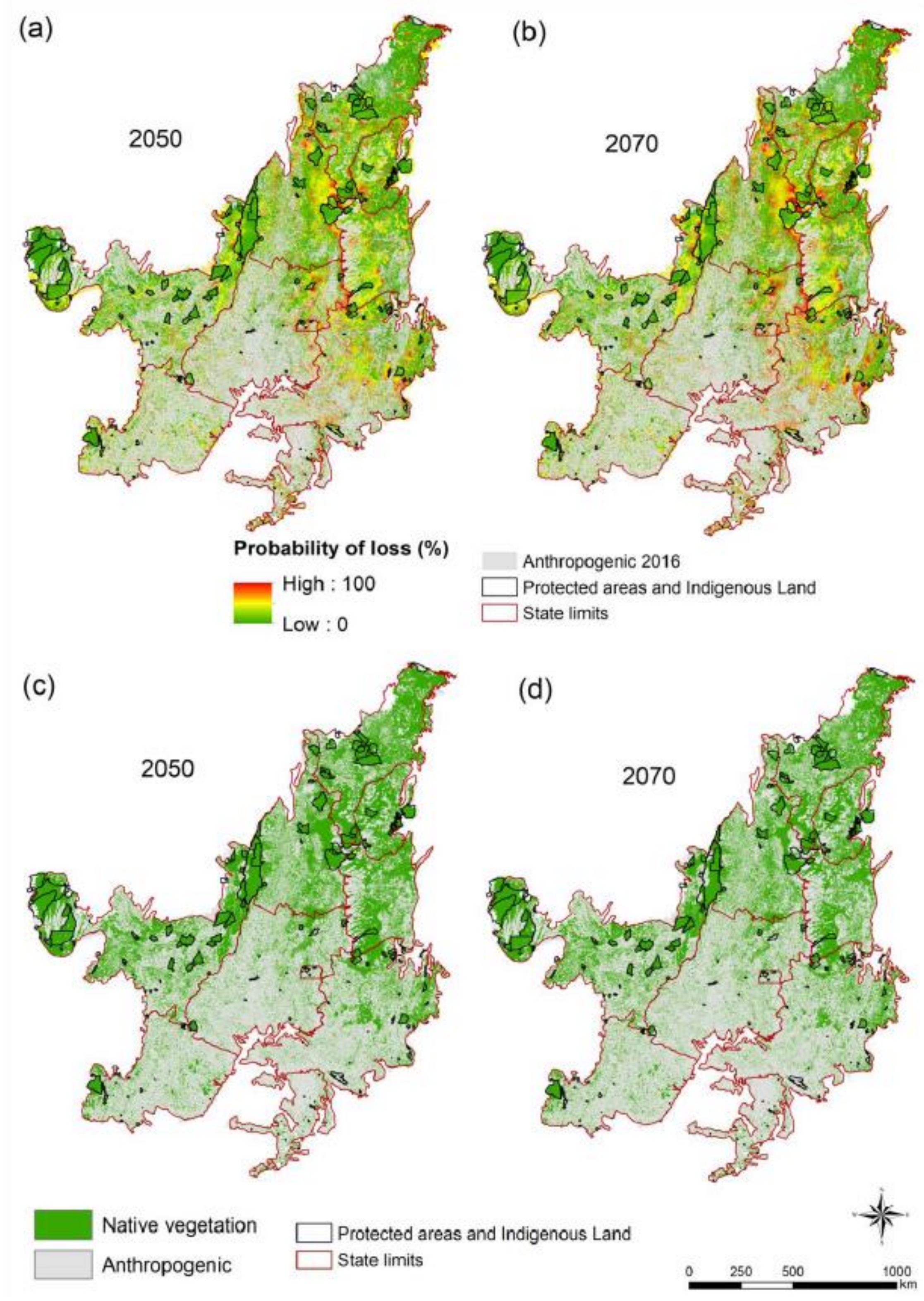

Fig 3. Projections of accumulated native vegetation loss by (a) 2050 and (b) 2070, and native vegetation remaining for (c) 2050 and (d) 2070 for the mean values of the four periods (2008–2010, 2010–2012, 2012–2014 and 2014–2016).

4. Discussion

Our study adds more evidence that under the existing environmental protection framework, the Cerrado hotspot will face rapid land use changes in the coming years if nothing is done to change the current trajectory (Machado et al. 2004; Soares-Filho et al. 2014; Strassburg et al. 2017; Brandão-Jr et al. 2020). Our spatial model enabled us to identify areas most likely to lose native vegetation. Moreover, we showed that considering the agrarian structure (the distribution of assets and rights linked to land among populations that live in rural areas or derive a significant income from rural activities (Albertus et al. 2019)), the size of the properties and their probability of land use change could be a very useful tool to support sustainable management plans.

The agrarian structure is very relevant to predict future trajectories of land use as many decisions are made at this level. In addition, the size of the property is a proxy for political influence. In the Cerrado, there is a predominance of small properties in terms of numbers and large properties in terms of area (these occupy more than 60% of the biome's area). Furthermore, large properties have a greater tendency to have greater coverage of native vegetation and comply with NVPL, although this relationship was found to be very weak, particularly so in the Cerrado of Mato Grosso do Sul (Stefanes et al. 2018). There are multiple reasons that can explain these patterns. Commodity and export markets are highlighted as they can be found in these large properties that seek to meet the minimum requirements determined by the NVPL. Large landowners receive more subsidies from government programs (Oliveira and Marques 2002), while smallholders tend to keep less native vegetation on their properties to compensate for the low profitability of their properties (Michalski et al. 2010). Moreover, this may be a result of the size of the area vs recent activity time.

Agriculture and livestock did not have the expected impact on the loss of native vegetation, as they explained the loss in only one or two periods. This may have occurred because agriculture and pasture areas were introduced in areas already deforested before the increase in technologies allowed greater productivity in areas already occupied. It has already been shown that in the Cerrado, part of these areas is under the Integration-Harvest-Livestock-Forest regime, where the expansion of agriculture occurs mainly in pasture areas (Grecchi et al. 2014). In this integration, the fields are used interchangeably for agriculture and livestock, but tree threads are also planted between the fields, where cattle can forage. This came about aiming to increase the intensity of land use and crop rotation and livestock in order to feed more people without cutting down the forest (Sone et al. 2019). Agriculture in the biome area still has plenty of room for growth without compromising areas that are still preserved. There are 50 million hectares of underutilized pasture areas, which could be used for agricultural production (Brandão-Jr. et al 2020).

The construction of large roads in the Cerrado began when the city of Brasilia was founded in 1956. Since then, many roads have been built linking the capital to other parts of the country, enabling the region to flourish economically. The impact of building these roads on native vegetation occurred over the following years. In 2009, Brazil invested 0.35% of its GDP (2.2 billion dollars) in highways (Martins et al. 2013) and this explains how the distance from the roads affected the loss of vegetation in the Cerrado in 2010-2012. Road construction also turned villages into cities, increasing the population of these areas, and consequently caused a loss of native vegetation. Recently, cities have tended to increase their area to accommodate the increase in population, but new cities are hardly ever founded.

On the other hand, the proximity of rivers prevented a loss of vegetation from 2008 to 2014, showing that the PPAs (Permanent Protection Area; range of native vegetation required by the NVPL around the water bodies) are an important legal instrument for protecting native vegetation. Therefore, protected areas and Indigenous Lands prevented the loss of vegetation in all periods analyzed. This is clear in Figs. 1 and 3, which show that in these areas there is a large amount of native vegetation surrounded by areas of anthropogenic use in areas without protection.

Although the duration of the dry season and the altitude present great spatial variation in the Cerrado, they do not explain the loss of vegetation in the analyzed periods. This shows that elevation and drought do not restrict the expansion of human activities such as agriculture. This is clear in the MATOPIBA region, as the agricultural frontier of the Cerrado that has a prolonged dry season, albeit still sustains (Oliveira et al. 2019). In addition, the creation of new technologies and selection of crop varieties also helped agriculture to expand in the areas of Cerrado that were previously not conducive (The Economist 2010).

4.1 Projections

Assuming full implementation of NVPL and continuing the socio-economic trends of the past, the native vegetation in the Cerrado may decrease from 52.0% to 38.7% in 2050 and only 36.6% in 2070. Our projections are not as drastic as those from Machado et al. (2004) but more in line with those by Soares Filho et al. (2014), although slightly higher, possibly due to the recent increase in conversion rates. Although we were able to analyze temporal variation in the drivers of change (covering a period of 12 years), the study does not capture the whole expansion process in the Cerrado that started in the 1950s. For this reason, some variables that seemed weak over the last 12 years may have been key in the past, such as roads and cities. For an overview of the process, it would be important to expand the analysis to the 1950s until now, which unfortunately is not possible due to the lack of data.

The decrease in native vegetation in the Cerrado can have serious consequences on ecosystem services, affecting biodiversity (Kennedy et al. 2016; Strassburg et al. 2017), water fluxes (Anache et al. 2019), soil erosion (Oliveira et al. 2015; Resende et al. 2019), water quality (Kennedy et al. 2016), carbon sequestration (Resende et al. 2019), and is important in evaluating how the projections of vegetation loss presented in this study can impact these services. In addition, our model is unable to consider or quantify (a) changes in policies, (b) trade like import, export or changing intra- and international consumer demand, (c) changes in human behaviour and technological innovation or even that the magnitude of effects of the estimated drivers remain constant in upcoming decades. We also highlight that other variables not included in the model, such as fire and climate change, changes in laws, changes in land ownership, construction of small hydroelectric can lead to even worse results (Monteiro et al. 2018, Velazco et al. 2019).

The areas with the highest probability of loss occur mainly in Minas Gerais, Goiás, Mato Grosso, and Maranhão. The first four states were part of a federal program in 1975 aiming to accelerate economic development through various types of financing, aimed at building roads, silos, warehouses and agricultural research. Currently, the region is responsible for about 60% of the country's grain production (Rose 2017). MG and GO present most of their area with a requirement of only 20% of legal reserve, although NVPL requires values of legal reserve of 35% and 80% for most of the area of the states of TO and MA. This region is located in MATOPIBA, which is known as the agricultural frontier of the Cerrado, mainly with soy expansion (Rausch et al. 2019, Brandão-Jr. et al. 2020). In addition, the native vegetation is concentrated in the northeastern region of the Cerrado, where large properties with the largest fragments of native vegetation that are susceptible to suppression are found. Therefore, legal instruments or economic incentives for conservation need to be created (e.g. payments for environmental services) for owners to avoid converting surplus native vegetation within consolidated farms, as well as promoting the recovery of environmental liabilities. In addition to the incentives, the expansion of the soy moratorium (a zero deforestation agreement between civil society, industry and the government that prohibits the purchase of soy grown on recently deforested land in the Brazilian Amazon) is a way out to prevent converting areas for purposes of agricultural expansion (Soterroni et al. 2019).

