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Drivers and projections of vegetation loss in the Pantanal and surrounding ecosystems

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Abstract

Modeling scenarios can help identify drivers of and potential changes in land use, particularly in rapidly changing landscapes such as the tropics. One of the places where most of the recent anthropogenic land use changes have been occurring is the "arc of deforestation" of the Amazon, where several scenarios have been constructed. Such modeling scenarios, however, have been implemented less frequently in wetland areas, but these are also undergoing rapid change. An example is the Pantanal, one of the largest wetlands on the planet located in the Upper Paraguay River Basin (UPRB). The UPRB is formed by the lowland (Pantanal) and the plateau (Cerrado and Amazon where the spring-fed rivers are). We used a spatially explicit model to identify drivers of vegetation loss in the Pantanal and surrounding area (UPRB) and estimated potential vegetation loss for the next 30 years. The model is probabilistic and considers that vegetation loss is contagious, so that the local rate of deforestation increases over time if adjacent sites are deforested, also taking into account the drivers identified in those locations. Our study is the first to simulate vegetation loss at property-scale, over 20,000 properties, for the entire UPRB in Brazil, taking into account the relationship between the plateau, where headwaters are located, and the lowland, where flooded-areas are concentrated. The drivers of vegetation loss identified for the lowland (distance to roads and rivers and elevation) differed from those for the plateau (distance to cities), demonstrating the relevance of analyzing areas separately. The cumulative rate of native vegetation loss projected for 2050 was 3% for the lowland and 10% for the plateau, representing losses of 6,045 km² and of native vegetation area decreasing from 87% to 83% and 7,960 km² from 39% to 35% respectively by 2050, if

changes continue at the same pace and if the environmental legislation is followed. The projected vegetation loss in the UPRB forms a geographical arc, very similar to that observed in the Amazon, from the plateau into the lowland. The arc is directly related to areas with no or low flooding frequency because they are suitable for agriculture. The identification of this arc of vegetation loss calls for urgent conservation policies for this wetland and new perspectives for management.

Key words: Arc of vegetation loss; agriculture; cattle; Upper Paraguay River Basin; land cover; land use changes.

1. Introduction

Scenarios, produced using simulation models, are important tools for predicting how nature might be impacted by different patterns of future human development and political choices, and projecting the resulting dynamics of land cover and land use change (LCLUC) (Ferrier et al., 2016; Rosa et al., 2017). Such scenarios can also guide attitudes, choices, and actions that increase the probability of realizing a desirable future (Bai et al., 2016). In Brazil, most of these scenario modeling exercises have targeted the Amazon, highlighting potential impacts of maintaining historical rates of deforestation on biodiversity (e.g., Laurance et al., 2001, Soares-Filho et al., 2006), and estimating the impacts of implementing policies to prevent deforestation (Rosa et al., 2013, Bradley et al., 2017). In general, the use of scenario modeling is more common for forested areas than for non-forest biomes, such as periodically flooded savanna, that face significant conversion (Zedler & Kercher, 2005; Reis et al., 2017; Hartig & Bennion, 2017). In addition, to our knowledge, vegetation loss at the property-level has yet to be considered for any tropical wetland.

Simulation models and analysis of historical LCLUC have contributed to identifying areas experiencing rapid transformations. A great example of this is the so-

called “arc of deforestation”, located along the transition between the Amazon and the Cerrado (tropical savanna) biomes (Lathuillière et al., 2016), where the majority of anthropogenic land use change in South America has occurred. The identification of an arc of deforestation is related to both the current rate of transformation, which is faster in the arc than any other place, but also that will likely maintain a rapid rate of change in the coming years based on the modeling (Soares-Filho et al., 2006). Forest loss in the Amazon accounted for 41% of global forest loss (53 out of 129 Mha) from 1990 to 2015 (FAO, 2016), 70% of which was in the Legal Amazon in Brazil (36 Mha) (INPE, 2016). Other biomes within Brazil have also experienced significant LCLUC over the last few decades, such as the Cerrado (Spera et al., 2016) and the Pantanal (Roque et al., 2016), but have received fewer targeted conservation actions.

The Pantanal is a periodically flooded savanna (Junk et al., 2013), one of the most biodiversity-rich wetlands in the world (Junk et al., 2011), it is located within the Upper Paraguay River Basin (UPRB) and comprises a lowland area (Pantanal biome) and a plateau that includes the Pantanal and the surrounding Cerrado and Amazon biomes. It is also among the regions of Brazil that have experienced the greatest landscape change in recent years showing the need for improving public policies (SOS Pantanal et al., 2017, Tomas et al. 2019). Given the widely-expected near-future trend of agriculture expansion (Foley et al., 2005), there is an urgency to anticipate what this expansion might represent in terms of the future of this special biodiversity-rich biome (Junk et al., 2006) and an important area of multiple ecosystem services (ES) that is needed for global evaluation of ES monetization (Costanza et al., 1997; Davidson et al., 2019) in order to develop preventive conservation measures to minimize impacts.

Hence, scenario modeling can contribute to improve awareness and perception of future trends and problems related to land use change in the Pantanal, and thus inform

decision-makers with public power, especially lawmakers, and in the private sector. Brazil has recently introduced several bills that represent environmental setbacks, such as the bill that provides for the extinction of the ‘Legal Reserve’ (PL 2,362/2019) which was withdrawn after popular pressure (Abessa et al., 2019, Kehoe et al., 2019; Zeidan, 2019, Lorrán, 2019). Therefore, estimating the trends of vegetation loss and detecting their main drivers can support urgently-needed pleas to develop more ecosystem-based policies (Sacarano, 2017, Kasecker et al., 2018) and to help citizens communicate to policy-makers the need to avoid policies that further threaten the environment.

We used a published and validated spatially explicit model (Rosa et al., 2013) to initially identify the main drivers of vegetation loss in UPRB by considering the different dynamics of the plateau and lowland, owing to historically distinct land use and occupation, as well as the lowland flood pulse. Once main drivers of vegetation loss were identified, we used our model to generate projections of the probability of native vegetation loss by the year 2050 for the basin as a whole, and considering both the lowland and plateau separately. Our goal was to identify areas under greater threat of conversion and to identify potential geographical patterns of land use (e.g., Arc) in this biome, thus helping to guide and inform targeted conservation actions.

2. Materials and Methods

2.1 Study site

In Brazil, the Pantanal extends across the states of Mato Grosso and Mato Grosso do Sul, occupying 41% of the Upper Paraguay River Basin (UPRB). The basin includes three biomes: the Pantanal (lowland), which has 80% of its area flooded every year, the Cerrado and the Amazon, on the plateau where the spring-fed rivers are located (Fig. 1) (SOS Pantanal et al. 2017). The Pantanal is marked by an annual flood pulse that presents a great

variation of time and extension due to the heterogeneity of environments (Nogueira et al., 2002; Junk et al., 2013). The flood pulse spreads from north to south due to the influence of the Amazon rain regime on the northern Paraguay River (Bergier et al., 2018; Hamilton et al., 2002; Oliveira et al., 2018) and reaches the south of the Pantanal months later during the dry season. The pulse shapes the extent of terrestrial and aquatic environments on the lowland, which determines the region's livestock and agricultural production areas (Abreu et al. 2010).

