Simulating land use change trajectories of the Cerrado Hotspot reveals the importance of considering private property sizes for biodiversity conservation

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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 km^2 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 Brazilian Soil Classification System (SiBCS) (Oliveira et al. 2014) are: Latosols (~41%), Neossols

(~23%), Argisols (~12%) and Plintosols (~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 km²) 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).

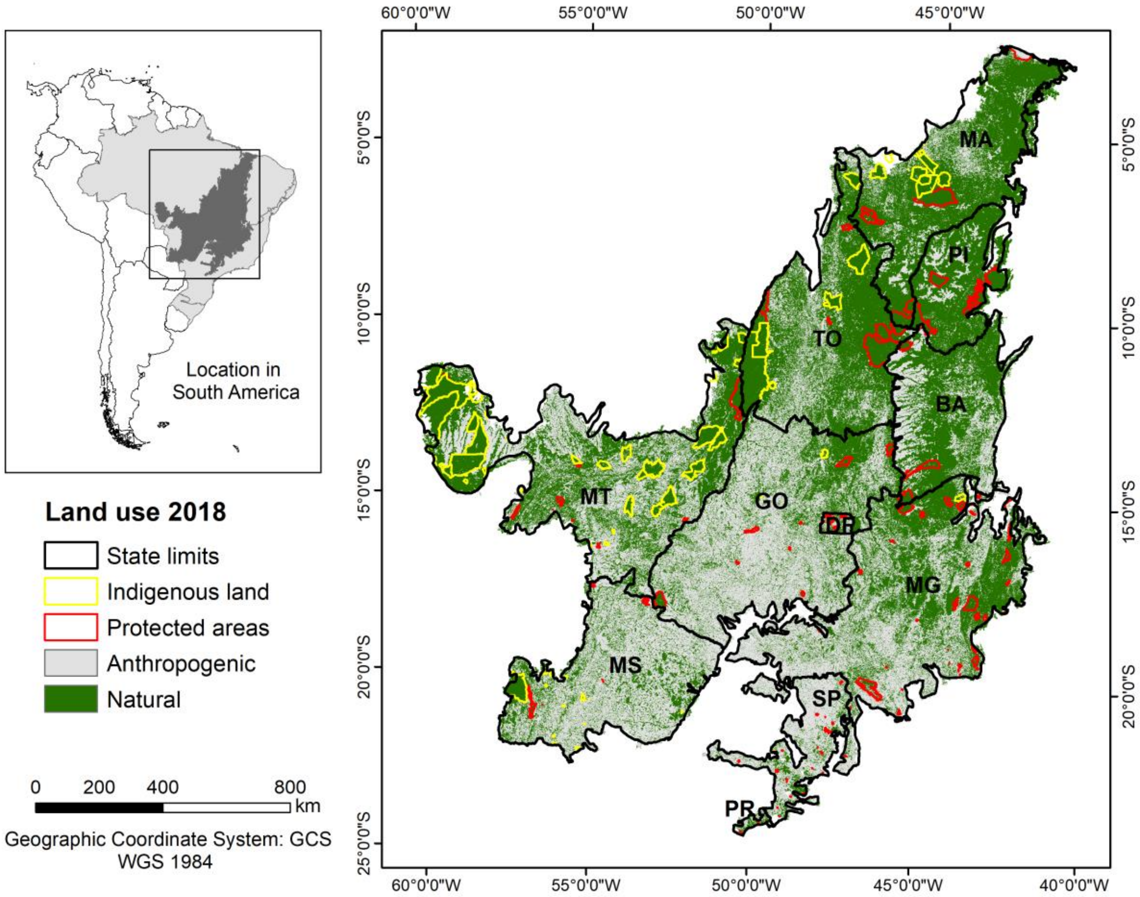

Fig. 1. Study area. States included in the Cerrado hotspot: Bahia (BA), Maranhão (MA), Tocantins (TO), Piauí (PI), Mato Grosso do Sul (MS), Mato Grosso (MT), Goiás (GO),

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 ≤ 150 ha), C2 (150 ≤ 400 ha), C3 (400 ≤ 1000 ha), C4 (1000 ≤ 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	3.773386	2.706573	2.450408	2.547661
Distance to roads	0	-0.000004	0	0
Distance to cities	0.000009	0	0	-0.000008
Dry season length	0	0	0	0
Elevation	0	0	0	0
Agricultural Potential	0.000225	-0.000058	0	0
Distance to Rivers	0.000078	0.000079	0.00003	0

Cattle	0	0	0.001643	0
Permanent Agriculture	0	0	0.000001	0
Annual Crop Agriculture	0	0.000022	-8.1E-05	0
Protected Areas	-1.727708	-1.379807	-1.45011	-1.078604

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).