Our results show evidence that applying NVPL alone is not sufficient for the conservation of the Cerrado, as large areas especially within large properties can be deforested under the protection of the law. In this context, there is first a need for inspection so that properties that do not comply with NVPL offset their liabilities. For properties within the law, there is a need to develop actions beyond the existing policies. These policies should focus on keeping the LR rates well above the NVPL and preventing the conversion of natural vegetation. This can be done by paying for environmental services, increasing pasture productivity, as well as an incentive to drive expansion agricultural land for already converted land, and expanding Soy Moratorium (currently restricted to the Amazon) to other commodities such as sugarcane and beef in native pastures (Strassburg et al. 2017). In addition, incentives must be designed according to the different reality faced by small and large owners, making the actions more profitable and increasing the probability of success (Stefanes et al. 2018). Our study shows that these actions are urgent, especially in the MATOPIBA region, in the agricultural expansion area of the Cerrado and where there are the largest remnants of native vegetation. More than 70% of soy and about 20% of beef produced in the country are sold on the foreign market, therefore the cattle and soy export chains are fundamental in changing part of the trajectory. Controlling the export chain is a relatively important mechanism for large companies focused on the foreign market (Zu Ermgassen et al. 2020).

The future of human influence on landscapes is critical for the conservation of Biodiversity hotspots. Projections of future land uses, as shown here, are useful tools to visualize and stimulate change against unsustainable trajectories. Due to increasing and severe human-induced impacts, ideally all kinds of properties, including private and public ones, should be regarded as targets for control, conservation and monitoring actions. The Cerrado is one of the most emblematic examples of this challenge, as this biome ranks among the top five biodiversity hotspots in the world and most of its land is occupied by private lands.

Taking our results as an example, if there were no political, social, financial, practical or personal constraints, we could recommend to decision-makers that all properties that we analyzed here should be included in a wide conservation strategy that includes different actions, such as those proposed by Strassburg et al (2017). However, this is not feasible in the near future because of the lack of time, money, political, social and economic constraints. In due course, our results indicate that using some selected properties, based on the size and likelihood of land conversation in the coming years, is essential to focus on developing strategies that can impact a landscape scale (saving time and money, social mobilization efforts). Considering this perspective, we initially propose focusing on negotiations with a group of landowners that may have a greater impact on the loss of vegetation in the Cerrado. For example, if all properties (located in the areas where 20 and 35% Legal Reserve is required) that have more than 2,500 hectares maintained 30% of their areas as protected areas or under sustainable management (in addition to the Legal Reserve) as was proposed by some authors to avoid abrupt declines in tropical biological diversity, more than 4.1 million ha would be saved. This value corresponds to 15% of the loss of native vegetation expected by 2050 and 13% by 2070 in our model.

In terms of reconciling conservation and agricultural production, focusing primarily on large farms that are generally characterized by highly capitalized large-scale commodities and export-oriented production and, as we have shown, are most likely to convert land (for example, in MATOPIBA) seems to be strategic because they are financially healthier, they receive more incentives from the Brazilian government (Graeub et al. 2016) and, potentially, have more capacity to adapt to climate change and social, economic and environmental challenges than family farmers in a world after a coronavirus pandemic.

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APPENDIX

Supplementary figures and tables related to the first chapter "SIMULATING LAND USE CHANGE TRAJECTORIES OF THE CERRADO HOTSPOT REVEALS THE IMPORTANCE OF CONSIDERING PRIVATE PROPERTY SIZES FOR BIODIVERSITY CONSERVATION".

The model is based on $P_{nvl,x,t}$, where P_{nvl} is the probability that a 'native vegetation' cell *x* is converted into 'anthropogenic use' within a defined time interval *t*. The fact that $P_{nvl,x,t}$ is specific for a given time t illustrates how the model updates the suppression of local native vegetation over time. This probability was defined as a logistic function:

$$P_{nvl,x,t} = 1 / (1 + \exp^{-k_{x,t}})$$

such that as $k_{x,t}$ goes from infinity to infinity, $P_{nvl,x,t}$ goes from 0 to 1, following the methodology developed by Rosa et al. (2013). One can then develop linear models for $k_{x,t}$ as a function of the variables that affect x at time t, and explore the effect of different sets of variables using a model selection procedure (figure S5 for all modeling steps).

The model uses Monte Carlo Markov Chains (MCMC) to obtain a posterior probability distribution for each parameter, from which the posterior mean and range of credibility can be extracted, given the model structure and data used for calibration. Binary maps of change are produced (1 – native vegetation, 0 – anthropogenic) for each time period, which are then integrated based on the 100 iterations of the model (sampling from the posterior distributions) to determine the overall probability of change (i.e., if a pixel is selected to be converted 100 times out of 100 iterations it has a 100% probability of conversion in time t). These steps were repeated for each of the four time periods as the model will project future conversion based on observed rates of change, and the periods (2008–2010, 2010–2012, 2012–2014, and 2014–2016) had different rates of change. Once all models were calibrated, the best one (with the combination of variables that yield the highest test likelihood in each calibration time period) was used to project future probabilities of native vegetation loss until 2050 (using two-year time steps). The accumulated probability of conversion by 2050 was determined for each model individually (2008–2010, 2010–2012, 2012–2014, and 2014–2016 models) as well as based on an ensemble of all model outputs (i.e. integrating all model projections made for a particular year). To assess the goodness-of-fit of the models, we calculated the area under the receiver operating characteristic (or AUC) values for each period of each analyzed area (Table A2).

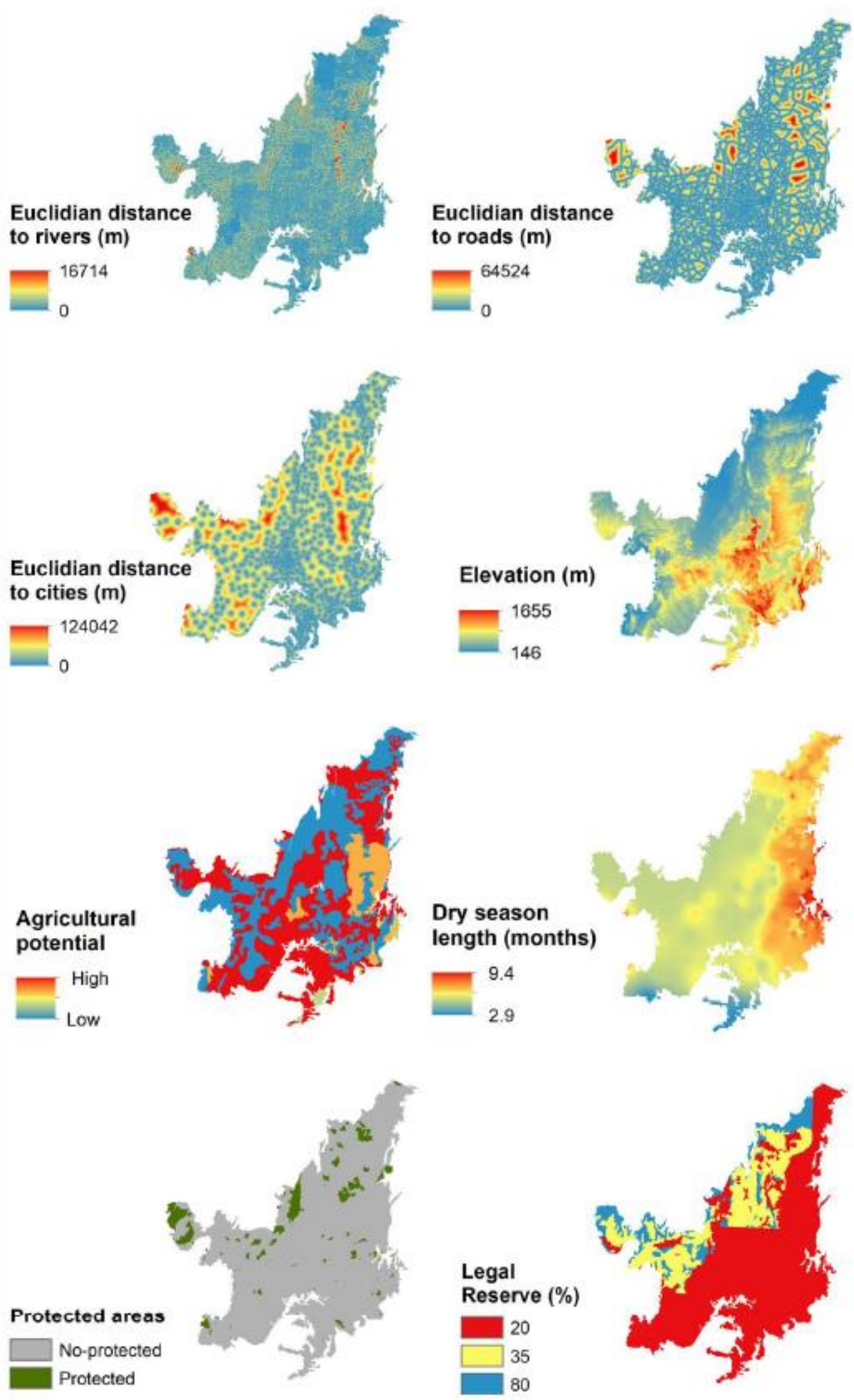

Fig A1. Spatialization of the static variables included in the model and the Legal Reserve.

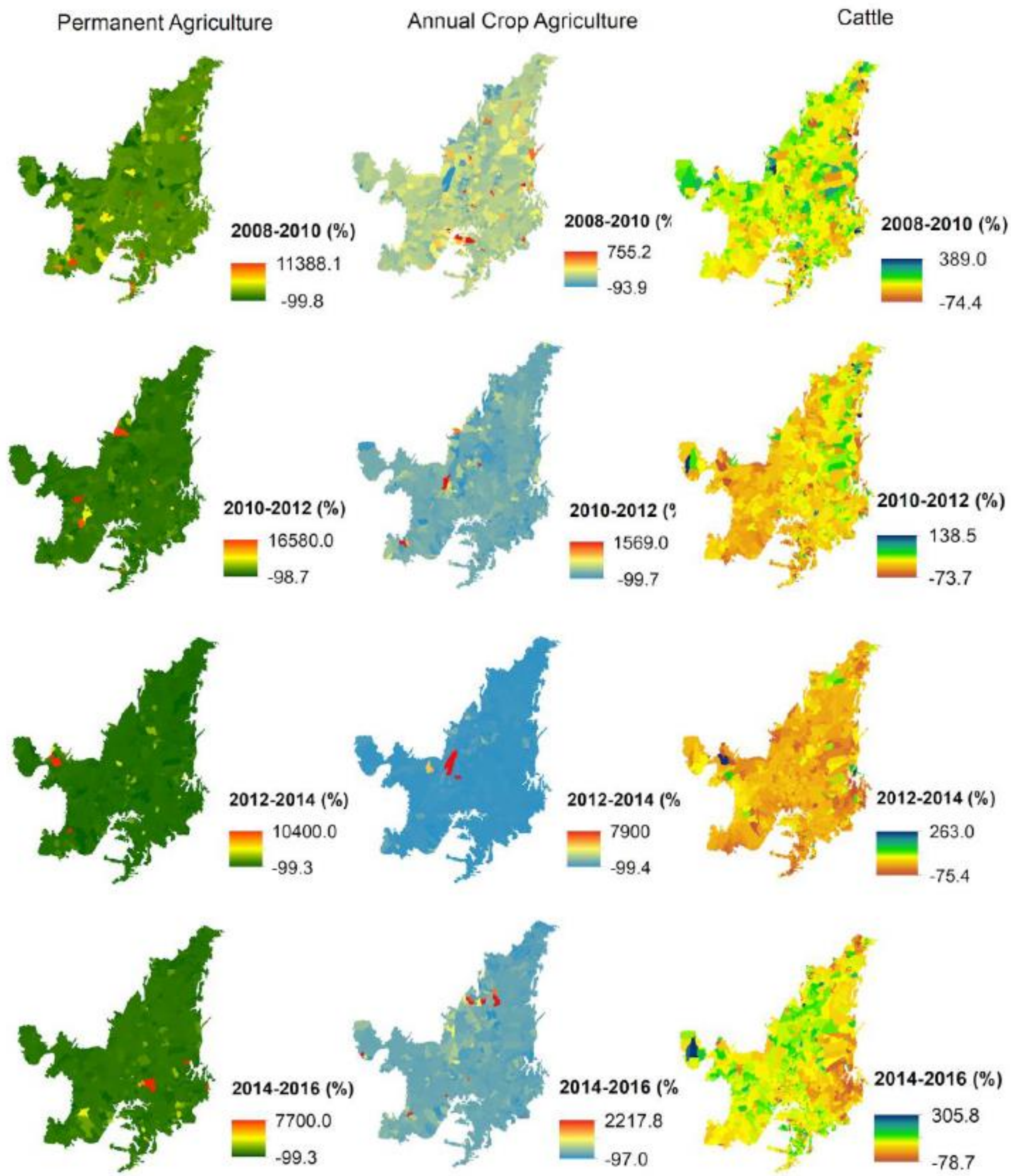

Fig A2. Spatialization of the dynamic variables included in the model in the four periods (2008-2010, 2010-2012, 2012-2014 and 2014-2016). Note: the % is the percentage change between t1 and t2.