The UPRB is also among the regions of Brazil that have experienced the greatest landscape change in recent years, with anthropogenic use reaching 61% in the plateau and 13% in the lowland in 2016 (SOS Pantanal et al., 2017). Agriculture, livestock expansion and associated infrastructure development have been suggested as the main drivers of habitat degradation across this biome (Silva et al., 2011; Miranda et al., 2018), and the flood pulse is a key element for the dynamics of this system (Fig. 1) (Junk & Wantzen, 2004).

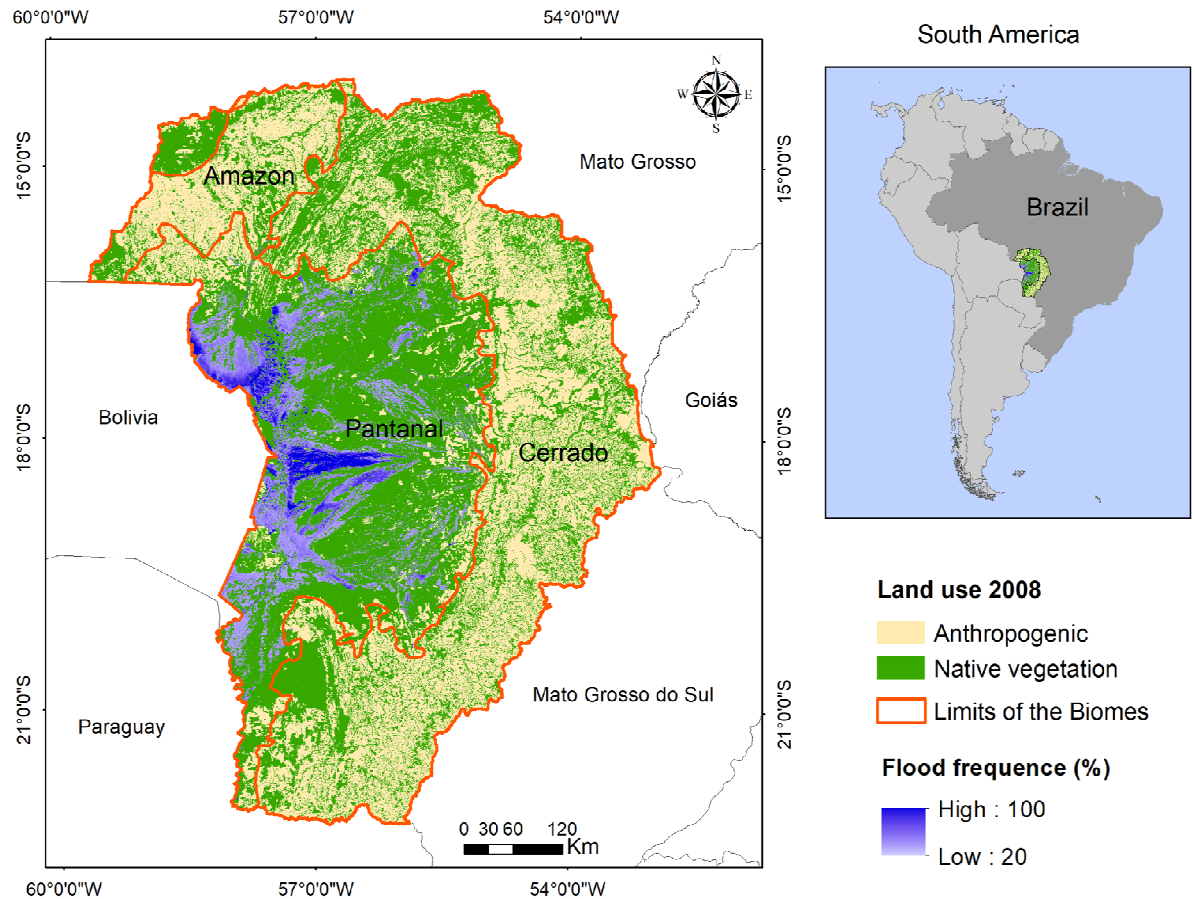


Fig. 1. Land use and flood pulse in the Upper Paraguay River Basin in 2008.

2.2 Data sources

To identify the drivers of native vegetation transformation in the studied area we first performed a literature review (Table A1). On the one hand, the expansion of agriculture and livestock were reported by several studies as the main drivers of native vegetation loss for the UPRB (Harris et al., 2005; Silva et al., 2011). In addition, owing to seasonal flooding in the Pantanal, many roads have been built using landfills to allow transit throughout the year (Tomas et al., 2009). It is known that the opening of roads, either officially or illegally, allows human expansion and (often illegal) occupation of land, and thus acts as a facilitator of native vegetation loss (Laurance et al., 2009). The expansion of cities into areas of native

vegetation also acts as a vector of deforestation (Seto et al., 2012). On the other hand, native vegetation loss is expected to be lower in protected areas owing to restrictive land use measures (Bensusan, 2006).

For our model we used the rules of the Native Vegetation Protection Law (NVPL), which establishes that the width of “*Área de Preservação Permanente*” (APP; Permanent Protection Area) depends on the width of the river channel and slope areas (Brazil, # 12,651, of 2012) (see details in Appendix A). To calculate Legal Reserve (LR) area, we followed the national legislation (NVPL), which establishes values of 20, 35, 50, and 80% depending on the biome in which the property is located and the size of the rural property (Soares-Filho et al., 2014, Brancalion et al., 2016). We also adopted the state legislation of Mato Grosso do Sul # 14,273 of 2015, which requires rural properties in the lowland Pantanal to have LRs of 40% in grassland formations and 50% in forest areas. We only used the Mato Grosso do Sul Decree because the Mato Grosso Decree does not mention legal reserve percentages for the Pantanal. Considering that the Pantanal has a greater proportion of grassland formations, we established a value of 40% for the entire area. Hence, the UPRB includes areas with LRs of 20, 35, 40, 50, and 80%, depending on where a rural property is located (Fig. A1). We used a shapefile with all properties located in the studied basin and registered in the “*Cadastro Ambiental Rural*” (CAR; Rural Environmental Registry, see details in Appendix A) until June 2018.

We obtained land use maps produced by SOS Pantanal et al. (2017), which is a non-governmental organization that has been regularly monitoring land use dynamics in UPRB. The following maps were available for our analysis: 2008-2010, 2010-2012, 2012-2014, and 2014-2016. These maps classify land as either ‘natural’ or under ‘anthropogenic use’ and were produced every two years. The thematic classification considers in its ‘natural’ class natural areas used as pastures, since cattle have been using native grasses as pasture

for a century in the region. Anthropogenic areas are only classified as such when conversion from natural vegetation has been identified (e.g., when planted pastures are identified). The process of interpreting changes in the UPRB monitoring follows the IBGE legend standards (scale 1:100,000) (Veloso et al., 1991), considering the first level of vegetation grouping.

Apart from the land use maps, we collected a set of ten input variables for the model based on the potential drivers identified above (Table A1). All data were converted to the same resolution as the land use maps (600 m x 600 m) and projected onto the same coordinate system (WGS 1984 UTM Zone 21S). We then separated the variables into two categories: static and dynamic. Static variables were kept constant over time, either because they were assumed to not change over the time period analyzed (e.g., elevation, distance to rivers) or because we lacked data to update them (e.g., distance to roads, distance to cities, protected areas). Dynamic variables represent characteristics of the landscape that change over time, namely land use. We calculated the static variables only once, at the beginning of the modeling process, while the dynamic variables were recalculated at each time period (every two years). Finally, we used a dynamic variable to account for the neighborhood effect — the proportion of anthropogenic cells within the vicinity of the focal cell — which updates the odds of local native vegetation loss (Rosa et al., 2013, 2015).

