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Land use and regulating ecosystem services scenarios for the Brazilian Pantanal and its surroundings under different storylines of future regional development

Angélica Guerra[1,2] | **Fernando Resende**[3,4] | **Ivan Bergier**[5,6] | **Alison Fairbrass**[7] | **Cássio Bernardino**[8] | **Daniel Amorim Souza Centurião**[9] | **Fábio Bolzan**[1] | **Guellity Marcel**[10] | **Isabel M. D. Rosa**[11] | **Julio Cesar Sampaio da Silva**[12] | **Letícia Couto Garcia**[1] | **Letícia Larcher**[2,13] | **Paulo Tarso Sanches de Oliveira**[14] | **Rafael Morais Chiaravalloti**[15,16] | **Renato Roscoe**[17] | **Rômullo Louzada**[1] | **Sandra Santos**[4] | **Walfrido Moraes Tomas**[4] | **André Valle Nunes**[18,19] | **Fabio de Oliveira Roque**[1,20]

Correspondence
Angélica Guerra, Programa de Pós-Graduação em Ecologia e Conservação, Universidade Federal de Mato Grosso do Sul, Campo Grande, Brazil.
Email: angelicaguerraufms@gmail.com

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Abstract

The Pantanal, the largest worldwide continuous wetland, is considered a global hotspot of ecosystem services. Based on process-based modeling, we assessed plausible scenarios of land use for the Brazilian Pantanal wetland and its surrounding highlands by the year 2050. The simulations indicate likely trajectories of land-use change and the corresponding consequences for ecosystem services by looking specifically at soil loss, sediment yield, water quality, and carbon storage. The "Economy based on sustainable principles" scenario, in which landowners maintain native vegetation above Brazilian law requirements can lead to large reductions in soil losses and sediment yield (45%), whereas an increase in nutrients retention efficiency of soils (2%) and aboveground carbon storage (7%) compared to the reference scenario of "Business as usual" (BAU). On the other hand, the scenario of "Accelerating anthropogenic changes" might lead to an increase in soil losses (8%) and sediment yield (11%), with a reduction in the efficiency of soil nutrients retention (3%) and carbon storage (15%). This study illustrates that the enhanced awareness of future potential impacts can pave the way for less harmful decisions in the mid-term, toward the adoption of suitable strategies aligned with sustainable practices. Based on this, we discussed several initiatives that demonstrate the feasibility of moving toward most collective desirable scenarios.

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KEYWORDS
carbon storage, nutrient retention efficiency, sediment yield, vegetation loss, water quality, wetland

1 | INTRODUCTION

Green growth is now a core component of the international economic development agenda. The idea that trajectories of land use change should not lead to further loss of biodiversity, climate change, and poverty is spreading globally, and world leaders have already incorporated it into their discourses (e.g., Leaders Summit on Climate, 4/2021). In fact, the process of socio-economic-environmental transformation toward more green-circular-bio-economies is at the heart of many multilateral agreements such as the Convention on Biological Diversity, Sustainable Development Goals (SDGs), and the Paris agreement. Under the perspective of potential socio-ecological transitions, simulating scenarios of land use change is of great importance to assess how nature responds to different paths of human development and vice versa (Rosa et al., 2017), in addition to assisting in decision-making and in the formulation of a combined agenda of conservation and development (IPBES, 2016).

Countries in the Global South, however, face a greater challenge than wealthy economies. Their policies, strategies, and implementation capacities vary greatly, and they depend strongly on the production of goods (or commodities) that drive land use and land cover change (Foley et al., 2005). It is particularly difficult to consolidate economic growth while conserving biodiversity in countries whose economies are heavily dependent on commodities. Agribusiness is one of the major drivers of environmental change in most Global South countries, and huge land conversion from natural systems (e.g., wetlands, savannas, and forests) to agriculture is expected in the coming years (Stehfest et al., 2019).

Despite wetlands being known to be critical to the delivery of ecosystem services (Mitsch et al., 2015), they are among the ecosystems suffering the greatest transformation worldwide (Davidson et al., 2019), disappearing three times faster than forests (Ramsar Convention on Wetlands, 2018). On the other hand, there are still several examples in the Global South where agricultural or pastoralist systems are in balance with nature conservation. One example is the Pantanal wetland, the largest worldwide continuous wetland (179,300 km^2). Although over 90% of the region is occupied by cattle ranches, raising over 4.1 million cattle heads (Oliveira et al., 2016; Santos et al., 2023), approximately 80% of the native vegetation remains, between forested areas, savannas, wetlands, and native grasslands (Padovani, 2017). The Pantanal floodplain is occupied by large ranches that extensively rear beef cattle, particularly the production of calves, due to the presence of abundant natural grasslands that are appropriate for use as pastures. However, over the past decades, economic pressures and the creation of competitive markets have led to the introduction of exotic grasses which increase the productivity of the grasslands for cattle grazing (Santos et al., 2011). The region is an important location for biodiversity and hosts healthy populations of species such as jaguar (*Panthera onca*), blue macaw (*Anodorhynchus hyacinthinus*), and marsh deer (*Blastocerus dichotomus*) that are endangered or threatened elsewhere (Tomas et al., 2019).