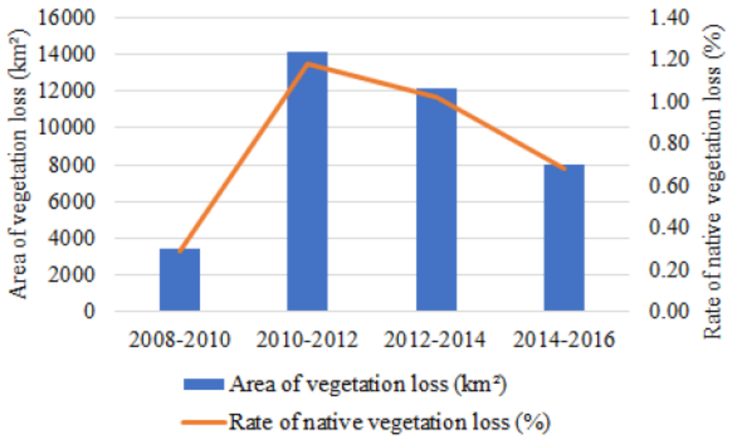

Fig A3. Area and rate of native vegetation loss in the Cerrado in the periods analyzed.

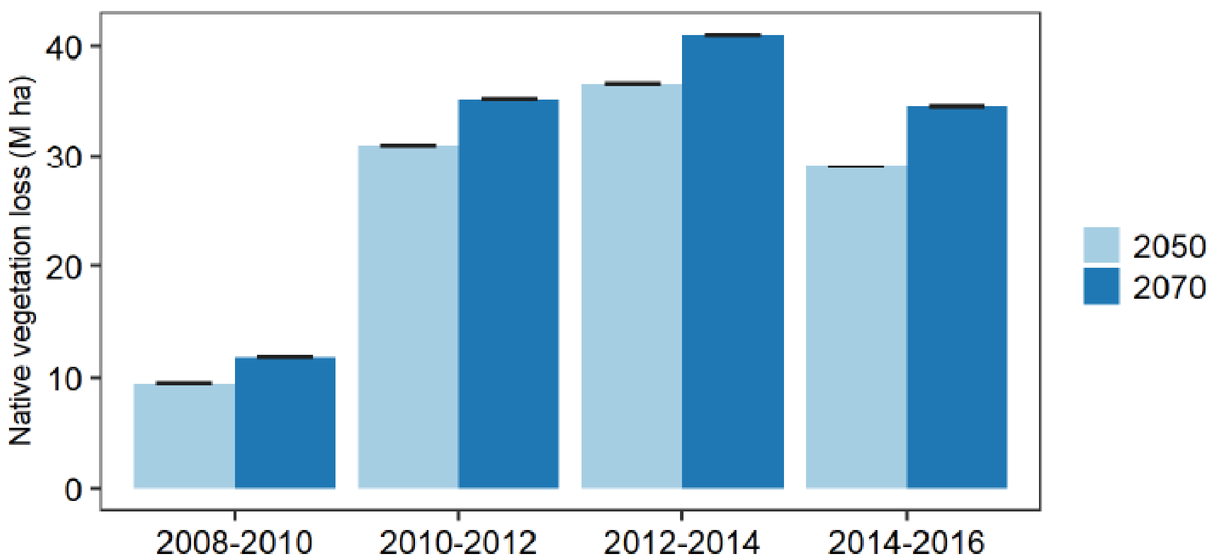

Fig A4. Native vegetation loss by 2050 and 2070 in each period analyzed.

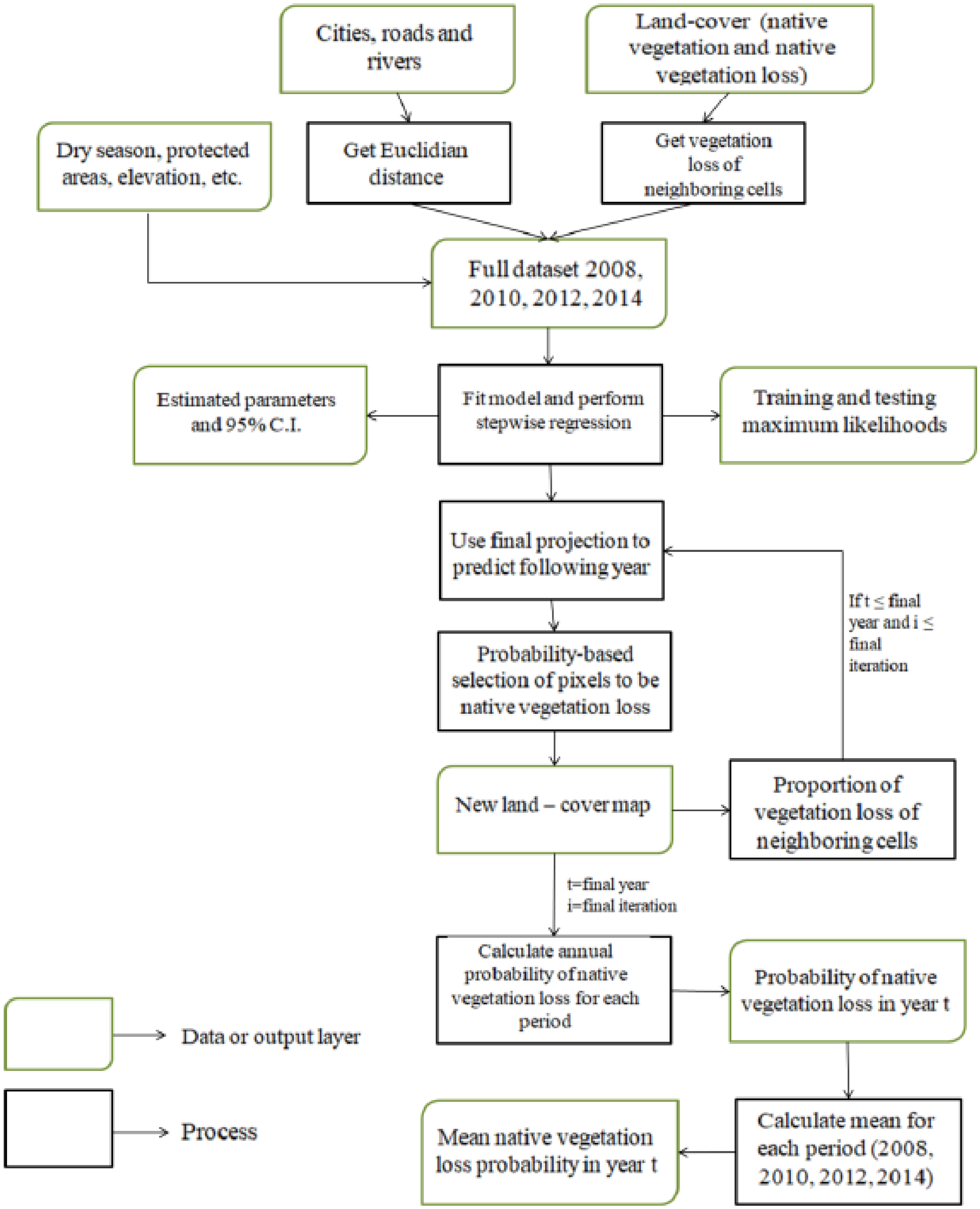

Fig A5. Flowchart of modeling procedure (Guerra et al. 2020), illustrating the construction and running of the vegetation loss model. i is the model iteration, and t the time step.

Table A1. Details of the input data used to calibrate the model for transition period 2008-2010, 2010-2012, 2012-2014, and 2014-2016 (data name, description, source, and reference year).

Name	Description	Source	Year
Land Cover	Natural (1), Anthropogenic (0)	MapBiomas[1]	10-12-14-16-18
Distance to roads	Euclidean distance to nearest road (m)	IBGE[2]	-
Distance to cities	Euclidean distance to nearest city (m)	IBGE[2]	-
Dry season length	Number of months with precipitation <100mm	WMO[3]	-
Elevation	Altitude (m)	MERIT-DEM[4]	-
Agricultural potential	Quality of soil/climate for agriculture	IBGE[2]	-
Distance to Rivers	Euclidean distance to nearest rive (m)	IBGE[2]	-
Cattle	Change in cattle heads	IBGE[2]	10-12,
Permanent Agriculture	Change in permanent agriculture area	IBGE[2]	12-14, 14-16,
Annual Crop Agriculture	Change in temporary agriculture area	IBGE[2]	16-18
Protected areas	Protected areas (1), unprotected (0)	IBGE[2]	-

[1]MapBiomas (https://mapbiomas.org/download).

[2]IBGE – Instituto Brasileiro de Geografia e Estatística (http://www.ibge.gov.br/home/download/geociencias.shtm).

[3]WMO – World Meteorological Organization (http://www.agteca.com/climate.htm).

Table A2. AUC values for each period analyzed.

Período	2008-2010	2010-2012	2012-2014	2014-2016
AUC	0.78	0.83	0.85	0.84

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CHAPTER 2

IDENTIFYING PRIORITY REGIONS AND TERRITORIAL PLANNING STRATEGIES FOR CONSERVING NATIVE VEGETATION IN THE CERRADO (BRAZIL) UNDER DIFFERENT SCENARIOS OF LAND USE CHANGES

Colman, C.B., Guerra, A., Roque, F.O., Rosa, I.M.D., Oliveira, P.T.S. Identifying priority regions and territorial planning strategies for conserving native vegetation in the Cerrado (Brazil) under different scenarios of land use changes, Science of The Total Environment, 807, https://doi.org/10.1016/j.scitotenv.2021.150998. (Impact factor 2021: 9.963)

Abstract

The Cerrado biome covers approximately 20% of Brazil and it is crucial for the Water, Food, Energy, and Ecosystems (WFEE) nexus. Thus, in recent years, large areas of the undisturbed Cerrado have been converted into farmland. In this biome, according to the Brazilian Forest Code, farmers need to keep 20% of native vegetation (Legal Reserves – LRs). By exploring combined and isolated impacts of different scenarios of LR and Protected area (PA) arrangements, this study evaluated the importance of complementarity between LR compliance and the amount of PAs (including Conservation Units - CUs and Indigenous Lands - ILs) to reduce deforestation and conserve native vegetation in the Cerrado. Seven scenarios were investigated: a scenario that considers the current PA and the LR values foreseen in the Native Vegetation Protection Law – NVPL; three scenarios focused on production; and three focused on conservation. Considering the trend of the current scenario, the estimated loss of native vegetation will be 30% (30.6 million ha) by 2070. According to the model simulations, for two periods (2050 and 2070), the LR Elimination scenario (LRE) would cause a greater loss of native vegetation than the PA Elimination (PAE), and as expected, the exclusion of both (PALRE) would provide a greater loss of native vegetation. Native vegetation is concentrated mainly on agricultural properties. Taking our conservation-oriented scenarios as an example of conservation strategies, if there were no financial, practical, political, social or personal constraints, there is no doubt that the CPALRI scenario (Creation of Protected Areas and Legal Reserve Increase) is the best trajectory for conserving biodiversity. Therefore, private properties, through LRs, are essential for efficient planning of land use/cover as they ensure security in the WFEE nexus. The resulting projected scenarios are important to help decision makers in territorial planning and how to arbitrate territorial demands aiming at the rational use of the natural resources of the Cerrado.