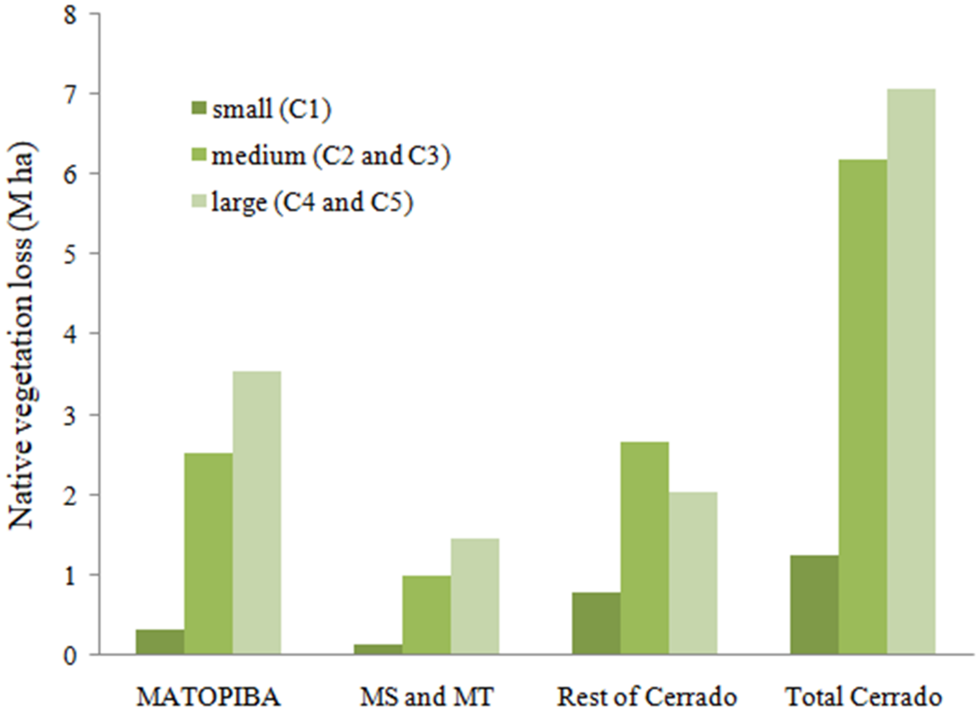

Fig. 2. Native vegetation loss per property size in the Cerrado by 2070.

We spatialized the projected native vegetation losses in the Cerrado for 2050 and 2070 (Fig. 3a,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).