2.3 Model

Our model is based on $P_{nvl,x,t}$ (Eq. 1), where P_{nvl} is the probability that a ‘native vegetation’ cell x is converted into ‘anthropogenic use’ within a defined time interval t (for full details see Rosa et al., 2013, 2015). 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:

$$P_{nvl,x,t} = 1 / (1 + \exp -k_{x,t}) \quad \text{Eq. 1}$$

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 (Fig. 2 for all modeling steps).

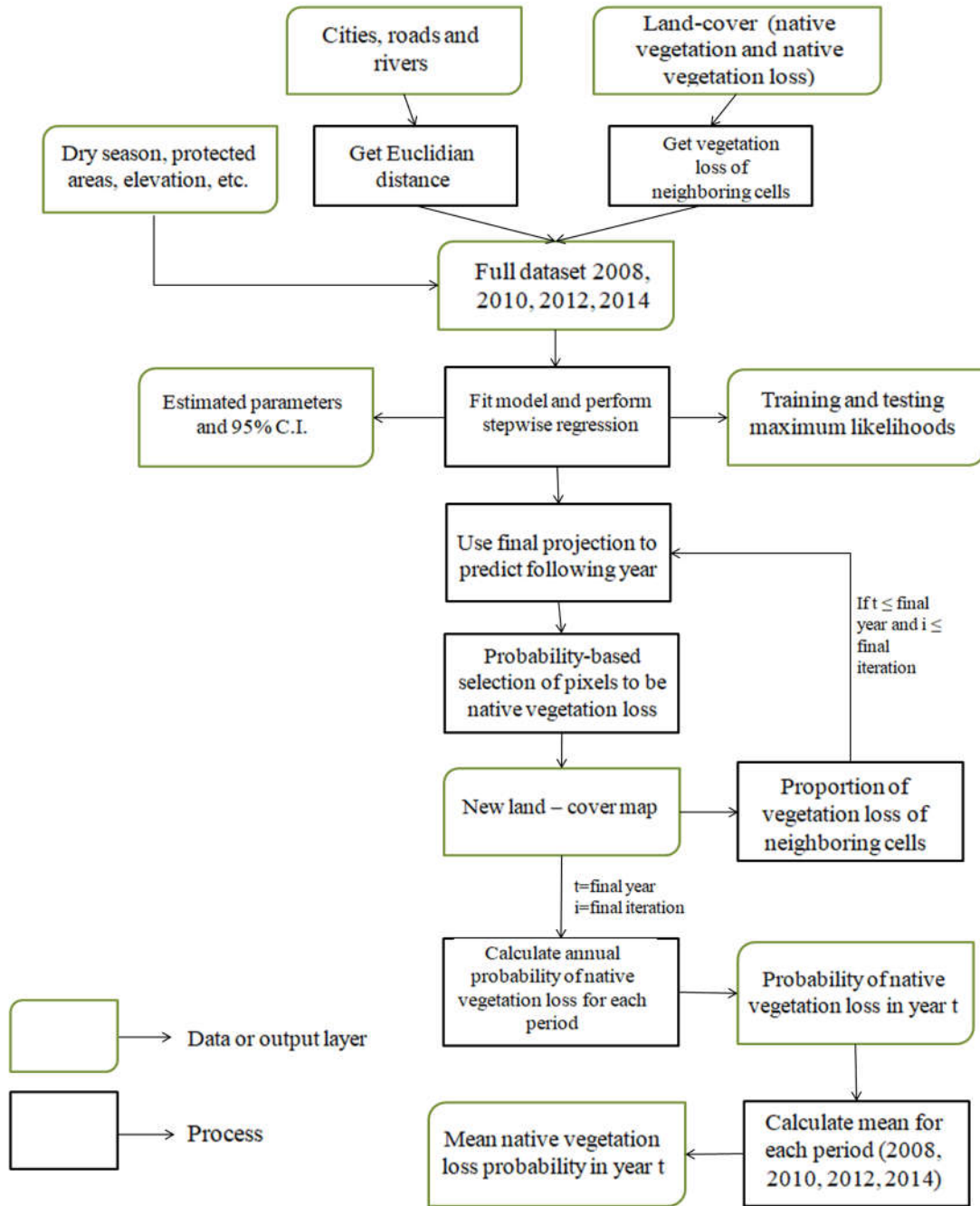


Fig. 2. Flowchart of modeling procedure (adapted from Rosa et al., 2013), illustrating the construction and running of the vegetation loss model. i is the model iteration, and t the time step.

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 (see Fig. A2).

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 of Appendix A).

We generated projections for native vegetation loss patterns in UPRB for: (1) the basin as a whole; (2) the lowland; and (3) the plateau (allowing for the drivers to weigh in differently for the two regions). After calculating the average rate of vegetation loss for the four periods (2008-2010, 2010-2012, 2012-2014, and 2014-2016) for the two areas and the areas combined, we obtained the UPRB projection by executing the model for the whole

area (UPRB) and for the lowlands and plateau (Low+Plat) separately, thus better reflecting sub-regional dynamics (Fig. A3).

Once we simulated future vegetation loss, we used MapBiomas Alert (a deforestation alert validation and refinement system in Brazil, <http://alerta.mapbiomas.org/>) to validate the areas with the highest land use conversion projected by our model.

3. Results

3.1 Drivers of native vegetation loss

Most of the variables had the expected impact on observed native vegetation loss but their importance varied both spatially (between lowland and plateau) and temporally (among the different calibration periods [2008, 2010, 2012, 2014, Table 1]). Commodity agriculture, represented in our models by agricultural potential, cattle ranching, area of permanent agriculture, and area of temporary agriculture, consistently led to higher probabilities of native vegetation loss over time, particularly in the plateau (Table 1). Conversely, protected areas were significant in reducing the probability of vegetation loss, with less native vegetation loss than in unprotected areas, except in 2010 (both in the plateau and lowland). Elevation was found to be a driver for vegetation loss for the lowland in 2010, 2012, and 2014, and for the plateau in 2010. Accessibility played a significant role in determining vegetation loss in the lowland, with the variable distance to roads leading to higher vegetation loss, but with no impact on the plateau. Finally, distance to cities and distance to rivers had a positive impact only in one time period (2010-2012), for the plateau and lowland, respectively (Table 1, see Model UPRB Table A3).

Table 1. Means for single variable models for the plateau and lowland separately.