Keywords: Brazilian savanna, conservation unit, indigenous land, land use/cover changes, legal reserve, conservation areas.

1. Introduction

Tropical savannas cover about 20% of the Earth's surface and are home to about 20% of the world's human population (Collinson, 1988; Scholes and Archer, 1997). Tropical savannas are undergoing rapid conversion to other land uses worldwide (Wynn et al., 2017), mainly for agricultural use, which has led to serious consequences to ecosystem services provided by the biome (Zhan, 2015; Oliveira et al., 2019; Resende et al., 2019; Guerra et al., 2020a; Barral et al., 2020). The Cerrado, also known as the Brazilian savannah, is the largest and most threatened tropical savanna in the world (Silva and Bates, 2002; Strassburg et al., 2017), responsible for approximately 45% of the national agricultural area, producing around 35% of the cattle herd, 52% of the soybeans, 52% of sugarcane, 54% of corn and 96% of cotton (CONAB (Brasil), 2018; IBGE, 2018), which makes the country one of the largest agricultural producers in the world (EMBRAPA, 2020). In the last 30 years, this biome has undergone significant changes in land use/cover, in which more than 14,000 km^2 of native vegetation has been converted to agriculture and livestock annually between 2000 and 2017 (Grande et al., 2020). As a result, the biome has just over 53% of its native vegetation (MapBiomas, 2020; Sano et al., 2019). The Cerrado, in turn, is considered a global biodiversity hotspot (Mittermeier et al., 2004), as well as a region of extreme ecological importance that is home to a great richness of fauna and flora. This biome is crucial for the dynamics of Brazil's water resources and for the country's food production and much of what is exported. In addition, 70% of the country's energy production comes from hydroelectric generation in the region's rivers (Oliveira et al., 2014). Projections show that more agricultural areas will be needed to meet the increase in global food demand, while also increasing water and energy consumption (Pastor et al., 2019). This connection makes the Cerrado fundamental to the country's Water, Food, Energy, and Ecosystems (WFEE) nexus (D'Odorico et al., 2018; Oliveira et al., 2019). Over the last year, Brazil attained its record agriculture production, reaching more than R$ 168 billion dollars, and had a 7% increase in exports (Brazil, 2021a). Most of this production comes from the states of Mato Grosso, Mato Grosso do Sul, Bahia, Minas Gerais, which are part of the Brazilian Cerrado (Brazil, 2021b; MAPA, 2020).

The protection strategies established by law, such as Conservation Units (CUs), including public and private lands and Indigenous Lands (ILs), can increase the purchasing power (Naidoo et al., 2019) and welfare of the people (Ban et al., 2019), biodiversity conservation (Campos-Silva and Peres, 2016; Castello et al., 2009), and forest cover (Joppa et al., 2008). In Brazil, these areas have already been shown to be adequate safeguards for reconciling land use/cover changes with the provision of ecosystem services (e.g., soil erosion and sedimentation control, water and energy supply), including conservation of native vegetation and biodiversity (Campos-Silva and Peres, 2019; Metzger et al., 2019; Resende et al., 2021). Studies have also demonstrated the importance of maintaining PAs established by government programs in soil and water conservation (Sone et al., 2019), in the preservation of wetlands (Guerra et al., 2020a), and in maintaining fauna and flora (Clemente et al., 2020; Frederico et al., 2018; Heringer et al., 2020).

In addition to PAs, LRs, which is a minimum area of native vegetation required in private rural properties in Brazil through the Native Vegetation Protection Law, known as the Forest Code (Brazil, # 12,651, of 2012), are essential for maintaining ecosystem services and biodiversity (Metzger et al., 2019), mainly because the Cerrado is occupied mostly by private properties. Despite being important protection strategies established by law, CUs, ILs and LRs may undergo changes, arising from other regulatory measures, such as Bill # 2362/2019, which aimed to eliminate the requirement for LRs, Bill #191/2020, which regulates mining, oil exploration and electric power generation in ILs, and the Normative Instruction #9/2020, which allows the occupation and sale of ILs without authorization. In other words, they are regulations that have the potential to affect agricultural activities and ecosystem services in the region.

Currently, the Cerrado has 2.8% of its PA in CUs and 109 ILs (4.3% of the biome's area), as well as other areas that are claimed and regularized, mainly concentrated in public lands. However, more than 50% of the remaining native vegetation in the country is on private land (Soares-Filho et al., 2014). Considering that 44% of Brazil is in private areas (Sparovek et al., 2019) and some regions are undergoing strong land use conversion processes to produce commodities (Azevedo et al., 2017; Rajão et al., 2020), it is essential to evaluate the role of these areas for conservation considering different policies and territorial planning strategies. Thus, this study compares the vegetation loss in the Cerrado until 2050 and 2070 in different scenarios. The combined and isolated impacts of the different amounts and arrangements of LR and PAs were explored. Moreover, the importance of complementarity between LR compliance and PA cover (including CUs and ILs) was evaluated in terms of reducing deforestation and conserving native vegetation in the Cerrado. Seven scenarios were explored: one scenario that considers the current PA and LR predicted values in the NVPL; three scenarios that focused on production; and three on conservation. Scenario modeling is an important tool to foresee how nature responds to different pathways of future human development and policy choices (Ferrier et al., 2016; Rosa et al., 2017). Furthermore, studies on future scenarios of land use changes may contribute to land use planning strategies (Gomes et al., 2019), as well as support decision makers from government authorities regarding different kinds of futures (de Barros Ferraz et al., 2005; Gutzler et al., 2015; Veldkamp and Lambin, 2001) for the native vegetation of the Cerrado biome, considering Brazilian environmental legislation (Soterroni et al., 2018; Resende et al., 2019, Resende et al., 2021).

2. Methods

2.1. Study area

The Cerrado biome, also known as the Brazilian Savanna, covers almost a quarter - or 2.04 million km^2 - of the country, with a mosaic of 23 types of vegetation, consisting of tropical savanna forests, fields, and forests. The biome has 12,000 cataloged plants, of which more than 4000 are endemic (Brazil, 2014). Conservation International considers it one of the 34 biodiversity hotspots in the world. Distributed in 11 States (Goiás, Tocantins, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Bahia, Maranhão, Piauí, Rondônia, Paraná and São Paulo) and the Distrito Federal (Fig. 1) and four geopolitical regions (North, Northeast, Midwest and Southeast), the Cerrado biome is mostly occupied by private properties. Approximately 78% of about one million properties in the biome belong to small owners.

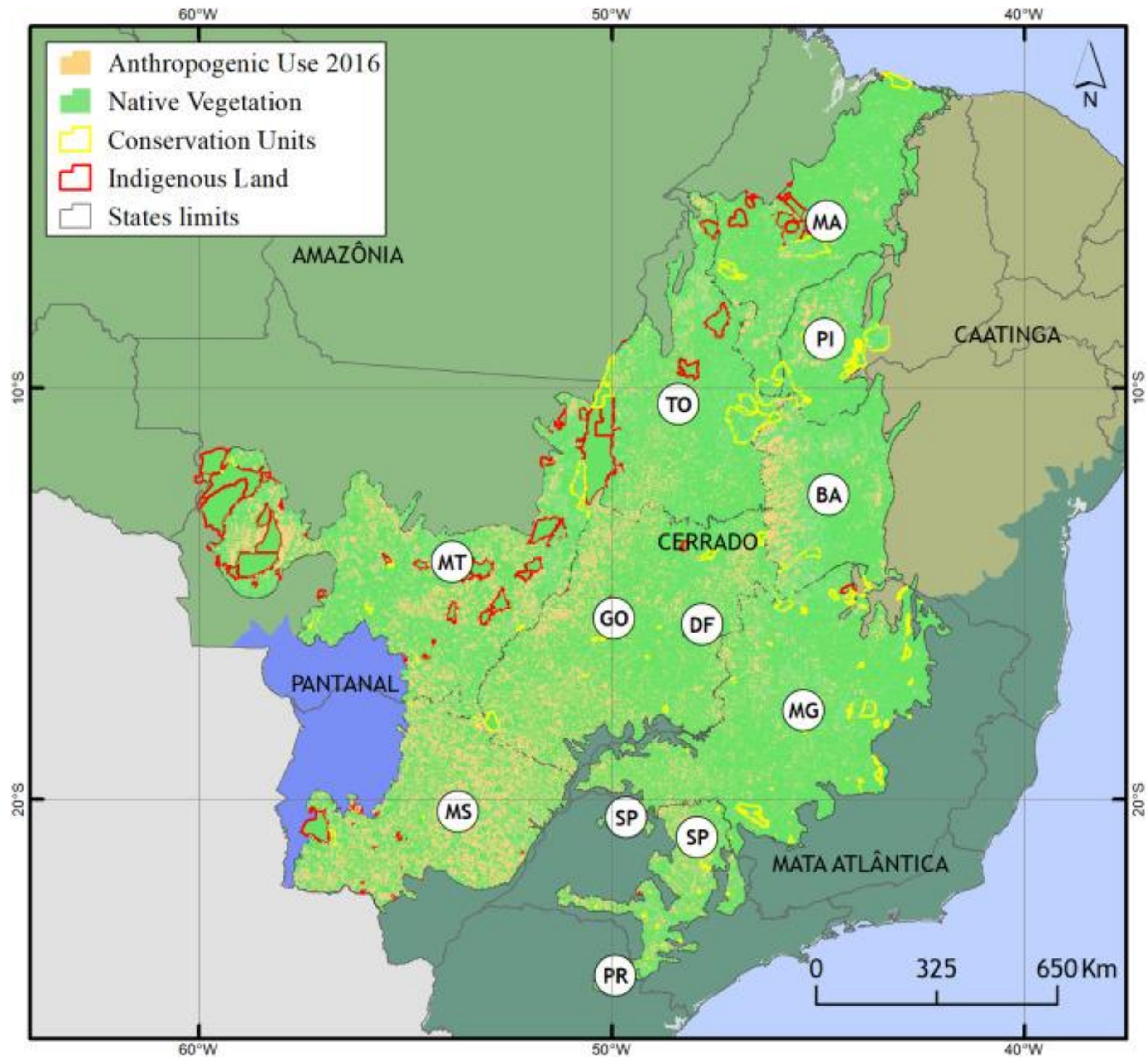

Fig 1. Study area. States included in the Cerrado hotspot: Bahia (BA), Maranhão (MA), Tocantins (TO), Piauí (PI), Mato Grosso do Sul (MS), Mato Grosso (MT), Goiás (GO), Distrito Federal (DF), Minas Gerais (MG), São Paulo (SP), and Paraná (PR). Anthropogenic Use = Pasture, Agriculture, Urban Infrastructure and Mining. Native vegetation = Forest Formation, Savanna Formation, Grassland Formation and Wetland.