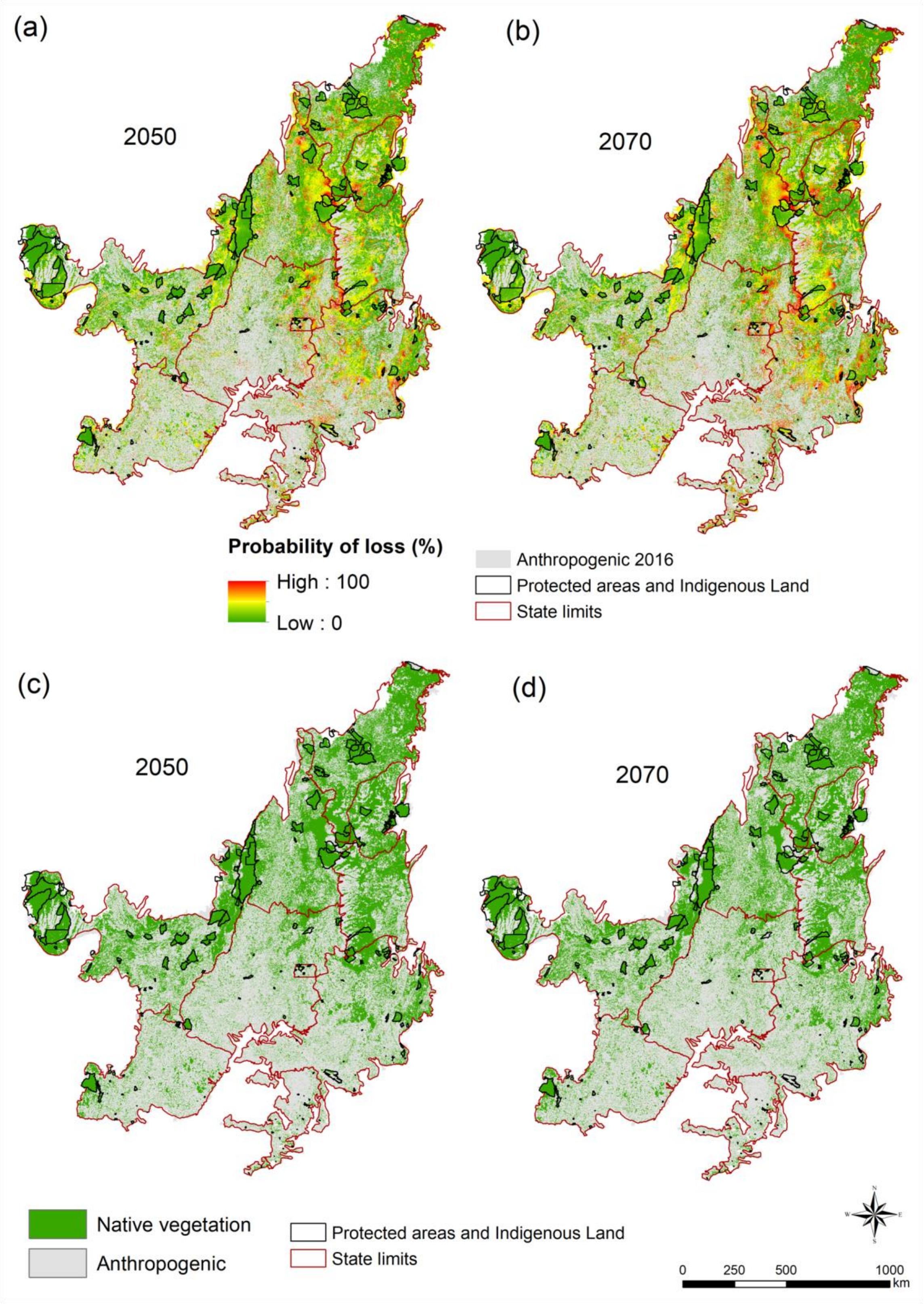

Fig. 3. Projections of accumulated native vegetation loss by (a) 2050 and (b) 2070, and native vegetation remaining for (c) 2050 and (d) 2070 for the mean values of the four periods (2008–2010, 2010–2012, 2012–2014 and 2014–2016).

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 Methods

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).