The Pantanal is located in the Upper Paraguay River Basin (UPRB), a region that has undergone an intense conversion of land use in the last 30 years, mainly in the highland area, where the headwaters of the floodplain rivers are located (Roque et al., 2016). At the same time, agricultural expansion, climate change, and new infrastructure projects are putting pressure on those sustainable landscapes. One of these consequences is the silting up of rivers as a response of ecohydrological changes (Bergier, 2013). The greatest example is the Taquari River, which receives sediments exported from the highland areas and results in river avulsion, that is, the silting up and disruption of its banks (Assine, 2005). The avulsion leaves thousands of hectares of land permanently submerged, altering the flood pulses and interfering in the socio-ecological dynamics (Guerra, Roque, et al., 2020) and in the balance between supporting and regulating ecosystem services of the biome (Louzada, Bergier, et al., 2021).

The Pantanal is considered a global hotspot for ecosystem services (Costanza et al., 1997). A recent study estimated the monetary value of approximately US $60 billion for the ecosystem services provided by the biome (US $3932.05 ha^{-1} year^{-1}) (Bolzan et al., 2021). Reconciling food production and conservation of ecosystem services is a critical issue in the UPRB (Schulz et al., 2019; Tomas et al., 2019). It has been shown that increased land use conversion in the basin can cause major soil losses, leading to nutrient losses, which would require high land reclamation costs to avoid loss of productivity (about US $15 million per year) (Guerra, Oliveira, et al., 2020).

Rural landowners can contribute to the maintenance of ecosystem services by complying with the Native Vegetation Protection Law (Brazil, # 12,651, of 2012), which

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establishes the minimum percentage of native vegetation required to be conserved by law within private properties, termed Legal Reserves (Brancalion et al., 2016). In addition, rural landowners are fundamental agents for the conservation of regulation services in the Pantanal and in the world for several reasons: (i) they are important players in regional, national, and international policies, (ii) they are beneficiaries of regulation services, as (iii) they can be considered regulation service providers (e.g., in payment programs for services and ecological incentives); and (iv) agricultural land provision services (for example, agricultural land provision services depend on regulating services) (Carmenta et al., 2020; Kremer & Merelender, 2018; Sayer et al., 2013). Besides, keeping native vegetation within properties above what is required as Legal Reserve can increase the conservation of critical regulating services in the Pantanal. As private properties occupy more than 90% of the territory, we should expect that rural landowners' engagement is crucial in developing any strategy of conservation in the region, both by complying with legal requirements, such as legal reserve, and by going beyond them.

Although some recent studies have addressed land use change trends and its potential economic and ecological consequences in the Pantanal (Guerra, Oliveira, et al., 2020; Guerra, Roque, et al., 2020; Roque et al., 2021), analyzing some of the consequences of different land use change scenarios for regulating ecosystem services is critical to implement desirable futures. Here, we develop plausible land use scenarios for the Brazilian Pantanal wetland and its surrounding uplands till the year 2050, simulating potential trajectories of land use change in the UPRB and the consequences of legal regulation on ecosystem services by looking specifically at soil loss, sediment yield, water quality, and carbon storage across the UPRB. Using a spatially explicit model (Guerra, Roque, et al., 2020; Rosa et al., 2013), we evaluate the effect on regulating ecosystem services of three competing scenarios of future regional development: (1) Business as usual; (2) Acceleration of anthropogenic changes: with agriculture and livestock over new lands (deforestation or land use conversion) due to the relaxation of environmental laws to try to increase production of commodities, and (3) Economy based on sustainable principles: adopt conservation and protection strategies based, for example, on smart (digital) agriculture and bioeconomy, aligned to the UN-SDG agenda (see e.g., Bergier et al., 2021). We focus on plausible transitions toward positive, sustainable futures based on the idea that real-world agents of current social-ecological transformation (e.g., projects and initiatives) can be currently marginal but have the potential to grow in impact (Bennett et al., 2016; Raudsepp-Hearne et al., 2019).

2 | METHODS

2.1 | Study area

The UPRB is 368,656 km^2 in size. Approximately 40% of the basin is occupied by the Pantanal floodplain, and the rest is the highland, which is predominantly formed by Cerrado grassland and a portion of the Amazon Forest (Figure 1). It is on the highland that the springs that form the Pantanal rivers are found, and this gives these two areas great functional interdependence (Roque et al., 2016). In general, changes in lowlands are largely driven by changes in highlands due to the planetary gravitational force. Nevertheless, to some degree, the overall summer rainfall in the highlands is reliant also on the orographic effect, as depicted in Bergier (2013). Besides, the Piracema, or the fish mass migration (see Alho, 2008) may also be regarded as an ecological dependence of the highlands on lowlands. In any case, these intricate processes can be considered bidirectional. Our study focuses only on the Brazilian portion of the UPRB.

2.2 | Story lines and land use scenarios

We defined three story lines and associated land use scenarios for the UPRB up to the year 2050 based on Schulz et al. (2019), who described future stories for the Pantanal considering the prospects for a large-scale implementation of Payments for Ecosystem Services (PES) schemes. To illustrate that current decisions can have potentially large impacts on future land use with cascading effects on ecosystem services, we focused on baseline stories of social and economic conditions. We investigated regulating ecosystem services because they have huge impacts on the functioning of the Pantanal wetlands and human activities in the long term.

We chose 2050 as a baseline for our 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. To build the scenarios and illustrate trade-offs and synergies between conservation and food production, we manipulate two main variables "trends in land use change associated with agriculture" and the size of Legal Reserve.