Currently, Brazil is the largest producer and exporter of grains and meat, and a large part of the production comes from the Cerrado (CEPEA, 2019). The biome holds approximately 60% of Brazil's soybean acreage (Lima et al., 2019). Therefore, this region is partially responsible for the country's participation in the global market, which currently corresponds to 45%, making Brazil the largest exporter of soybeans followed by the United States with 38% (OEC, 2019). Brazil also has the greatest potential for the production of hydroelectric energy in the world (FAO, 2003), where the Cerrado rivers are the source of 70% of the hydroelectric energy generated in the country, in addition to being fundamental in the dynamics of water resources and biodiversity.

2.2. Scenarios

To create the scenarios, two categories of protection strategies established by law were considered: the Legal Reserve (LR) and Protected Area (PA). The LRs, instituted by Law No. 12,651, of May 25, 2012 (Native Vegetation Protection Law - NVPL), refers to the area intended to maintain a minimum percentage with native vegetation coverage, located inside a rural property. The delimitation of LRs depends on the location of the property. For rural properties located in the Legal Amazon, the LR area is 80%, in the Cerrado biome, 35%, and in other regions of Brazil, 20%. On the other hand, CUs and ILs were considered in the same category, and they were called Protected Areas (PA). CUs are environmental protection areas, regulated by Law No. 9985, of July 18, 2000, and ILs are lands occupied by indigenous communities, regulated by Law No. 6,001 of December 19, 1973.

Fig. 2 shows the scenarios used for simulation native vegetation distribution over the Cerrado biome in 2050 and 2070, in which all scenarios consider the trends in land use/cover conversion in recent years (2008–2016). The first one (1) BAU (Business as usual) considers the LR amount provided for in NVPL and the current PA. The following three scenarios are production-oriented and are as follows: (2) LRE (Legal Reserve Elimination), which considers the elimination of the mandatory LR and maintains the current PA; (3) PAE (Protected Areas Elimination), which considers the same LR values provided for in the NVPL and a total elimination of PA; and (4) PALRE (Elimination of Legal Reserves and Protected Areas) which considers the total elimination of mandatory LRs and PAs (Table 1).

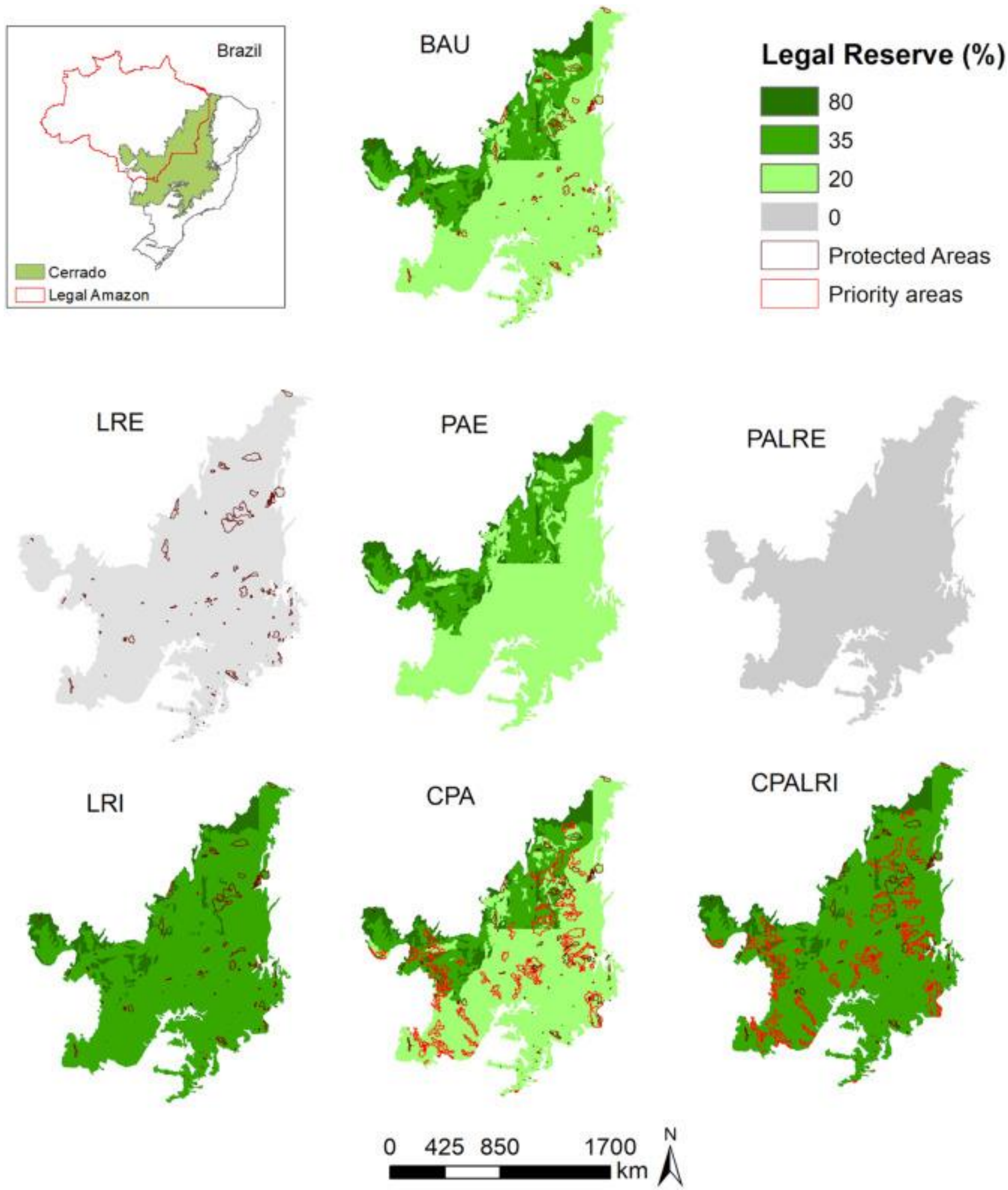

Fig 2. Spatialization of scenarios. Legend: BAU - Business as usual; Production-oriented scenarios: LRE - Legal Reserve Elimination, PAE - Protected Area Elimination, PALRE - Legal Reserve and Protected Area Elimination, Conservation-oriented scenarios: LRI - Legal Reserve Increase, CPA - Creation of Protected Areas, CPALRI - Creation of Protected Areas and Legal Reserve Increase.

Table 1. Details of the Legal Reserve and Protected Areas values (including Conservation Units and Indigenous Lands) used in the modeling of each scenario.

Scenario	Legal reserve	Protected areas
BAU - Business as usual	20, 35 and 80% (according to Native Vegetation Protection Law – NVPL)	7% (Currently Protected Areas)
Production-oriented scenarios		
LRE - Legal Reserve Elimination	Elimination	7% (Currently Protected Areas)
PAE - Protected Area Elimination	20, 35 and 80% (according to Native Vegetation Protection Law – NVPL)	Elimination
PALRE - Legal Reserve and Protected Area Elimination	Elimination	Elimination
Conservation-oriented scenarios		
LRI - Legal Reserve Increase	35 and 80% (based on the Cerrado areas of the Legal Amazon)	7% (Currently Protected Areas)
CPA - Creation of Protected Areas	20, 35 and 80% (according to Native Vegetation Protection Law – NVPL)	Creation of areas considered high priority for conservation
CPALRI - Creation of Protected Areas and Legal Reserve Increase	35 and 80% (based on the Cerrado areas of the Legal Amazon)	Creation of areas considered high priority for conservation

Seven scenarios were used: a scenario that considers the current PA and LR values foreseen in the Native Vegetation Protection Law - NVPL, in three scenarios focused on production and three scenarios focused on conservation.

Another group of scenarios is conservation-oriented scenarios, which are: (5) LRI (Legal Reserve Increase) that considers the increase in the LR value from 20% to 35% (except for the Legal Amazon area, where LR of Cerrado is already 35%), maintaining the current PA; (6) CPA (Creation of Protected Areas) considers the LR values provided for in the NVPL and that all high priority areas for conservation are effective; and (7) CPALRI (Creation of Protected Areas and Legal Reserve Increase) considers the increase in the LR value from 20% to 35% and that all high priority areas for conservation are effective.

2.3. Native vegetation loss model

A spatially explicit model (Guerra et al., 2020b; Rosa et al., 2013) was used that was already applied for the Cerrado biome (Colman et al., 2021). The model calculates the likelihood that a pixel of ‘native vegetation’ (Forest Formation, Savanna Formation, Grassland Formation and Wetland) will be converted to ‘anthropogenic use’ (Pasture, Agriculture, Urban Infrastructure and

Mining) in a time series. The model is divided into two stages: the first identifies drivers that affect the loss of native vegetation in the analyzed periods (in this case 2008–2010, 2010–2012, 2012–2014, and 2014–2016). The variables included in the model were identified as possible predictors of Cerrado vegetation loss based on a literature review. Input data used to calibrate the model were land cover, distance to roads, distance to cities, dry season length, elevation, agricultural potential, distance to rivers, cattle, permanent agriculture, and the model was calibrated for four periods (2008–2010, 2010–2012, 2012–2014 and 2014–2016) due to these periods having different rates of vegetation loss (the description of the inputs can be found in Colman et al., 2021). In the second step, a model selection procedure was carried out based on different combinations of linear models, depending on the variables that affected the loss of native vegetation over time.

The model uses Monte Carlo Markov (MCMC) chains to obtain a posterior probability distribution for each parameter, from which the posterior average and the credibility range can be extracted, given the model structure and the data used for the calibration. Binary maps of change are produced (1 - native vegetation, 0 - anthropogenic) for each time series, which is integrated based on the model's 100 iterations (sampling of posterior distributions) to determine the overall probability of change (that is, if a pixel is selected to be converted 100 times in 100 iterations, it has a 100% probability of conversion at time t). Rural properties of the “Cadastro Ambiental Rural” (CAR; Rural Environmental Registry), and the LR values as a scale for calculating the loss of vegetation according to the Native Vegetation Protection Law - NVPL (Brazil, # 12,651, of 2012) were used, which establishes 20% of the legal reserve for Cerrado areas and 35, 50 and 80% for the Legal Amazon (see Soares-Filho et al., 2014; Brancalion et al., 2016).

Fig. 3 presents a study framework. For the Cerrado biome, over the time series 2008–2010, 2010–2012, 2012–2014 and 2014–2016, the model identified different drivers. Among them, the distance from roads, cities, rivers, agricultural potential, temporary and permanent agriculture and cattle raising explain the loss of native vegetation in at least one period. This was calculated using a spatially explicit model (Guerra et al., 2020b; Rosa et al., 2013, Rosa et al., 2015) which considered eleven possible drivers that lead to loss of vegetation in the Cerrado. From the input data, this model identifies which drivers actually caused the loss of vegetation in the period analyzed (see details in Colman et al., 2021). On the other hand, the presence of PAs prevented the loss of native vegetation in all the periods analyzed (Colman et al., 2021).