Variables	Plateau				Lowland			
	2008	2010	2012	2014	2008	2010	2012	2014
Land Cover	1.109E+00	5.999E-07	9.564E-07	6.605E-07	3.635E+00	4.202E+00	2.426E+00	3.196E+00
Distance to roads	0	0	0	0	-1.000E-11	0	-1.100E-11	0
Distance to cities	0	1.000E-12	0	0	0	0	0	0
Dry season length	0	0	0	2.500E-07	-9.842E-07	-9.758E-07	-9.874E-07	-9.876E-07
Elevation	0	0	0	0	2.102E-09	0	5.910E-09	3.045E-09
Agricultural potential	1.825E-08	0	2.430E-10	7.000E-12	0	2.043E-07	0	0
Distance to rivers	0	0	0	0	0	3.000E-12	0	0
Cattle	6.574E-09	0	-1.470E-10	2.711E-09	1.429E-08	0	4.596E-09	0
Permanent agriculture	0	0	-2.930E-10	-6.450E-10	0	5.562E-09	0	0
Annual crop agriculture	-3.196E-09	0	3.150E-10	-2.179E-09	-6.319E-09	-5.377E-09	-1.582E-09	1.432E-09
Protected areas	-7.805E-07	0	4.222E-07	-4.968E-07	-1.679E+00	0	-1.576E+00	-1.787E+00

3.2 Projection of native vegetation loss

The cumulative rate of native vegetation loss projected by 2050 was 3% for the lowland and 10% for the plateau. These values represent an accumulated loss of 6,045 (± 363 95% C.I.) km² for the lowland and 7,960 ($\pm 1,574$ 95% C.I.) km² for the plateau, for a total of 14,005 ($\pm 1,937$ 95% C.I.) km² of native vegetation converted to anthropogenic use from 2018 to 2050 in the entire basin. The annual rate of vegetation loss was higher for the plateau than for the lowland for all periods (Fig. 3a), and these rates tended to decrease over the years. The rates of vegetation loss projected by the Lowland + Plateau models were lower than the UPRB model (Fig. 3b; see model UPRB in Appendix A).

We mapped the probability of native vegetation loss in the UPRB by 2050 (Fig. 4) based on the cumulative annual probabilities of native vegetation loss generated for the plateau and lowland separately (the equivalent of the whole UPRB model presented in Appendix A, Fig. A4). The chance of losing vegetation by 2050 reaches 74% in several areas of the plateau and in some bordering areas between the plateau and lowlands near areas already under high anthropogenic pressure (Fig. 4). An animation of the progression over time of the probability of loss of native vegetation from 2018 to 2050 under the UPRB can be found in <https://tinyurl.com/y28xpl6b>.

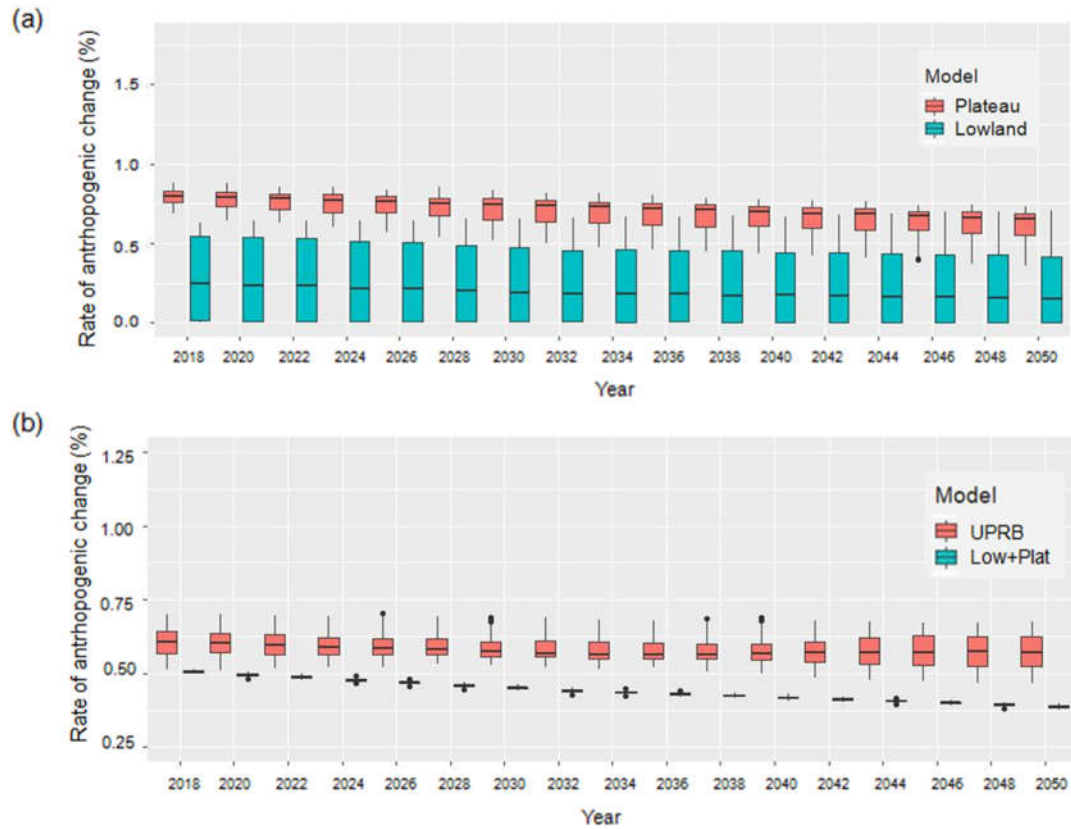


Fig. 3. Projections of annual rate of vegetation loss between 2018 and 2050 for the models of plateau and lowland separately (a), and for the model of the entire Upper Paraguay River Basin (UPRB) (b) where the model was executed for the whole area at the same time (UPRB) and for the lowlands and plateau (Low+Plat), where the model was run separately for the two regions, thus better reflecting sub-regional dynamics.

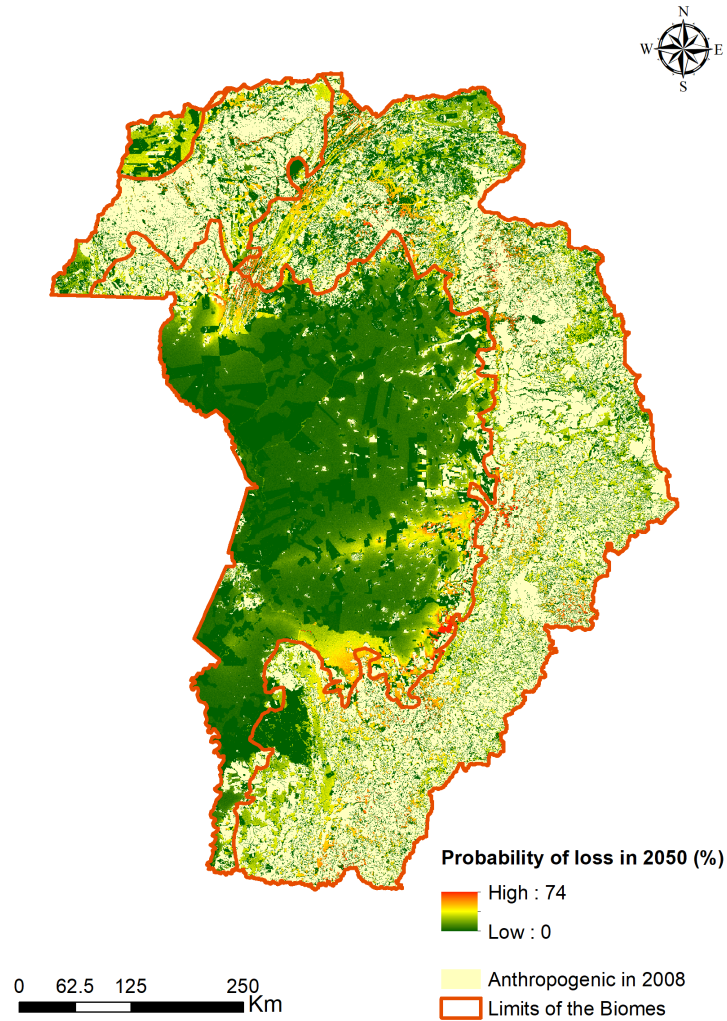


Fig. 4. Projections of accumulated native vegetation loss by 2050 for the mean values of the four periods (2008-2010, 2010-2012, 2012-2014 and 2014-2016) for models of lowlands + plateau.