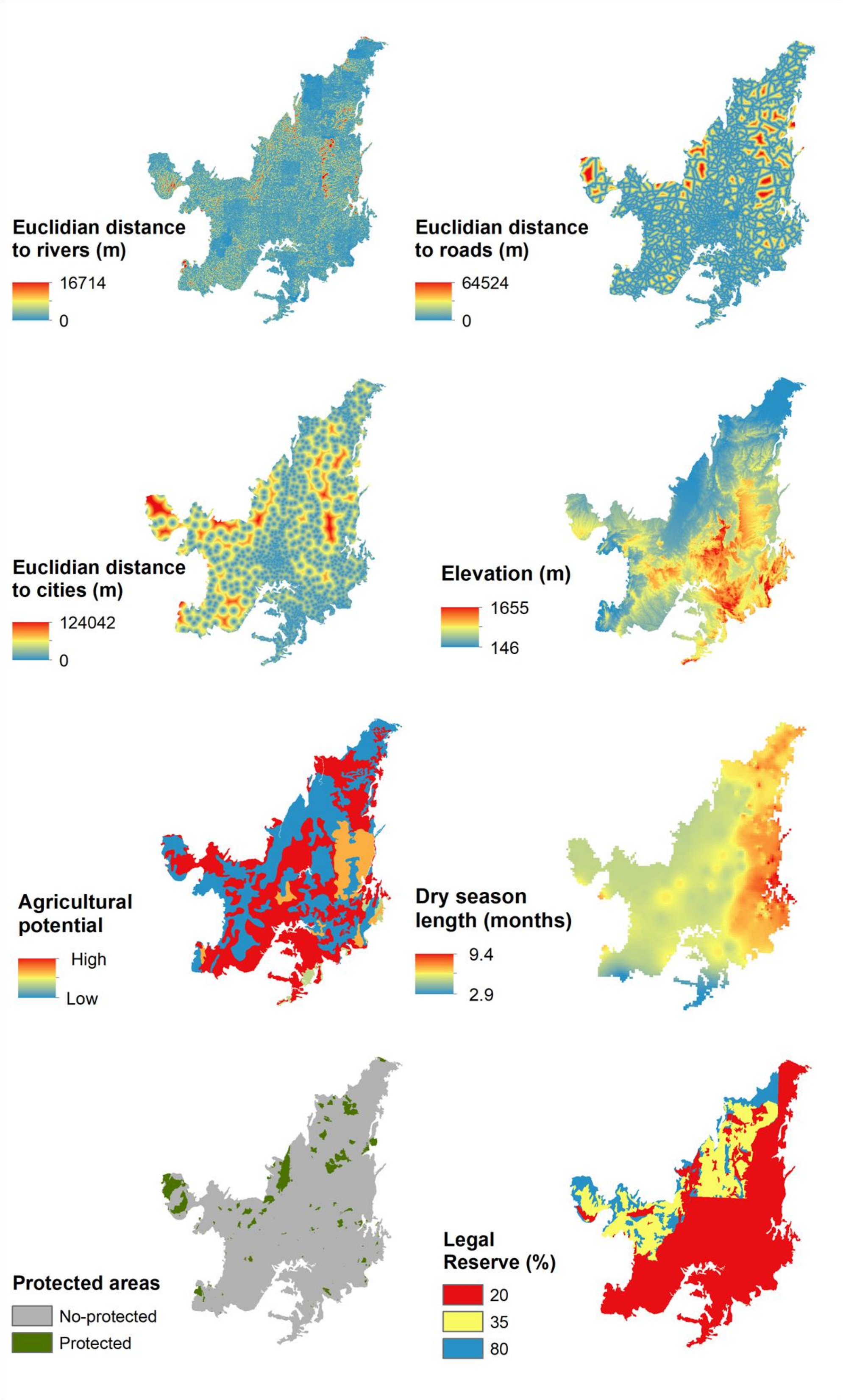

Figure A1. Spatialization of the static variables included in the model and the Legal Reserve.