2.2.1 | Scenario 1—Business as usual

This storyline is based on the idea that political and social trends remain unchanged. It also assumes that although the modernization (digitization and intensification) of agricultural techniques in Brazil has still not resulted in

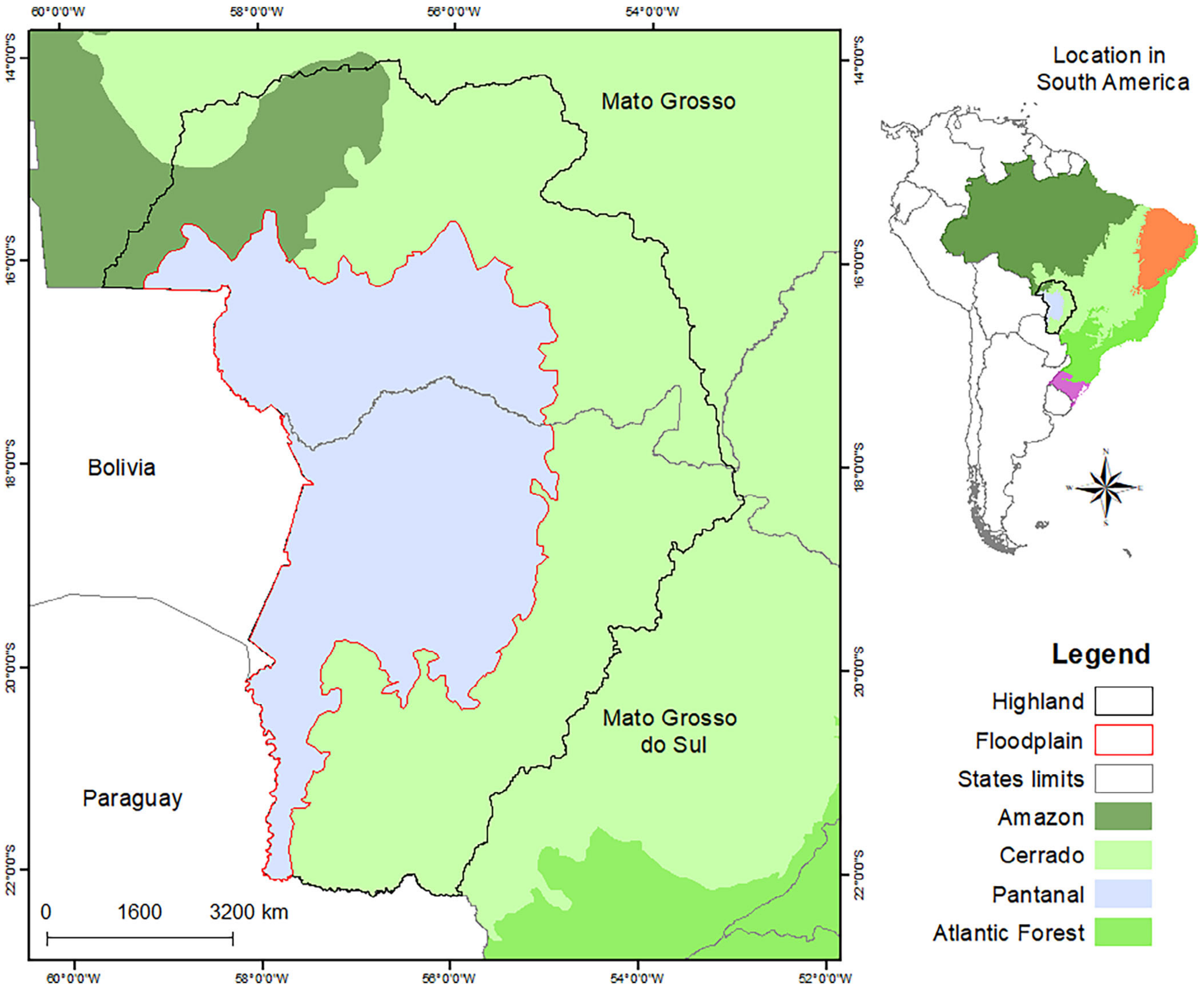

FIGURE 1 Study area.

truly sustainable land use practices, due to excessive focus on short-term profits, their negative effects have not yet weakened the viability of smart agriculture in a bioeconomy context in the long term. Nonetheless, due to innumerable complexities and lack of support for decision-makers, projects for PES or incentives for conservation do not materialize on a large scale and could not compete economically with attractive profitability in the short term.

Land use: follows the trend of recent years (2008–2016), where livestock production and stocking rates are maintained (projections of Guerra, Roque, et al., 2020).

Legal Reserves: values provided for in Law 12,561 of 2012 ("New Forest Code") for the Mato Gosso (for highland and floodplain) and for the highland of Mato Grosso do Sul, as well as the State Decree of Mato Grosso do Sul 14,273 of 2015, which determine 20% of Legal Reserves, safeguarding 50% of forest vegetation or 40% of savanna vegetation present in the rural property (for floodplain).

2.2.2 | Scenario 2—Acceleration of anthropogenic changes

This storyline assumes an aggravated version of the previous scenario, especially with regard to the lack of environmental awareness and the focus of the economy on maximizing short-term benefits through the expansion of agriculture and livestock, as well as industrial production, mainly to accomplish the demands of commodity production for export. Projections of beef production show that Brazil will increase production by 2.1% per year in the coming years (Brasil, 2018). Scientific warnings from the research communities remain without adequate political responses due to political inertia.

Land use: follows the trend of recent years (2008–2016) with the unsustainable intensification of agriculture and livestock and with the relaxation of the existing environmental legislation.

Legal reserves: elimination of mandatory Legal Reserves.