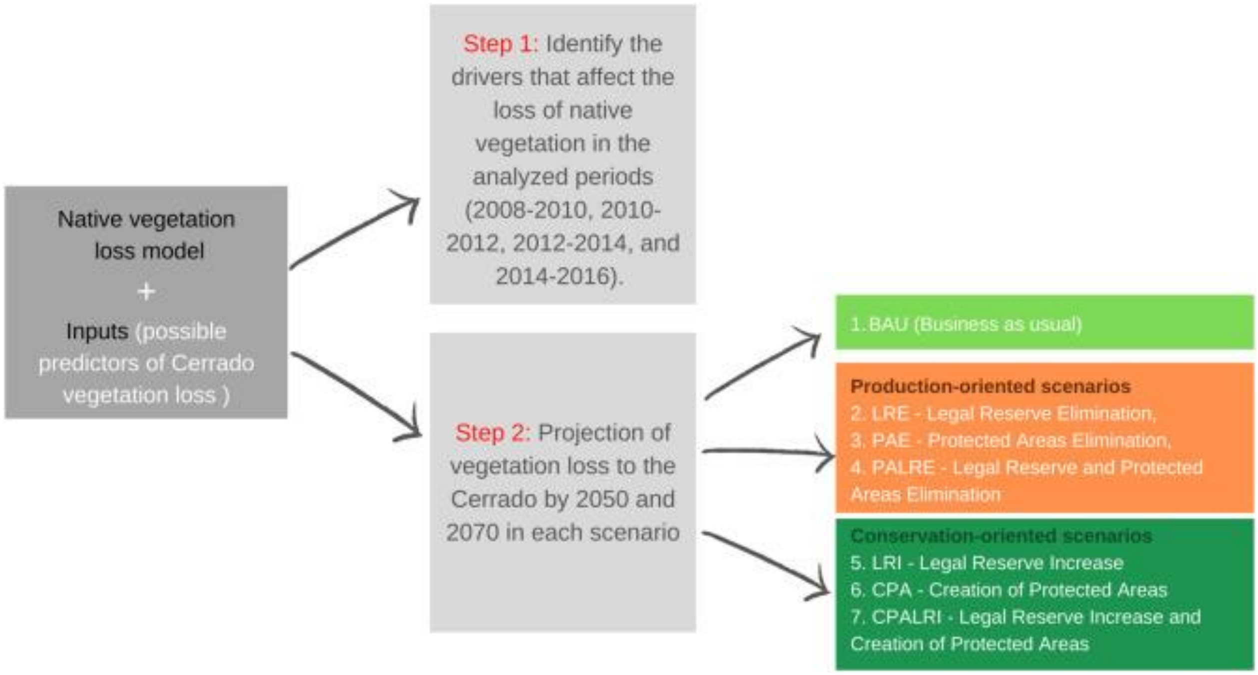

Fig 3. Study framework.

The steps were repeated for each time series to simulate native vegetation loss for 2050 and 2070, based on observed rates of change in the previous time series. Moreover, 2050 was considered to be a medium-term period (29 years from now) and 2070 to be a medium-long term here (49 years from now). The year 2050 was chosen as a baseline for the analysis, because it represents the deadline of the Paris Agreement and 2050 Vision of "Living in harmony with nature" of the Convention on Biological Diversity. Furthermore, 2070 was chosen because it is the baseline for reaching 'carbon neutrality' to avoid global warming of more than 2 °C (UNEP, 2014). The combination of variables that produced the highest probability of testing in each calibration period was used to project future probabilities of loss of native vegetation until 2070 (using two-year time steps).

3. Results

3.1. Validation results

The model was validated obtaining large values of AUC (Area Under the Curve) for all scenarios and periods (Table 2). The validation was made for the first year of the forecasts for each period analyzed, reflecting the time period of the deforestation data used to calibrate the model. For each of the 100 model iterations, the area under the ROC (Receiver Operating Characteristic) curve (AUC) value and three measures of precision on a pixel-by-pixel comparison were calculated: perfect match (the model predicts the exact location of deforestation), commission (over-predicting, the model predicts deforestation events that did not happen) and omission (under-predicting, the model did not predict deforestation in a location where deforestation happened).

Table 2. AUC (Area Under the Curve) values for each period and scenario analyzed.

	2008–2010	**2010–2012**	**2012–2014**	**2014–2016**
BAU	0.78	0.83	0.85	0.84
LRE	0.78	0.83	0.85	0.84
PAE	0.77	0.80	0.85	0.84
LRI	0.78	0.82	0.82	0.84
CPA	0.78	0.82	0.84	0.82
PALRE	0.76	0.83	0.82	0.82
CPALRI	0.76	0.80	0.82	0.82

BAU - Business as usual; LRE - Legal Reserve Elimination, PAE - Protected Area Elimination, PALRE - Legal Reserve and Protected Area Elimination, LRI - Legal Reserve Increase, CPA - Creation of Protected Areas, CPALRI - Creation of Protected Areas and Legal Reserve Increase.

3.2. Scenarios

The seven scenarios presented different values of vegetation loss in 2050 and 2070 for the Cerrado. The BAU (Business as usual) scenario estimates a loss of 26.5 million ha (± 11.8 95% C.I.) and 30.6 million ha (± 12.8 95% C.I.) by 2050 and 2070, respectively. The three production-oriented scenarios (LRE, PAE, and PALRE) estimate greater losses of native vegetation compared to the current scenario. On the other hand, conservation-oriented scenarios estimate lower native vegetation losses in the Cerrado compared to the BAU scenario. For 2070, the largest expected loss of native vegetation is 47 million ha, referring to the PALRE scenario. In this scenario, it is considered that all LR and PA be removed. The lowest expected amount of native vegetation loss for 2070 is 17.3 million ha for the CPALRI scenario.

Fig. 4b shows the percentage estimate of the loss of native vegetation in each scenario compared to the BAU scenario. The LRE scenario reveals an increase of 32% in the loss of native vegetation by 2050 and 34% by 2070 compared to BAU. Under the PAE scenario, there is an increase of 5% by 2050 and 7% by 2070 compared to BAU, corresponding to 32.8 million ha

(±12.9 95% CI). The PALRE scenario estimates the larger increase of native vegetation loss, 57% by 2050 and 54% by 2070 compared to BAU, reaching 40.9 million ha (±11.6 95% CI) (Fig. 4a). On the other hand, the LRI scenario estimates a 6% reduction in native vegetation loss by 2050 and 5% by 2070 compared to BAU (Fig. 4b), with 29.2 million ha (±12.7 95% CI) of loss by 2070 (Fig. 3a). The CPA scenario estimates a 34% reduction by 2050 and 35% by 2070 (Fig. 3b), reaching 20.0 million ha (±12.8 95% CI) of loss by 2070 (Fig. 2a). The CPALRI scenario is the most positive with a 42% decrease in native vegetation loss by 2050 and 43% by 2070 compared to BAU (Fig. 4b).

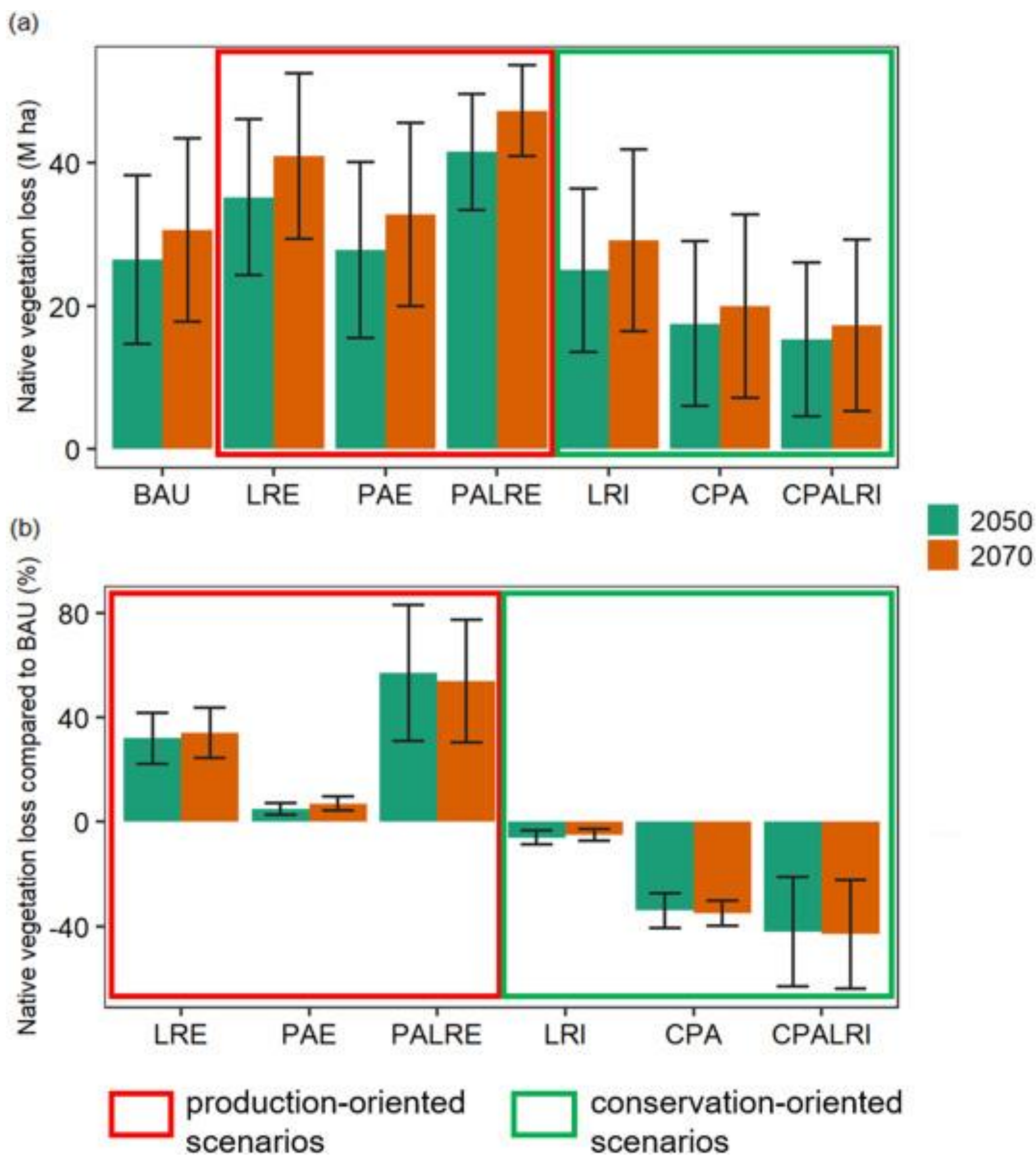

Fig 4. (a) Native vegetation loss (Mha) in each scenario. (b) Native vegetation loss (%) compared to BAU scenario. Legend: BAU - Business as usual; Production-oriented scenarios: LRE - Legal Reserve

Elimination, PAE - Protected Area Elimination, PALRE - Legal Reserve and Protected Area Elimination, Conservation-oriented scenarios: LRI - Legal Reserve Increase, CPA - Creation of Protected Areas, CPALRI - Creation of Protected Areas and Legal Reserve Increase. The error bars correspond to the standard error of the mean generated from the simulations, using the Monte Carlo Markov Chains (MCMC) method.