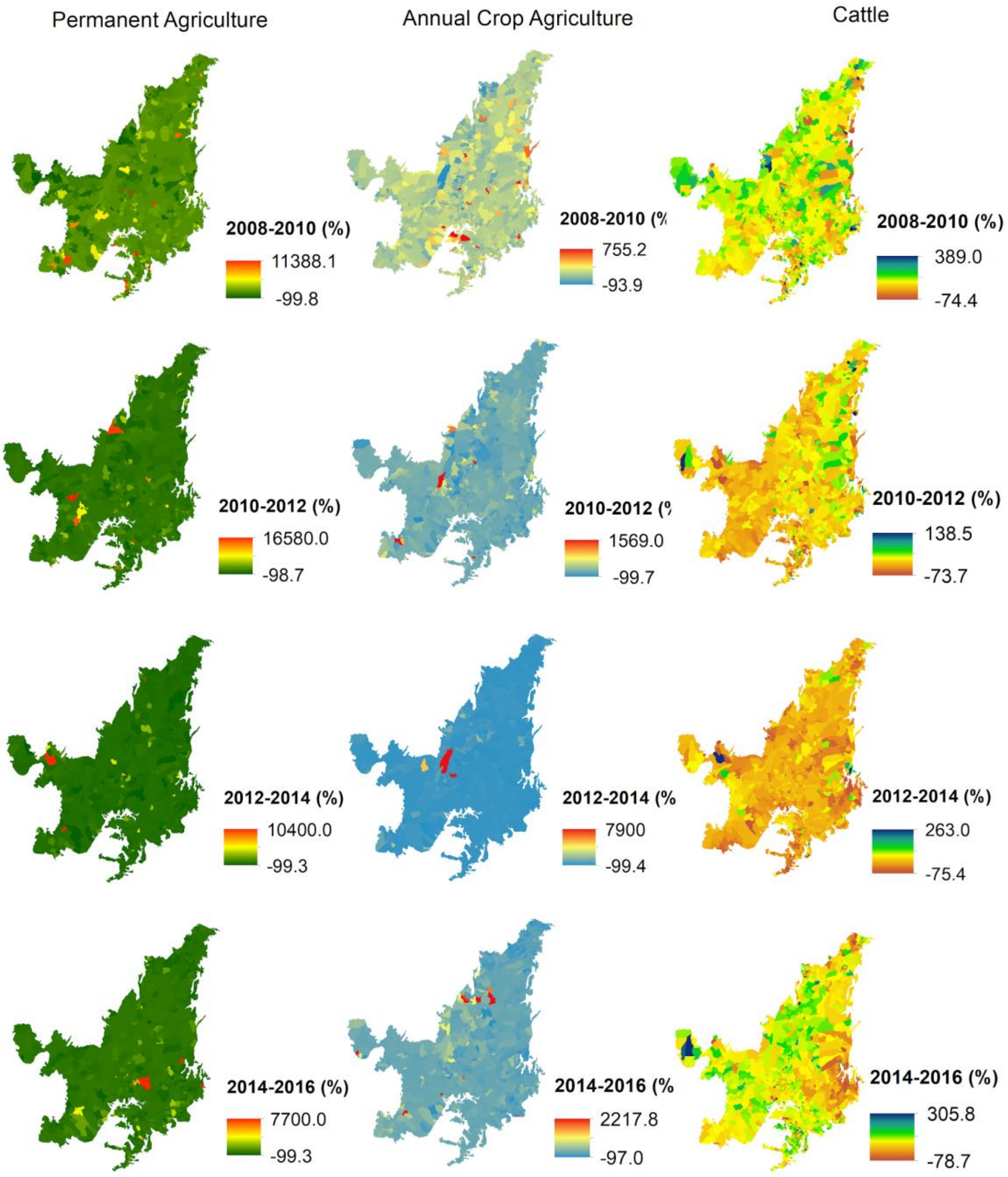

Figure A2. Spatialization of the dynamic variables included in the model in the four periods (2008-2010, 2010-2012, 2012-2014 and 2014-2016). Note: the % is the percentage change between t1 and t2.