2.2.3 | Scenario 3—Economy based on sustainable principles

In this story line, the UN-SDGs are considered central to the economic, environmental, and social strategies in the Pantanal. Moreover, green technologies, bioeconomic development, and to some degree the digital revolution will accompany an increase in environmental awareness among stakeholders, decision makers, and the population. Policy makers will therefore aim to develop innovative strategies to protect the environment, with a strong emphasis on solutions based on smart agriculture and bioeconomy. In unprecedented social cooperation, policy makers, government agencies, private companies, non-governmental organizations (NGOs), traditional communities, farmers, and other rural landowners have the opportunity to collaborate and share a common agenda, for example, the UN-SDGs, to address future socio-environmental challenges. The intensification of sustainable agriculture, based on bioeconomy and the digital revolution, will pave the path for payments and other incentives in PES projects for overall rural landowners and rural workers who achieve higher standards of living. Funding arrives from different government levels, as well as from private companies aware that economic success also depends on well-functioning ecosystems and everyone's wealth. As PES and other incentives evolve to viable business models, they will succeed alternative environmental policies that do not achieve sustainable goals on hydrographic basin or landscape scales.

Land use: Following the trend of recent years (2008–2016), however, due to better agricultural practices combined with sustainable agribusiness, the productivity of the farmlands is maximized; hence, avoiding the suppression of more pristine landscapes for pasture formation.

Legal reserves: agribusiness and rural landowners adopt low-level digital technologies of communication to work together with the government and NGOs to ensure that properties maintain areas of native vegetation above what is required as a Legal Reserve. For the latter case, native vegetation must cover 80% of the area of farmlands in the floodplains and 35% of those in the highlands. The values were suggested based on the legal reserve of the Amazon (80%) and the Cerrado areas of the Legal Amazon (35%) (Guerra, Oliveira, et al., 2020).

2.3 | Data sources

To model the loss of native vegetation in each scenario, we followed the approach proposed by Guerra, Roque, et al. (2020), who used a spatially explicit model (Rosa et al., 2013, 2015) to project the conversion of native vegetation for anthropogenic use in the UPRB by 2050. The projection was based on land use maps for the periods 2008–2010, 2010–2012, 2012–2014, and 2014–2016 (SOS Pantanal et al., 2017), and other variables identified as drivers of vegetation loss in the area of study (Table S1). We chose to analyze different periods of land use because there is a wide variation in vegetation loss in these periods (Table S2). In applying this model to the area in question previously (Guerra, Roque, et al., 2020), it was shown that highland and floodplain present different vegetation loss rates and variables and, therefore, the analyses must be carried out separately in the two areas.

All datasets were converted to the same spatial resolution of the land use maps (600 m × 600 m), but separated into two categories: static and dynamic (Table S1). Static variables are those kept constant over time, either because they were not changed in the analyzed period of time (e.g., distance to rivers) or because future data was lacking to update them (e.g., flood frequency, distance to roads, distance to cities). Dynamic variables, on the other hand, represent characteristics of the landscape that change over time, that is, land use. We calculated the static variables only once, at the beginning of the modeling process, while the dynamic variables were recalculated every 2 years. Finally, we also used a dynamic variable to explain the neighborhood effect, that is, the proportion of anthropogenic cells in the vicinity of the focal cell, which updates the chances of loss of local native vegetation (for further details see Rosa et al., 2013, 2015).

Legal reserve area and land use trends were the only variables that varied between models (Table S3). The variables identified as drivers of vegetation loss in the two areas in each period are shown in Table S4.

2.4 | Native vegetation loss model

The native vegetation loss model is divided into two steps: first, the model identifies what the main drivers of vegetation loss in the UPRB are, considering the different dynamics of the plateau and floodplain, due to historically different land uses and occupations, as well as the flood pulse dynamic in the floodplain; in the second step, the model generates projections of the probability of loss of native vegetation by the year 2050 within each rural property, respecting the Legal Reserve limits.

The native vegetation loss model is based on $P_{\mathrm{pvn},x,\mathrm{t}}$, where P_{pvn} is the probability that a cell x of native vegetation will be converted into "anthropogenic use" within a defined time interval t. The fact that $P_{\mathrm{nvl},x,t}$ is specific to a given moment t illustrates how the model updates the suppression of local native vegetation over time. This probability was defined as a logistic function.

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

where $k_{x,t}$ varies from infinity to infinity and $P_{\mathrm{nvl},x,t}$ from 0 to 1, following the methodology developed by Rosa et al. (2013). After defining the model, it is possible to write simple linear regression models for $k_{x,t}$ as a function of variables affecting x at time t and explore the effect of different sets of variables.

We used the C++ library "Filzbach" (http://research.microsoft.com/en-us/projects/filzbach/) to return, for each parameter being considered in the model. A posterior probability distribution using Monte Carlo Markov Chains (MCMC) to return for each parameter a posterior probability distribution, from which we can extract the posterior mean and a range of credibility, given the structure of the model and the data used for calibration. For each time step, binary maps of change are produced (1—native vegetation: forest formation, savanna formation, grassland formation, wetland; 0—anthropogenic: agriculture, pasture, urban infrastructure, mining), which are then integrated based on the model's 100 iterations (sampling of later distributions) to determine the overall probability of change. These steps were repeated for each of the four time periods available, as the model will project future conversion based on observed rates of change, and these had different rates of change (2008–2010, 2010–2012, 2012–2014, and 2014–2016). Once all models were calibrated, the best (with the combination of variables that produce the highest probability of testing) was used to project the future probability of loss of native vegetation by 2050 (using 2-year time intervals). The cumulative probability of conversion in 2050 was determined for each model individually (models 2008–2010, 2010–2012, 2012–2014, and 2014–2016), as well as based on a set of all model outputs (i.e., integrating all projection models made for that year). By spatializing the probability of loss of vegetation for the UPRB in each scenario, we identified the areas with the highest probability of loss.