The estimates show that by 2050, the Cerrado is expected to lose 26.1% of native vegetation under the BAU scenario, 41% by the PALRE, 34.7% by the LRE, 27.4% by the PAE, 24.6% by the LRI, 17.3% by the CPA, and 15.1% by the CPALRE. Furthermore, by 2070, it is estimated that the Cerrado will lose 30.2% of its native vegetation according to the BAU, 46.7% for the PALRE, 40.4% for the LRE, 32.3% for the PAE, 28.8% for the LRI, 23.5% for the CPA and 17.1% for the CPALRI.

Fig. 5 shows the probability of loss of native vegetation in the Cerrado in each scenario until 2070. The loss of vegetation occurs mainly in the northern region of the Cerrado biome, close to areas that were previously covered by pasture and agriculture in the MATOPIBA region (states of Maranhão, Tocantins, Piauí and Bahia). The two scenarios that most differed in terms of the places with the highest probability of loss of native vegetation are CPA and CPALRI, as they did not present any loss in the areas of creating PAs. The simulations have also generated the percentage of native vegetation remaining for the Cerrado biome. By 2070, for the current scenario, the percentage of native vegetation remaining is 41.1% (Fig. 6). For the other scenarios, the percentage of native vegetation remaining in the Cerrado biome by 2070 is 36.2% for the LRE scenario, 40% for the PAE scenario and 34.8% for the PALRE scenario. For conservation scenarios, 40.1% of vegetation remains for LRI, 45.2% for the CPA scenario and 47.5% for the CPALRI scenario (Fig. 6).

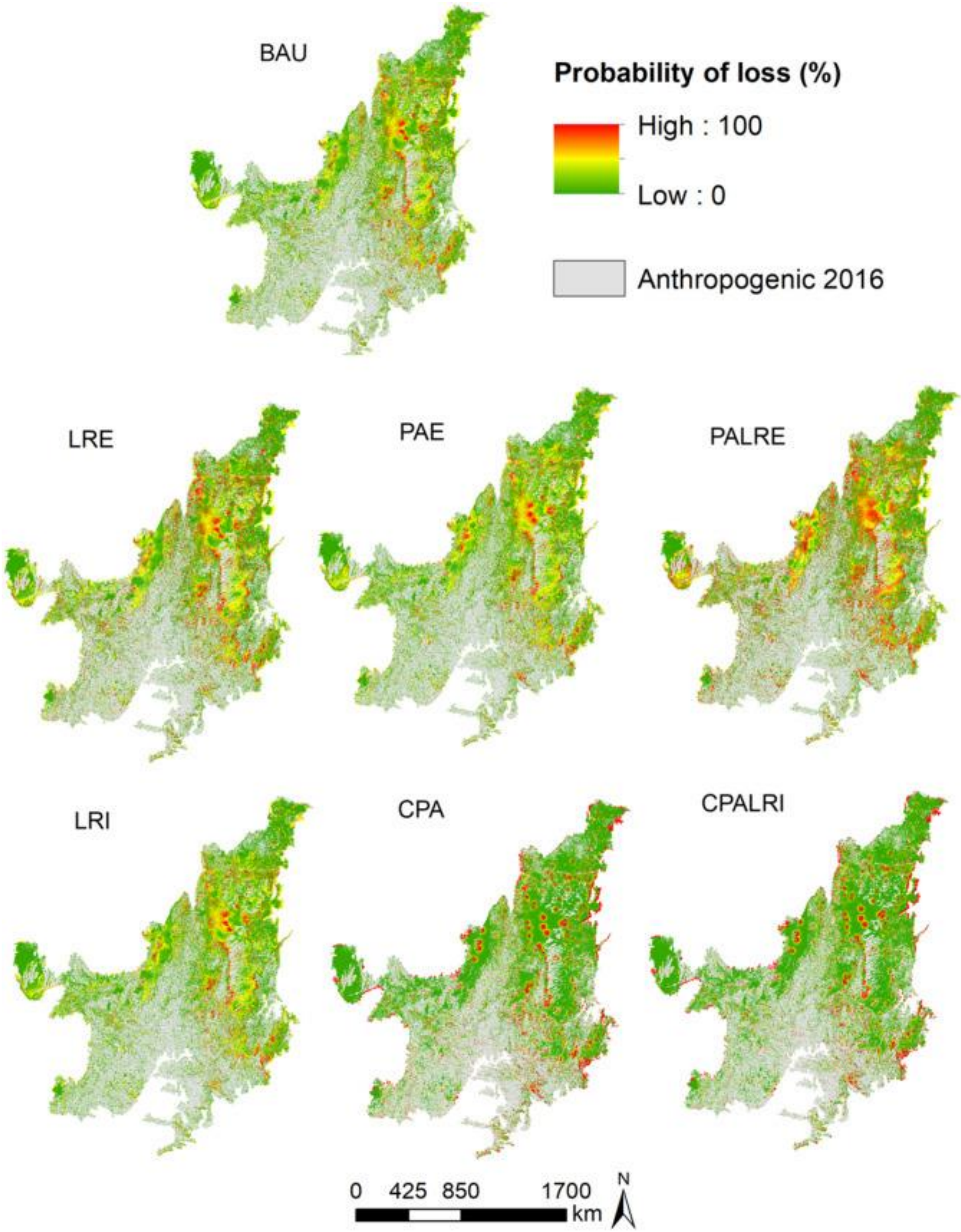

Fig 5. Probability of native vegetation loss in each scenario until 2070. Legend: BAU - Business as usual; Production-oriented scenarios: LRE - Legal Reserve Elimination, PAE - Protected Area Elimination, PALRE - Legal Reserve and Protected Area Elimination, Conservation-oriented scenarios: LRI - Legal Reserve Increase, CPA - Creation of Protected Areas, CPALRI - Creation of Protected Areas and Legal Reserve Increase.

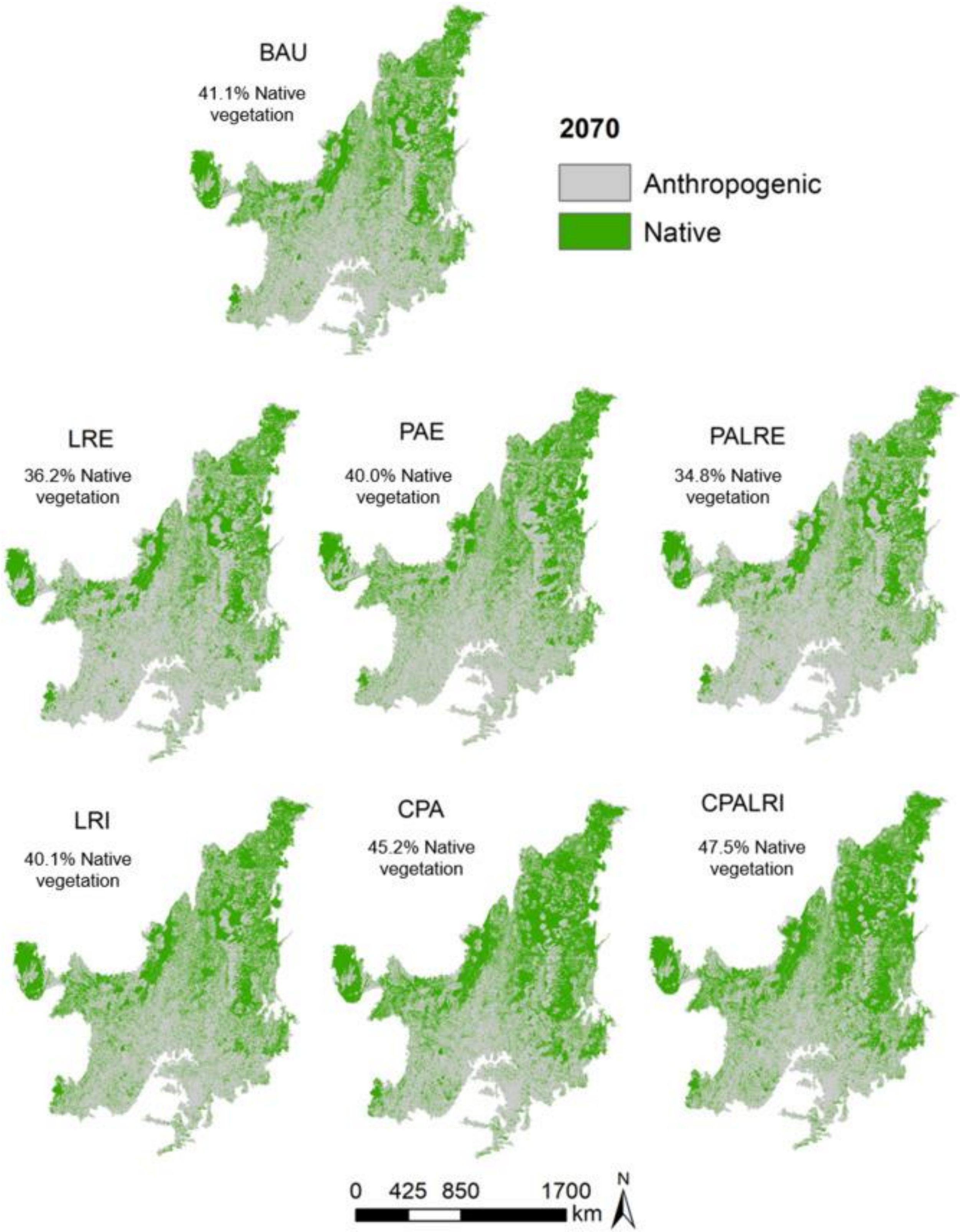

Fig 6. Native vegetation remaining until 2070. Legend: BAU - Business as usual; Production-oriented scenarios: LRE - Legal Reserve Elimination, PAE - Protected Area Elimination, PALRE - Legal Reserve and Protected Area Elimination, Conservation-oriented scenarios: LRI - Legal Reserve Increase, CPA - Creation of Protected Areas, CPALRI - Creation of Protected Areas and Legal Reserve Increase.

4. Discussion

In this study, the loss of native vegetation in the Cerrado was simulated considering seven scenarios, taking into account the existence of LR and PA. For all scenarios, the results show that native vegetation will suffer a significant loss, particularly in regions with large farms and high probability of agriculture expansion (e.g. the states of Maranhão, Tocantins, Piauí and Bahia, a region known as MATOPIBA) as other studies have already shown (Carneiro-Filho and Costa, 2016; Zu Ermgassen et al., 2019; Colman et al., 2021). Even the conservation-oriented scenarios predict large areas of potential vegetation loss which adds evidence to an increasing number of studies that made the Cerrado, the world's most biologically rich savannah, one of the most threatened hotspots on the planet by the expansion of the agricultural frontier (Carneiro-Filho and Costa, 2016; Strassburg et al., 2017; Soterroni et al., 2019).

The results also show the importance of complementarity between LR compliance and increased PA cover for reducing deforestation and conserving native vegetation in the Cerrado (Soterroni et al., 2018; Resende et al., 2021). As a whole, considering that 44% of Brazil is private land (Sparovek et al., 2019) and the current level of enforcement is becoming weaker and more flexible in Brazil, at least in the short term (Abessa et al., 2019; Artaxo, 2019; Kehoe et al., 2019; Zeidan, 2019), mechanisms that promote conservation by improving sustainable economic chains, encouraging leadership from the agricultural sector in conserving native vegetation, in addition to legal requirements, national and international agreements, are urgently required to reconcile the conservation and production of food in the Cerrado.