3.3 *Arc of native vegetation loss*

Our simulations revealed that vegetation loss in the UPRB forms a geographic arc, much like what has been observed in the Amazon, i.e. the “arc of deforestation”. The arc starts on the plateau and continues through the border of the lowlands, i.e. the transition areas, where land use conversion has been occurring and is projected to continue at a faster rate (Fig. 5).

Furthermore, we found a strong coincidence between our model's projections and the alerts from MapBiomas (Fig. 5).

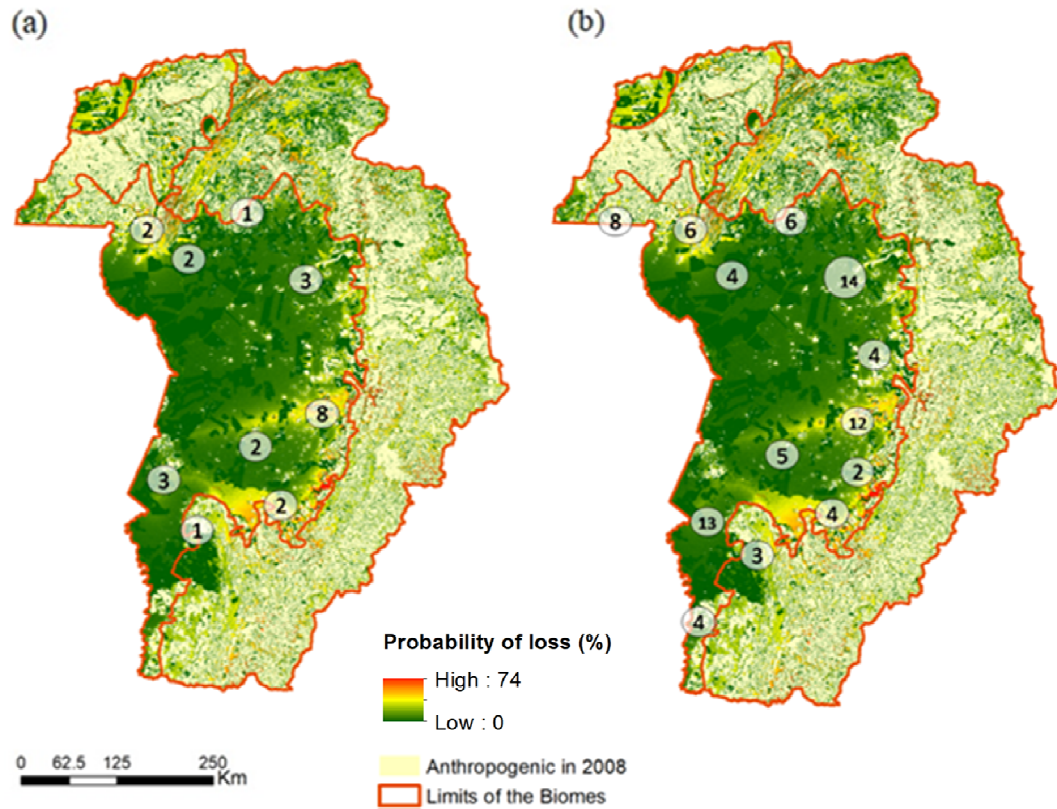


Fig. 5. Projection of vegetation loss in the UPRB based on the Lowland + Plateau model and validation by MapBiomas Alerta. Numbers (1 to 14) represent the number of areas experiencing vegetation loss as detected by MapBiomas Alerta for (a) July 2018 and (b) March 2019.

4. Discussion

4.1 Drivers of native vegetation loss

Building separate scenarios for the plateau and lowland allowed to estimate differential effects of LCLUC drivers within the two areas. Such differentiation is important from a

policy perspective because it provides useful information for developing more targeted actions at the main relevant actors in each part of the UPRB. This may be important not only for the Pantanal, but for wetlands in general, since these environments usually depend on their surrounding areas.

Agriculture has been the world's greatest driver of landscape and biodiversity change (Foley et al., 2005, Godfray & Garnett, 2014, Struik & Kuyper, 2017), and it is expected to continue as such (Ferrier et al., 2016). Our results show that this is also true for UPRB, with variables associated with commodity agriculture strongly weighting on all models, and especially the plateau, which does not experience a flood pulse. The native vegetation of the plateau has been experiencing rapid depletion with replacement by mechanized agriculture since the 1970s, with a predominance of grain monoculture (soybean, maize, and cotton) and of sugarcane for the production of biofuels (Azevedo & Monteiro, 2003). The annual area of agriculture increased by 39% from 2001 to 2013, while sugar cane production increased by approximately 48% during the same period (Coutinho et al., 2016). Soybean cultivation in the region doubled between 2009 and 2016, rising from 3,000 to 6,000 km² (SOS Pantanal et al., 2017), which represents less than half of the projected loss of native vegetation until 2050 (14,005 km²), evidencing the high-speed and recent increase of land conversion.

The change of natural areas to agriculture in the plateau has caused soil erosion and silting of rivers, altering their flow and hydrological regimes in the lowland, as has already been observed in the Upper Taquari Basin (Assine, 2005, Galdino et al., 2006). Furthermore, cattle density has increased more rapidly in the plateau than in the lowland (SOS Pantanal et al., 2017). Livestock farming was established in the UPRB in 1990, and contributes significantly to the region's economy. Today cattle breeding is an important tradition in the Pantanal, where it accounts for 65% of its economic activity (WWF, 2015).

The states of Mato Grosso do Sul and Mato Grosso, where the UPRB is located, are the main cattle producers in the country, concentrating, respectively, 10% and 14% of the Brazilian herd (IBGE, 2018). Our model demonstrates that the trend is to continue - that is, the drivers of vegetation loss identified in the model are those that have historically shaped the landscape in the region, i.e. commodity agriculture, such as crop production and cattle ranching.

The role of roads in driving vegetation loss differed in the lowland and plateau. Much as in other tropical biomes (Laurance et al., 2009), we found that roads are important catalysts of native vegetation loss in the lowlands, and historically in the plateau where agriculture expansion was associated with rapid expansion of the road network (Castillo et al., 2011). In addition to a dense road network, the highest density of cities in UPRB is on the plateau. This location is also due to the flood dynamics in the lowlands where occupation is less frequent. Hence, our results showed that roads do not have an influence on vegetation loss in the plateau, probably due to these effects occurring in the past when the roads were built, well prior to the period of our analysis (from 2008). The UPRB Law (State Law # 8,830, of 2008) of the state of Mato Grosso allows the construction of roads to access rural properties in permanent conservation areas (floodplains, corbels, river meanders, marginal bays, lagoons, mountain ranges, natural marginal dikes, bush beds, and murunduns), as long as they do not block water flow. Our analyses only took into account official roads; in the case of the lowland, which holds a large number of unofficial roads, this variable should have a larger effect (e.g., Barber et al., 2014). Furthermore, our model did not consider new roads (e.g. trans-ocean construction), which may open new frontiers for agriculture development and hence native vegetation loss. Future road construction will lead to increased transportation and consequently more land use change. However,

projecting when and where these roads will actually be built is highly uncertain, therefore, we adopted a conservative approach of retaining the road network as it is presently defined.