We generated projections for patterns of native vegetation loss observed in the UPRB, for the floodplain and for the highland, allowing the variables to weigh differently over the two regions. After running the model for the four periods (2008–2010, 2010–2012, 2012–2014, and 2014–2016), we calculated the average for the two regions. The three scenarios had apparently strong predictive power with mean AUC values of 0.88 for S1, 0.83 for S2, and 0.85 for S3.

All modeling steps can be summarized in Figure 2 of Guerra et al. (2020).

2.5 | Soil loss and sediment yield

To calculate soil loss and sediment yield, we used the module sediment delivery ratio (SDR) of Invest 3.7.0

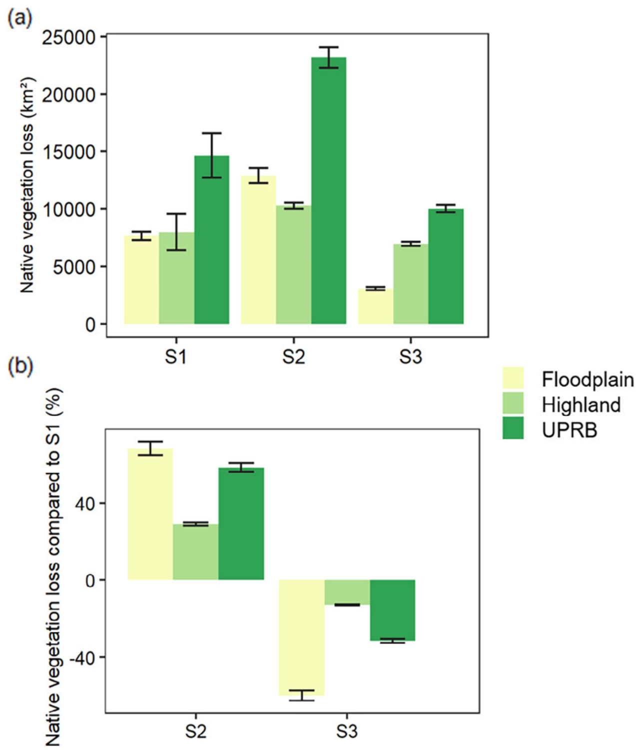

FIGURE 2 (a) Native vegetation loss (km^2) by 2050 under the three scenarios, and (b) native vegetation loss under scenarios S2 and S3 compared to scenario S1 (%), in the floodplain, highland, and Upper Paraguay River Basin (UPRB). Legend: S1—Business as usual, S2—Accelerating anthropogenic changes, S3—Economy based on sustainable principles. The error bars correspond to the standard error of the mean generated from the simulations, using the Monte Carlo Markov Chains (MCMC) method.

(Sharp et al., 2020), which is based on the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978).

$$\mathrm{A} = \mathrm{R} \times \mathrm{K} \times \mathrm{LS} \times \mathrm{C} \times \mathrm{P} \quad (2)$$

where A is the average loss of soil per unit area (t ha^{-1} year^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}); K is the soil erodibility factor (t MJ^{-1} mm^{-1}); LS is the topographic factor (dimensionless); C is the land use and management factor (dimensionless); and P is the conservation dimension factor (dimensionless). See the full description of the model and variables in the Supporting Information.

2.6 | Water quality

The regulation of water quality can be determined through models that consider the sources of nutrient loads (in this case, phosphorus and nitrogen) for a given use and land cover, their transport to rivers, and the holding capacity (difference between loading and export) of nutrients by vegetation. To assess the nutrient retention efficiency in the soil, we used the module Nutrient Delivery Ratio (NDR) of the Invest 3.7.0 model. Based on the mass balance approach, the model calculates the amount of nutrients produced by each part of the study region that streams or is retained by vegetation or soil (Sharp et al., 2020). All the details of the model and the description of the variables are provided in the Supporting Information.

2.7 | Carbon storage

To calculate carbon storage in natural formations, we used the above-ground carbon stock values of the Brazilian Inventory of Anthropogenic Emissions and Removal of Greenhouse Gases (MCTI, 2010). We calculated the amount of carbon stored in each class of natural land use (forest, grassland, savanna, wetland) by averaging the corresponding native vegetation types. We also separated the values by biomes (Pantanal, Cerrado, and Amazon) in order to consider the different quantities stored by the land use classes in each biome. The above-ground carbon storage values for each class of land use in UPRB biomes are shown in Table S4. As the Pantanal is a wetland with large flooded areas and the aquifer is closer to the soil surface (Salis et al., 2014), the above-ground biomass may retain about 80% of plant biomass (Bergier et al., 2015). However, the present analysis may underestimate the whole carbon pool due to additional soil carbon storage in flooded and flooding sites (Rasbold et al., 2020). We also did not consider the occurrence of wildfires. By taking these constraints into consideration, we assigned the estimated carbon stock values for each class of land use for each scenario.