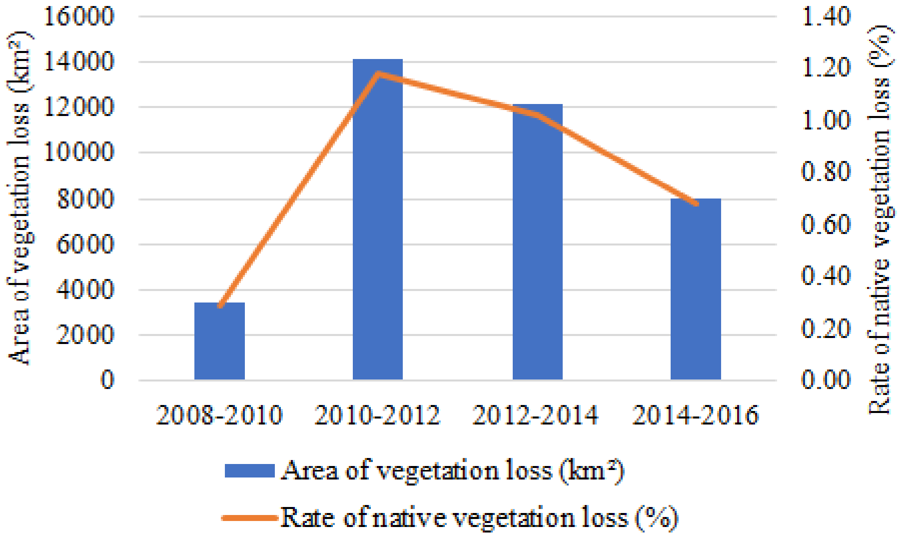

Figure A3. Area and rate of native vegetation loss in the Cerrado in the periods analyzed.

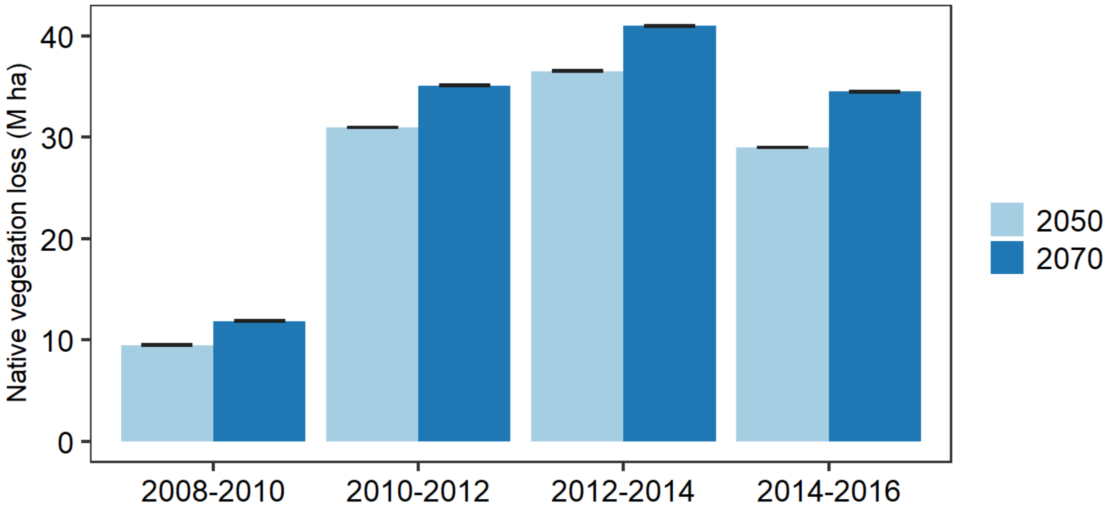

Figure A4. Native vegetation loss by 2050 and 2070 in each period analyzed.