The result indicating that the distance of rivers only explained the loss of vegetation in the lowland and only in the period 2010-2012, it is possibly due to the extreme drought that occurred in 2012 in the Pantanal (see <http://glo.bo/QXRrS3>), suggesting that in periods of severe drought, land use change tends to occur closer to rivers. Our results showed the importance of considering wetland dynamics, such as with the Pantanal, that are governed by a flood pulse. Flood pulses add complexity to models since they are related to the presence of other drivers of native vegetation loss, such as the presence of roads, cities and permanent agriculture. Although we did not include flood pulse in the model of the present study, it is evident that vegetation loss was not predicted for areas with 20% or more flood frequency, owing to the biophysical constraints it presents (Figs. 1 and 4).

Besides the conversion of land for specific uses, including livestock and agriculture, environmental legislation also has an impact on conversion rates. We highlight an increase in land conversion in the lowland during 2008-2010, whereas it increased in the plateau between 2014-2016 (Fig. A2). The Cerrado experienced a decrease in conversion rates from 2005 to 2010, and then remained constant until 2015 when it began to rise and continued to do so in subsequent years (Rochedo et al., 2018). This trend may have been partially a result of the soy expansion, a major driver of recent clearing in the Cerrado (Rausch et al., 2019; Sorretoni et al., 2019). Moreover the increase in the land-use conversion for agriculture may be associated to the Native Vegetation Protection Law (NPVL) of Brazil, popularly known as the 'New Forest Code' in 2009 (Sorretoni et al., 2018). From that year onwards (when the bill that intended to change the Forest Code of 1965 was presented in Congress), the bill opened up possibilities for decreasing several conservation and restoration requirements in the Cerrado, while in the Pantanal there was a

time lag after the approval of a new law (NPVL) in 2012 allowing for new legal land use conversions (Garcia et al., 2013; Soares-Filho et al., 2014; Brancalion et al., 2016). Hence, improved legal enforcement will do little to eliminate clearing for agriculture in the Cerrado (see Rausch et al., 2019) and the Pantanal because most of it takes place within legal limits. Compared to the previous law (from 1965) this new law (NPVL) allows certain vegetation to be legally converted.

4.2 Projection of native vegetation loss

By 2016, the percentage of the lowland in UPRB under anthropogenic use was 13%, while on the plateau it was 61% (SOS Pantanal et al., 2017). Our projections reveal that these areas can reach, respectively, 17% (± 1.4 95% C.I.) and 65% (± 1.2 95% C.I.) by 2050. These values may be conservative because they do not consider a strong increase in commodity agriculture, neither do they include potential future infrastructure development. Furthermore, the current government recently revoked (Decree # 10,084/2019) a legal impediment of agro-ecological zoning (Decree # 6,961/2009) that used to prevent the advance of sugarcane plantations in Pantanal, the UPRB, and the Amazon. Hence, releasing the ban on sugarcane farming in these ecologically vulnerable regions may lead to further land use conversion beyond those projected by our model.

In addition, the low conversion rate of native vegetation projected for the lowlands considers the entire area of the region (151,119 km²), and not only the areas that can be converted, which are areas that do not have a flood pulse. As a result, the projected loss of more than 6,000 km² for the lowlands is concentrated in a small area in the transition with the plateau, which can result in the loss of important ecosystem services. It is worth emphasizing that these values are considering full compliance with the NPVL. This loss of vegetation, mainly on the plateau, is likely to have environmental impacts (river

sedimentation, change in the flood regime, habitat loss) in the lowlands owing to sediment transport from the plateau (Abdon et al., 2005). Loss of vegetation can increase sediment flow to 191% and water discharge to 82% in the lowlands, which can lead to significant changes in flood dynamics and ecosystem functions and services (Bergier, 2013). Therefore, an expected increase in conversion of native vegetation into other uses can cause important changes in the intensity and duration of floods. This may have long-term impacts on the distribution and survival of species in the Pantanal (Junk et al., 2006), as is the case with migratory species of fish and birds (Resende, 2003, Nunes & Tomas, 2004). In addition, 62 plant species that are listed among three threat categories (IUCN) (Loyola et al., 2014) occur in the basin (12 in the Pantanal), with the effect of changing land use on them remaining unknown. Hence, there is an urgent need not only to understand what drives LCLU in this wetland, but also to map existing priority areas for conservation and restoration of the Pantanal and its surroundings. The present study aims to support such efforts by highlighting areas under greater threat of conversion.

4.3 Arc of native vegetation loss

Our simulations revealed a geographic pattern in land use change at the borders between the Cerrado, Pantanal, and Amazonia biomes in the form of an arc. Instead of an “arc of deforestation”, as in the Amazon, this pattern is better referred to as an arc of vegetation loss, since much of the area is actually represented by non-forest systems including grassland and savanna. Identifying this arc offers new perspectives for management and the urgent development of policies for the conservation of this wetland. Mapbiomas Alerta revealed that, as of October 2018, the UPRB had 24 vegetation loss alert areas, and that the number increased rapidly to 85 areas in 2019, with most being in the area of transition between the Pantanal and Cerrado, in the area of the arc (Fig. 5). The arc is located on areas

that do not, or infrequently, flood, demonstrating a clear pattern of agricultural expansion into non-flooding areas. It is expected, therefore, that land conversion would extend through borders into wetlands until reaching areas that flood, since flood dynamics will always be a significant challenge for the most common crops or pastures. The loss in the arc of vegetation is likely to be accompanied by a higher frequency of fires in the future. Fire management (such as prescribed fires and creation of firebreaks) should be one of the priorities. However, it is noteworthy that fire management in wetlands is extremely complex, as it involves relationships between flood pulse, biomass, and land uses (De Oliveira et al., 2014; de Sá Arruda et al., 2016).

Our results corroborate other studies that highlight an urgent need for clear conservation policies for the Pantanal and its surroundings involving different sectors and based on scientific evidence (Alho & Sabino, 2011, Roque et al., 2016). Such efforts should include the creation of new protected areas, particularly in areas under greater pressure, and the maintenance of the current conservation unit system, which seems to have been efficient in preventing the loss of native vegetation in the UPRB (Table 1). Considering that 85% of the Pantanal is occupied by private lands, strategies to preserve this important biome should focus on strategies for private properties, such as payments for ecosystem services, tax incentives and for sustainable value chains.

Simulations, such as those performed here, can help society develop social, ecological and environmental strategies towards sustainability. By identifying areas of rapid land use change, our study allows stakeholders and decision-makers to make decisions about where actions are more relevant to transform the future. For example, we believe that for the arc of vegetation loss, beyond the general actions already suggested for the entire Pantanal and surrounding area (Lourival et al., 2009, Roque et al., 2016, Tomas et al., 2019, Schulz et al. 2019), innovations that consider the rapid rate of change and

opportunities expected for the zone in the coming years are needed. Among these innovations, we suggest that approaching the arc as a Sustainability Transition Zone would open new avenues for management and governance (see Loorbach et al., 2017). Under this perspective, a wider range of governance instruments can be employed, such as incubation of spaces for disruptive initiatives of economic chains based on ecological services, facilitated by government interventions. Such instruments can change the current trend in the arc from being just one more case of rapid land use change focused on the production of commodities in the tropics, towards a new history of conciliation between food production and the conservation of biodiversity and ecological services.