3 | RESULTS

3.1 | Native vegetation loss

As expected, the three scenarios led to different values of vegetation loss by 2050 (Figure 2a). The scenario S2 (Accelerating anthropogenic changes) predicts a 58% increase in vegetation loss in the UPRB (total predicted loss of 24,000 km^2) compared to scenario S1 (Business as usual, total predicted loss of 14,005 km^2, see Guerra, Roque, et al., 2020) (29% on the highland and 68% on the floodplain). However, the scenario S3 (Economy based on sustainable principles) predicts a 32% decrease in vegetation loss in the basin compared to S1 (12% on the highland and 60% on the floodplain) (Figure 2b).

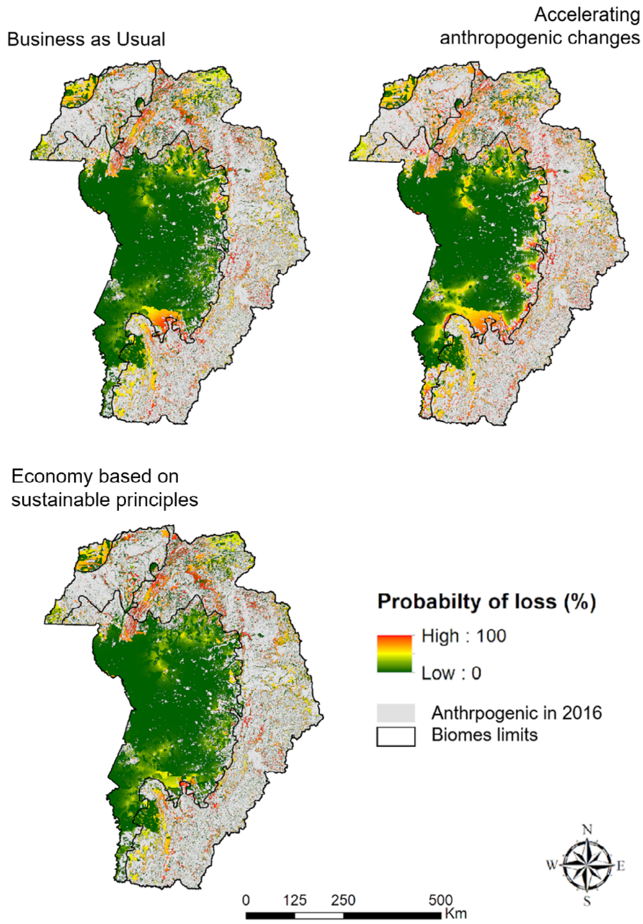

FIGURE 3 Probability of native vegetation loss in 2050 in the Upper Paraguay River Basin in three alternative scenarios.

The scenario 1 (S1) shows that by 2050, 18.1% of the native vegetation in the floodplain and 65.0% in the highland would be converted by human activities. Considering S2, which predicts the highest values of vegetation loss, 21.5% of the floodplain and 65.8% in the highland would be converted. On the other hand, S3 predicts that by 2050, land reclamation would be 64.0% of the highland and 15.0% of the floodplain (Table S8). In all scenarios, the areas most likely to be lost are in the highland and in the transition areas between the highland and the floodplain (Figure 3).

3.2 | Soil loss and sediment yield

Our results showed that UPRB currently loses about 519 million tons of soil per year (465 on the highland and 54 on the floodplain) (Figure 4a). Changes in land use tend to increase these losses. S1 shows a 259% increase in soil loss in UPRB by 2050 (263% in the highland and 222% in the floodplain). S2 predicts the biggest increase among the three scenarios of land use change, with a

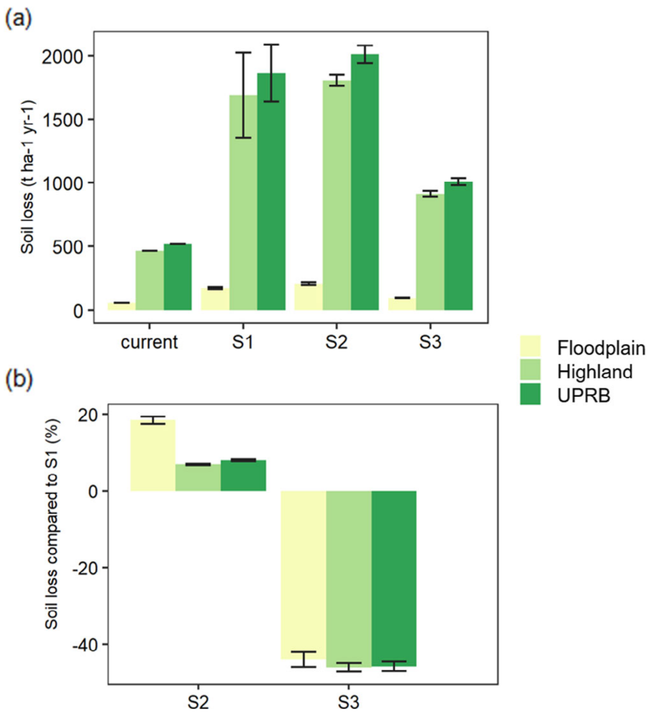

FIGURE 4 (a) Soil loss (t ha^{-1} $year^{-1}$) and (b) soil loss compared to scenario S1 in each scenario. Legend: S1—Business as usual, S2—Accelerating anthropogenic changes, S3—Economy based on sustainable principles. The error bars correspond to the standard error of the mean generated from the vegetation loss simulations for each scenario using the Monte Carlo Markov Chains (MCMC) method. The dark green bars of the UPRB were summed in a didactical way, to simplify understanding, but, we acknowledge that the entry and exit of sediments are not exactly additive since part of the entry sediment from the plateaus, is stored by its granulometry, and released by the plain at the other end. However, currently, there are no exact calculations with accuracy for this account.