According to the model simulations, for the two periods, 2050 and 2070, the LR elimination scenario (LRE) would cause a greater loss of native vegetation than the PA elimination (PAE), and as expected, the exclusion of both (PALRE) would provide a greater loss of native vegetation. For the latter scenario, which represents the total removal of existing LR and PA, ~35% of the remaining vegetation would remain until 2070. This causes a great deal of concern because evidence from many studies has continued to support that in tropical landscapes with less than 40% of native vegetation no longer maintain biodiversity able to survive in it while maintaining a high delivery of biodiversity-based ecosystem services (Banks-Leite et al., 2014; Roque et al., 2018; Arroyo-Rodríguez et al., 2020).

The ability to predict consequences of native vegetation loss for agriculture production is still limited, however it is expected that quick and large-scale land use and cover changes in the Cerrado may lead to dramatic impacts not only in biodiversity (Strassburg et al., 2017), soil erosion

(Guerra et al., 2020a), carbon emission (Soterroni et al., 2018), carbon storage, water yield, nutrient retention, net primary productivity and wild food provision (Resende et al., 2019) but also in the crop production itself, which largely depends on regulating services for proper productivity. Some of the most important Brazilian agricultural products and commodities (e.g. oranges, soybeans, coffee, cacao, tomatoes), depend on biodiversity for pollination or seed dispersal, reaching monetary values near R$100 billion according to the IBGE, 2018 (Brazilian Institute of Geography and Statistics). Thus, a clear message from this study is that all of our unique production-oriented scenarios must be avoided in the future to maintain critical ecosystem services for agriculture over the long term.

Taking conservation-oriented scenarios as an example of conservation strategies, if there were no financial, practical, political, social or personal constraints, there would be doubts that the CPALRI scenario is the best trajectory for biodiversity conservation. However, if, for any reason, an individual needs to decide among the three scenarios, it is suggested that the LRI scenario be prioritized, because: (1) in terms of occupied area, the LR would occupy greater areas than the PA (at least considering our criteria). According to 2019 data from the "Cadastro Ambiental Rural" (CAR; Rural Environmental Registry) in the Cerrado, to meet the environmental requirements of the NVPL, farmers reserved part of their land equivalent to 29% of the entire biome (EMBRAPA, 2019). PAs correspond to approximately 7% (2.8% are from protected areas and 4.3% from ILs) in the Cerrado (2) concerning most of the natural vegetation to be found on private land. About 53% of the remaining native vegetation of the Cerrado biome is on private properties (Soares-Filho et al., 2014). In addition, rural properties with more than a thousand hectares occupy 60% of the Cerrado (Colman et al., 2021). Therefore, there is more quantity of native vegetation to be preserved within the LR inserted in private rural properties with a large area. It is important to note that the idea of prioritizing actions towards the LRI scenario is an oversimplication.

Beyond compliance of LR and potential increase of their areas, many other strategies should be considered to conserve biodiversity in the Cerrado, varying from more ethical and moral arguments to more economic perspectives. Many of these strategies have already been proposed, for example: improving restoration and protection of key Cerrado habitats while enabling agricultural expansion by using clear criteria in land-use planning, stimulating deforestation-free agricultural expansion, increasing pasture productivity, promoting economic mechanisms of bioeconomy (e.g. carbon markets, local products based on native species), and expanding the Soy Moratorium to the Cerrado for sugarcane and beef (Strassburg et al., 2017; Soterroni et al., 2018; Brock et al., 2021; Flach et al., 2021).

4.1. Limitations of our analysis and challenges

This study has some limitations concerning the factors considered for modeling native vegetation, such as the Brazilian agricultural dynamics and the scenarios considered, paving the way for new approaches concerning future studies. Some gaps shown in our study can be highlighted. First, to discover the effectiveness of LR and PA in the availability of water, soil and water conservation and the provision of ecosystem services. For example, assessing the impact that the absence of an LR would have on the local ecosystem and on the water availability of that specific rural property. Another gap emerges based on a recent study that showed that smaller farms have greater biodiversity and are more productive than larger farms, highlighting the importance of small rural properties in food security (Ricciardi et al., 2021). It is important to highlight that our model does not take into account the restoration of areas. Therefore, in all scenarios, LR-deficient properties still do not meet the NVPL. Restoring the biome's LR deficits would add up to create 12.9 Mha of new forest areas (Soterroni et al., 2018).

Regarding the vegetation loss model, although very useful to forecast general land use/cover trends, is purely a data-driven biophysical model. Consequently, the model is unable to consider or quantify changes in: (a) policy, (b) trade in agricultural crops, such as import, export or changing intra-and international consumer demand, (c) human behavior and (d) technological innovation, in addition to climate change. Furthermore, the magnitude of effects of the estimated drivers may not remain constant in upcoming decades. Finally, studies are also needed that consider the water, food, energy and ecosystem service nexus in scenarios where there is climate change and changes in land use/land cover on multiple scales. Therefore, local, regional and global pressure would be better evaluated in the Brazilian Cerrado (Oliveira et al., 2019).

Despite the current limitations, the information derived from the model provides a useful comparison among the different scenarios considered, and an indication of general trajectories of change. This comparison can be used to inform the development and ongoing monitoring of more sustainable land use/cover policies, and influence decision makers and other stakeholders to consider necessary changes in land use/cover policies. Future scenarios can be included in regional planning strategies and instruments, such as ecological-economic zoning of the Cerrado, however huge social, educational and cultural challenges still remain for effective use of scenario modeling in the construction of public policies in Brazil.

4.2. Implications of the study for management and land use planning

The Cerrado biome has just over half of its native vegetation, about 53% (MapBiomas, 2020). Although the spotlight has always been focused on the Amazon biome, recent research shows that the Cerrado was the Brazilian biome that most lost native vegetation in proportional terms, representing 23% of the net loss of vegetation between 1985 and 2019 (MapBiomas, 2020). This loss of native vegetation gave way, mainly, to agricultural expansion, making the Cerrado responsible for 40% of Brazil's total production of annual agricultural crops (EMBRAPA, 2020). By 2050, agricultural production is expected to double, mainly on undisturbed land, due to increased food demand, a consequence of population growth (Pastor et al., 2019; World, 2019). Despite the accelerated advance of agriculture over native vegetation, environmental legislation has a fundamental role in ensuring the existence of LR and PAs (Bonanomi et al., 2019). Rural producers have already been cited as the professional category in Brazil that has the most important role in preserving native vegetation (EMBRAPA, 2019). Therefore, it is crucial to help the economic development of Brazil and at the same time preserve the Brazilian Cerrado.

Food production depends on several factors, soil conditions, climate, type of cultivation and legal conditions. For decades, producers have had to increase their productivity, invest in technological advances, (including the use of pesticides), ensuring record productions every year. Last year, Brazil registered an increase of 2% in the gross domestic product by the agricultural sector (Brazil, 2021a). Therefore, collaboration between the government, the private sector and civil society is essential to provide the training and incentives necessary for adequate use of the land, for intensification in the sectors of livestock and agriculture (CEA, 2016). Moreover, a growing number of studies in the Cerrado have used scenario approaches and spatial modeling tools for territorial planning to help decision-makers, government and farmers to create strategies that avoid conflicts between biodiversity conservation and food production (e.g., Grecchi et al., 2014; Diniz-Filho et al., 2020; Lemes et al., 2020; Monteiro et al., 2020).

There are several control mechanisms that help landowners to take care of their land. They range from environmental records, which allow the delimitation of land use/cover to monetary incentives for conservation in private areas. An example is the payment for environmental services (PES); it works both in the preservation and in the sustainable use of natural resources. A study showed that PES, implemented in an environmental protection area, achieved its goal by reducing soil erosion and increasing water production in a tropical basin in the Brazilian Cerrado (Sone et al., 2019). Another example is policies to encourage rural producers to invest in pivot irrigation systems, a demand that has grown in rural properties in the Cerrado (Althoff and Rodrigues, 2019; Issa, 2021).

These incentive policies can help to maintain native vegetation, not only for rural landowners to comply with the Forest Code, but also to encourage land owners to preserve their land. The role of ILs is also worth highlighting in protecting indigenous peoples regarding their lands and subsistence for social, cultural, equity and native vegetation reasons, protecting long-term ethnocultural integrity (Resende et al., 2021). The main aim of ILs is to guarantee the right to IL in ancestral lands, but as demonstrated in other studies, they are also fundamental in preventing native vegetation in the Cerrado (Colman et al., 2021) and are essential for Brazil to fulfill its commitments to protect tropical biodiversity and mitigate climate change (Begotti and Peres, 2020).

5. Conclusion

In this study we explore the combined and isolated impacts of scenarios of Legal Reserves (LRs) and Protected area (PA) arrangements. We also investigate the importance of complementarity between LR compliance and the amount of PAs (including Conservation Units - CUs and Indigenous Lands - ILs) to reduce deforestation and conserve native vegetation in the Cerrado. Thus, seven scenarios were investigated: a scenario that considers the current PA and the LR values foreseen in the Native Vegetation Protection Law – NVPL; three scenarios focused on production; and three focused on conservation.

Our study support two main messages. First, the LR Elimination scenario (LRE) would provide a greater loss of native vegetation than the PA Elimination (PAE). Part of these outcomes happens due to native vegetation is concentrated mainly in farmlands. Second, under poor financial, practical, political, social or personal constraints, there is no doubt that the CPALRI scenario (Creation of Protected Areas and Legal Reserve Increase) is the best trajectory for conserving biodiversity in the Cerrado hotspot. In terms of implementation, this strategy should focus mainly on large properties. Therefore, private properties are essential for an efficient planning of land use/cover in order to provide a better Water, Food, Energy, and Ecosystems Nexus.

Simulations of native vegetation loss in scenarios such as those developed here are an important approach to help decision makers in territorial planning and how to arbitrate territorial demands aiming at the rational use of the natural resources of the Cerrado. Our findings open up new avenues of collaboration between scientists, governments, traditional and indigenous peoples, local people, and farmers for building a future that reconcile environment conservation, food production and security of Brazil and the world.

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GENERAL CONCLUSIONS

The results of **Chapter 1** show that distance to rivers, roads and cities, agricultural potential, permanent and annual crop agriculture and cattle led to observed/historical loss of vegetation, while protected areas prevented such loss. Assuming full adoption of the current Forest Code, the Cerrado may lose 26.5 million ha (± 11.8 95% C.I.) of native vegetation by 2050 and 30.6 million ha (± 12.8 95% C.I.) by 2070, and this loss will occur mainly within large properties.

In **Chapter 2**, by exploring combined and isolated impacts of different scenarios of Legal Reserve (LR) and Protected area (PA) arrangements, was evaluated the importance of complementarity between LR compliance and the amount of PAs (including Conservation Units - CUs and Indigenous Lands - ILs) to reduce deforestation and conserve native vegetation in the Cerrado. Considering the trend of the current scenario, the estimated loss of native vegetation will be 30% (30.6 million ha) by 2070. According to the model simulations, for two periods (2050 and 2070), the LR Elimination scenario (LRE) would cause a greater loss of native vegetation than the PA Elimination (PAE), and as expected, the exclusion of both (PALRE) would provide a greater loss of native vegetation. Native vegetation is concentrated mainly on agricultural properties.

In general, Brazil is one of the only countries in the world capable of meeting the global challenge of expanding the supply of food in line with the conservation of natural resources, we see this, especially within the Brazilian Cerrado. Agriculture is the foundation of food security and world peace, said former Agriculture Minister Alysson Paolinelli, nominated for the 2021 Nobel Peace Prize and AgriTrop2021 honoree.