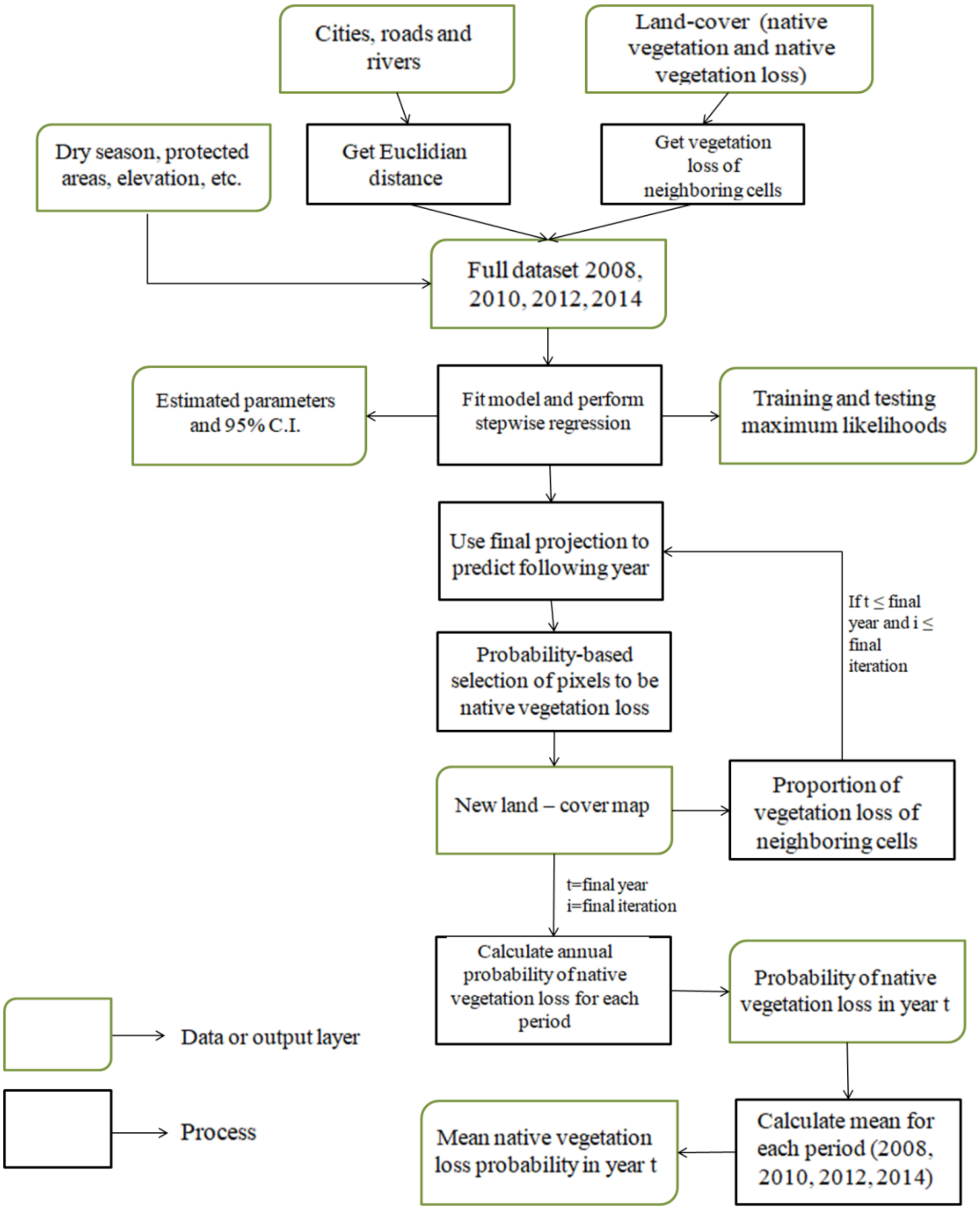

Figure A5. Flowchart of modeling procedure (Guerra et al. 2020), illustrating the construction and running of the vegetation loss model. *i* is the model iteration, and *t* the time step.

Table A1. Input data used to calibrate the model for transition periods 2008-2010, 2010-2012, 2012-2014, and 2014-2016 (dataset name, description, source, reference year and reference).

Name	Description	Source	Year	Reference
Land Cover	Natural (1), Anthropogenic (0)	MapBiomas[1]	08-10-12-14-16	Brandão Jr. et al. 2020
Distance to roads	Euclidean distance to nearest road (m)	IBGE[2]	-	Casella and Paranhos-Filhos 2013
Distance to cities	Euclidean distance to nearest city (m)	IBGE[2]	-	Seto et al. 2012
Dry season length	Number of months with precipitation <100mm	WMO[3]	-	Klink and Machado 2005
Elevation	Altitude (m)	MERIT-DEM[4]	-	Klink and Machado 2005
Agricultural potential	Quality of soil/climate for agriculture	IBGE[2]	-	Klink and Machado 2005
Distance to Rivers	Euclidean distance to nearest river (m)	IBGE[2]	-	
Cattle	Change in cattle heads	IBGE[2]	08-10, 10-12, 12-14, 14-16	Lapola et al. 2014
Permanent Agriculture	Change in permanent agriculture area	IBGE[2]		Lapola et al. 2014
Annual Crop Agriculture	Change in temporary agriculture area	IBGE[2]		Lapola et al. 2014
Protected areas	Protected areas (1), unprotected (0)	IBGE[2]	-	Bensusan 2006

[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).

[4] MERIT-DEM – Multi-Error-Removed Improved-Terrain DEM (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/).

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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