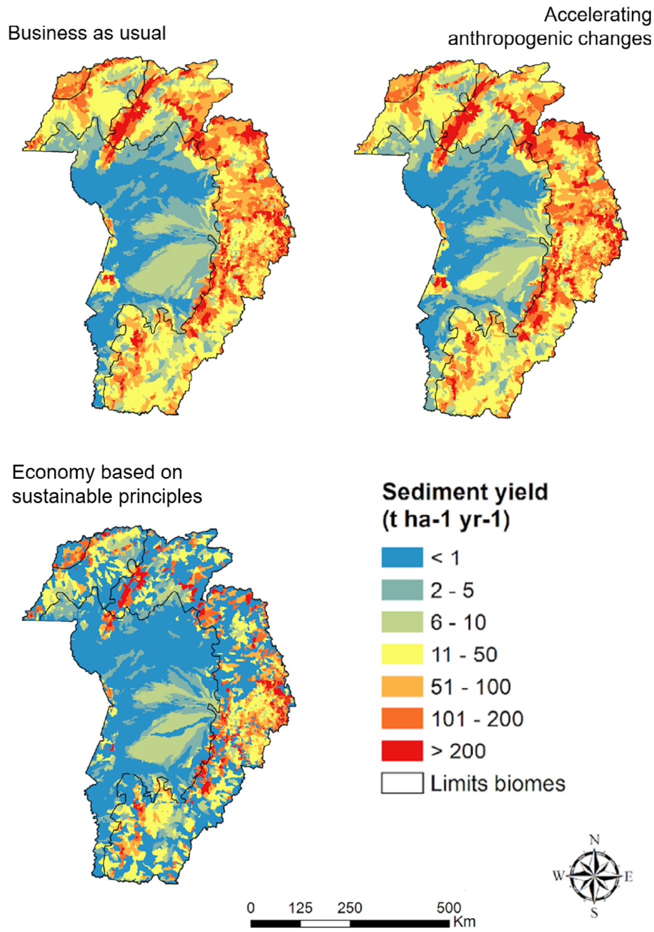

FIGURE 5 Sediment yield (t ha^{-1} $year^{-1}$) in the UPRB in each scenario.

287% increase in soil loss in the UPRB (288% in the highland and 281% in the floodplain). S3 predicts a 95% increase in soil loss in the UPRB by 2050 (96% in the highland and 80% in the floodplain).

Comparing the scenarios S2 and S3 to the scenario S1, S2 predicts an 8% increase in UPRB soil loss compared to S1 (7% on the highland and 18% on the floodplain) (Figure 4b). On the other hand, S3 predicts a decrease in soil loss in the UPRB by 45% compared to S1 (46% in the highland and 44% in the floodplain).

About 17 million tons of sediment are currently produced in UPRB per year (16 on the highland and 1 on the floodplain). According to S1, this number may increase by 404% in UPRB by 2050 (400% in the highland and 476% in the floodplain). S2 predicts a 462% increase in the sediment yield in UPRB (450% on the highland and 630% on the floodplain). S3 predicts an increase of 178% (175% on the highland and 209% on the floodplain) (Figure 5 and Figure S2). Comparing the scenarios with S1, S2 shows an 11% increase in sediment yield in UPRB until 2050 (10% in the highland and 27% in the floodplain). S3 predicts a 45% decrease in sediment yield in UPRB (45% in the highland and 46% in the floodplain) compared to S1 (Figure 5 and Figure S2).

3.3 | Water quality

Currently, at UPRB, the efficiency of nutrient retention between the highland and the floodplain presents similar values, with 54% for the highland and 53% for the floodplain.

The S1 foresees a reduction to 44% of efficiency in the highland and 50% for the floodplain. S2 foresees a reduction in efficiency compared to current conditions, with 41% for the highland and 47% for the floodplain. In S3, the efficiency decrease in the highland is forecast to be 46% and 51% in the floodplain. The results show that in all scenarios, the greatest reduction in the efficiency of nutrient retention will occur in the highland (Figure S3).

3.4 | Carbon storage

Currently, UPRB stores 894 million tons of carbon above the ground in its different land use classes. This value is divided almost equally between the highland and the floodplain (Figure 6a). With the change in land use, this storage is expected to decrease (Figure S4). S1 predicts a 36% decrease in UPRB's carbon storage by 2050 (33% on the highland and 39% on the floodplain). S2 predicts a 46% decrease in UPRB (45% in the highland and 47% in the floodplain). S3 predicts the smallest decrease, with 31% (27% on the highland and 35% on the floodplain) (Figure 6a). Comparing the scenarios S2 and S3 to the scenario S1, S2 foresees a 15% decrease in the carbon storage of UPRB by 2050 (18% in the highland and 13% in the floodplain), while S3 predicts a 7% increase in carbon storage in the soil compared to S1 (9% on the highland and 6% on the floodplain) (Figure 6b).