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Appendix A

Native Vegetation Protection Law

The Native Vegetation Protection Law (NVPL), which establishes that the width of “*Área de Preservação Permanente*” (APP; Permanent Protection Area) depends on the width of the river channel: (a) 30 m for water courses less than 10 m wide; (b) 50 m for water courses ranging from 10 to 50 m wide; (c) 100 m for water courses ranging from 50 to 200 m wide; (d) 200 m for water courses ranging from 200 to 600 m wide; and (e) 500 m for water courses greater than 600 m wide (Brazil, # 12,651, of 2012). However, we acknowledge that these minimum dimensions are not for rural properties that did not comply with the former law (Forest Code of 1964), for which NPVL defined that the width APP of riparian vegetation to be restored depends on the size of the rural property and not only the river width (see Fig. 6 of Brancalion et al., 2016). Hence, our model considered all vegetation as being on land of an owner who complied with the former law. We also considered APP in slope areas according to NVPL: on slopes greater than 45°, equivalent to 100% in the line of greatest decline.

According to the Decree #7,830 of 2012, the NVPL created the Environmental Rural Registry (“Cadastro Ambiental Rural,” CAR, in Portuguese). The CAR is a mandatory self-declaratory electronic registration system, which consists of collecting georeferenced information of all rural properties. Landowners are required to delineate Areas of Permanent Protection (APP), Legal Reserve (LR), remnants of native vegetation, consolidated rural areas, areas of social interest and public interest, in order to draw a full digital map of their properties from which the values of the areas for environmental diagnosis are calculated. To ensure that the property fits to the environmental regularization

in the Environmental Compliance Program (“Programa de Regularização Ambiental”, PRA, in Portuguese), after registration, the state environmental agency (IMASUL) verifies the mapping. If the property has environmental liabilities, the landowner will need to commit to recover the damage caused before the property or by buying an Environmental Reserve Quota (“Cota de Reserva Ambiental,” CRA, in Portuguese) in the case of environmental liabilities of LR (CRA is only for legal compliance of RL) or by restoring the LR. In case of environmental liabilities of APP, the owner has the obligation to restore the APP.

Results for UPRB Model

The important variables in all the periods for the UPRB model were dry season duration, elevation, cattle herds, and annual crop agriculture (Table A3). Permanent agriculture and protected areas were significant in three of the four periods. The agricultural potential was significant in just two periods and distance from the roads in only one period (2008-2010). The distance from the rivers and cities was not significant for the model (Table A3).

Our projection predicts that from 2016 to 2050, 14% of the native vegetation of the lowland and 23% of the plateau will be converted into anthropogenic areas. These rates result in 23% of anthropogenic use by 2050 for the lowlands and 75% for the plateau. These values are much larger than those designed by the Lowlands + Plateau models. We mapped the probability of loss of native vegetation by 2050 (Fig. A4), based on the cumulative probabilities of native vegetation. The probability of maximum loss of vegetation reaching 86%, with the highest rates located in the plateau. We constructed a video with the evolution of vegetation loss between the years 2018 and 2050 for UPRB Model (<https://tinyurl.com/y5l844kb>).

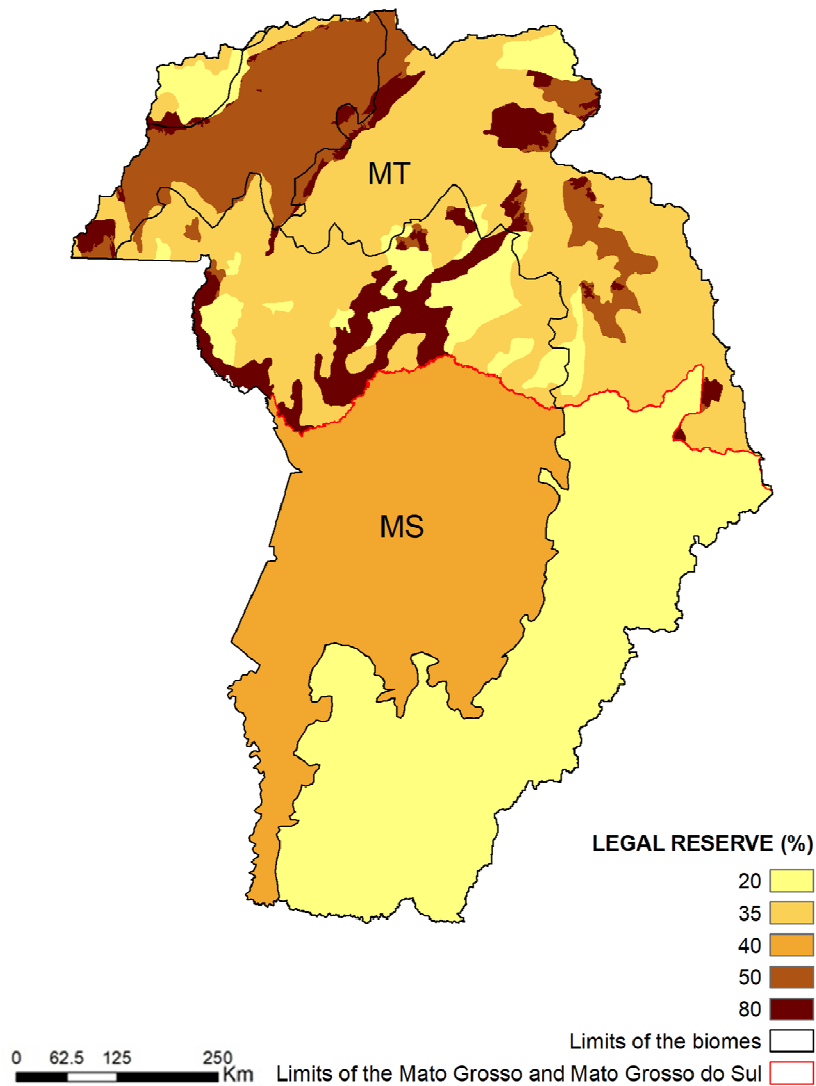


Fig. A1. Legal Reserve for property (%) in accordance with Law 12,561 of 2012 (“New Forest Code”) regulating different sizes depending on biome and legislation of Mato Grosso do Sul (#Decree 14.273 of 2015), regulating that LR should be 4% for grassland formations and 50% for forest areas of rural properties of Pantanal lowlands. Legend: MS: Mato Grosso do Sul, MT: Mato Grosso.

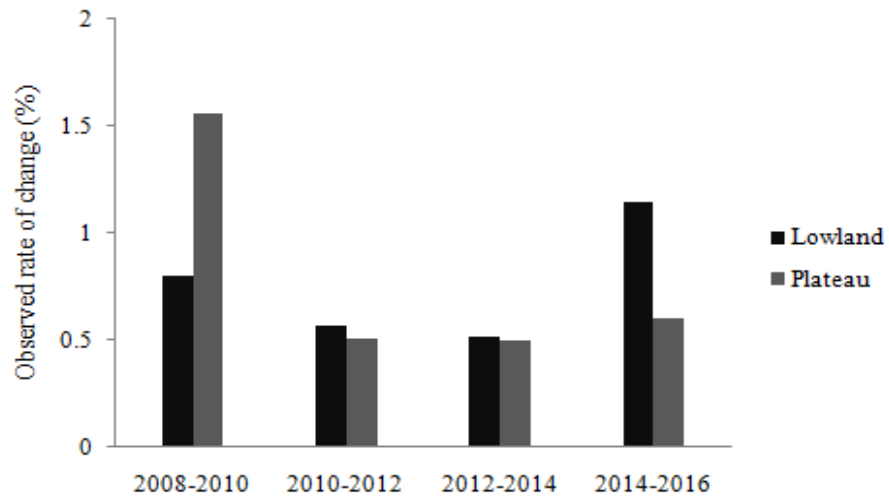


Fig. A2. Observed rate of native vegetation loss (%) per year in the lowland and plateau during the analyzed periods.

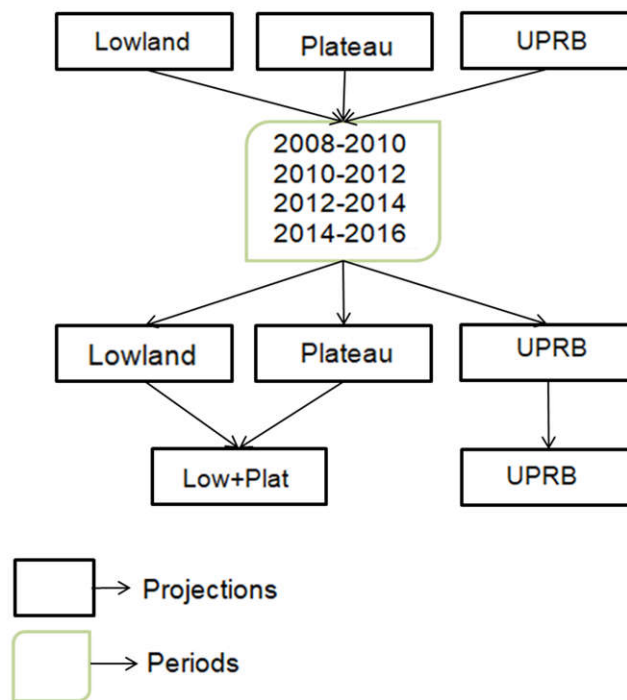


Fig. A3. Flowchart of projections for native vegetation loss in the Upper Paraguay River Basin, with Model UPRB (Upper Paraguay River Basin) and Lowland+Plateau models.

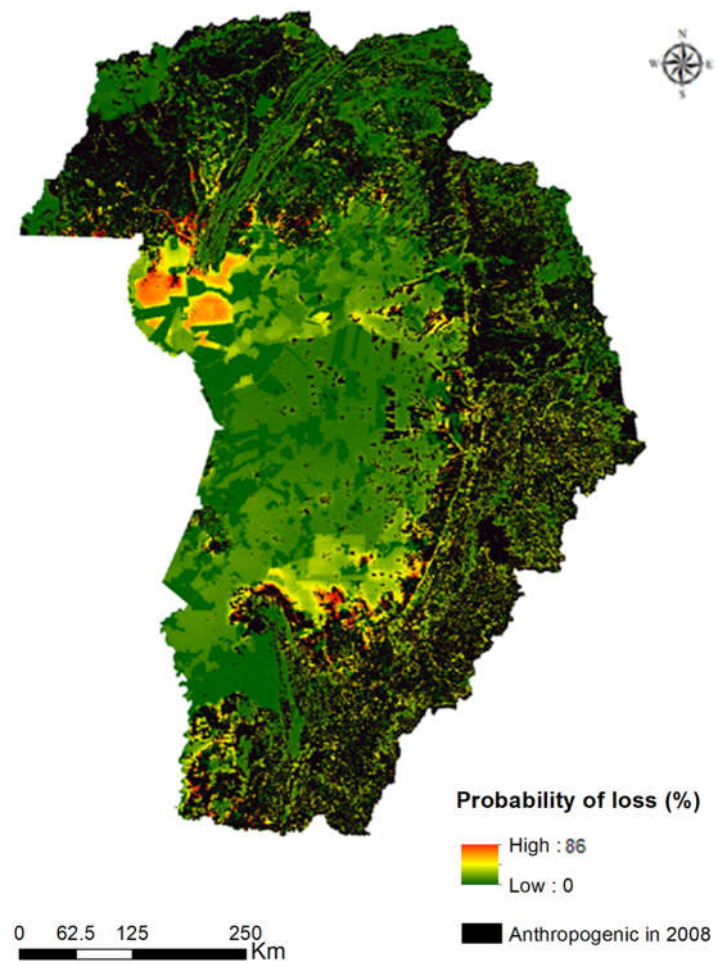


Fig. A4. Native vegetation loss predictions (in %) for the mean values of four periods (2008-2010, 2010-2012, 2012-2014, and 2014-2016) for the UPRB (Upper Paraguay River Basin) model accumulated by 2050.

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)	SOS Pantanal ¹	08-10-12-14-16
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)	SRTM ⁴	-
Agricultural potential	Quality of soil/climate for agriculture	IBGE ²	-
Distance to Rivers	Euclidean distance to nearest river (m)	IBGE ²	-
Cattle	Change in cattle heads	IBGE ²	08-10,
Permanent Agriculture	Change in permanent agriculture area	IBGE ²	10-12,
Annual Crop Agriculture	Change in temporary agriculture area	IBGE ²	12-14, 14-16
Protected areas	Protected áreas (1), unprotected (0)	IBGE ²	-

¹SOS Pantanal – SOS Pantanal (<https://www.sospantanal.org.br/arquivos/projetos/mapeamento-da-cobertura-vegetal-da-bacia-do-alto-paraguai-bap>).

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

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

⁴SRTM – The Shuttle Radar Topography Mission from National Aeronautics and Space Administration (NASA <http://www2.jpl.nasa.gov/srtm/>).

Table A2. AUC values for each period of each analyzed area. UPRB – Upper Paraguay River Basin.

	Lowland	Plateau	UPRB
2008-2010	0.872	0.824	0.831
2010-2012	0.874	0.823	0.826
2012-2014	0.849	0.824	0.827
2014-2016	0.853	0.831	0.813

Table A3. Mean of the single variable models, for UPRB (Upper Paraguay River Basin) model.

Variables	2008	2010	2012	2014
Land Cover	1.670E+00	1.08E+00	1.46E+00	1.58E+00
Distance to roads	-5.000E-12	0	0	0
Distance to cities	0	0	0	0
Dry season length	-7.463E-07	-6.17E-07	-7.81E-07	-5.58E-07
Elevation	-2.345E-09	2.76E-09	-1.68E-09	-1.89E-09
Agricultural Potential	0	1.36E-10	1.83E-10	0
Distance to Rivers	0	0	0	0
Cattle	2.123E-08	1.43E-09	7.95E-10	3.12E-09
Permanent Agriculture	0	-3.32E-10	-1.19E-09	-1.24E-09
Annual Crop Agriculture	-5.590E-09	-5.48E-10	3.15E-10	-1.99E-09
Protected Areas	-4.439E-07	0	3.48E-07	-5.63E-07