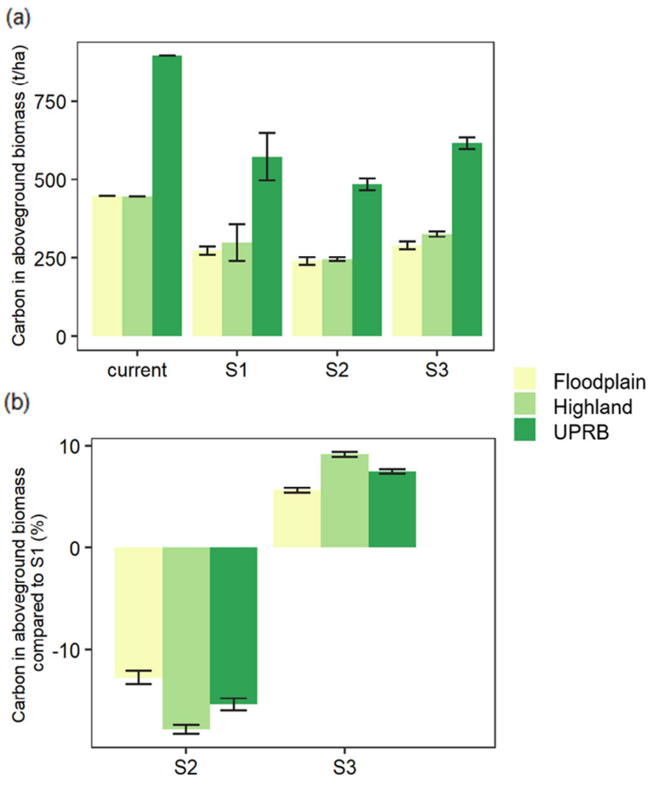

FIGURE 6 (a) Carbon in aboveground storage biomass (t ha^{-1}), (b) Carbon in aboveground storage biomass compared to scenario S1 (%) in each scenario. Legend: S1—Business as usual, S2—Accelerating anthropogenic changes, S3—Economy based on sustainable principles. The error bars correspond to the standard error of the mean generated from the vegetation loss simulations for each scenario using the Monte Carlo Markov Chains (MCMC) method.

4 | DISCUSSION

By considering the land use scenarios and their respective uncertainties, it is possible to better recognize connections between societal decisions on land use and land cover change and its consequences for ecosystem services in a studied system (Walker et al., 2019). In the UPRB case, our results show that differences in the underlying drivers of land-use change (e.g., agricultural demands), protected areas, and Legal Reserves can have large impacts on projected land-use change with cascading effects on the provision of critical regulating ecosystem services, such as carbon storage, water quality, and sediment regulation. This illustrates that moving from the default BAU scenario, here considered as "the most likely," to the more harmful or undesirable S2 (Accelerating anthropogenic changes) or to most preferable or target scenario S3 (Economy based on sustainable principles), society may become aware of the potential impacts of its decisions hence be able to develop strategies to transform the preferable future into reality in the long term.

According to our analyses, S3, where landowners keep native vegetation above what is required as a Legal Reserve, could lead to a huge reduction in soil loss and sediment yield (45%) and an increase in the efficiency of nutrient retention in the soil (2%) and carbon storage (7%) compared to the BAU (S1) scenario. On the other hand, the acceleration of agriculture and livestock combined with the elimination of the mandatory Legal Reserve in UPRB (S2) could lead to an increase in soil loss (8%) and sediment yield (11%) and a reduction in the efficiency of nutrient retention in the soil (3%) and carbon storage (15%) compared to the BAU scenario (S1). Unsurprisingly, many previous studies have shown that land-use change is one of the major determinants of the supply of ecosystem services, particularly regulating services, as those evaluated here, because they are strongly associated with native vegetation (Lambin et al., 2001; Lawler et al., 2014; Resende et al., 2019; Zhan, 2015). However, one could argue that keeping areas for promoting regulating services but at the expense of other services can lead to inevitable tradeoffs among services, such as cattle production vs. carbon storage in forests (Louzada, Bergier, et al., 2021). Under this perspective and assuming that most people would agree that a reduction in soil loss and sediment yield and a large increase in the efficiency of nutrient retention in the soil and carbon storage compared to the BAU is a desired future, a critical question emerges: how should we build a transition toward this desired future?

We assume in the story line S3 an increase of protected areas, Integrated Crop-Livestock Systems (ICLS) in the highland (Buller et al., 2015), payment for ecological services (Louzada, Roque, & Bergier, 2021), sustainable management of native pastures in the Pantanal (Santos et al., 2020), restoration of highlands where the spring-fed rivers occur (Garcia et al., 2022), and strong investments in education, science, and innovation for local development of digital technologies in the long-term, based on circular principles of the bioeconomy and sustainability (Bergier et al., 2021; Tang et al., 2021). Clearly, this story line represents an overoptimism toward sustainability and an oversimplification of reality. However, we argue that it is fundamental to identify "positive future visions" because inspirational and plausible views help building desirable futures for the commons (Hebinck et al., 2018; Wiek & Iwaniec, 2013). Under this perspective, most of the discussion in this study focuses on identifying ongoing initiatives that could be seen as early signals (future seeds) of routes toward the S3.

In terms of legal marks, several new policies can be seen as the first steps toward S3. As examples of the inclusion of ecosystem services in the Pantanal policy agenda, we can cite the recent policy legislations, such as payments for ecosystem services at a national and regional scale (Federal Law #14.119/2021 and Law #5235/2018 from Mato Grosso do Sul state); bioeconomy program (Regulatory act #121/2019 from Ministry of Agriculture, Livestock and Supply); the National Policy on Agroecology and Organic Production (Pnapo, Decree #7794/2012); the state of Mato Grosso do Sul Law on agroecological and organic production initiatives (Law #5279/2018); the state of Mato Grosso do Sul on Pantanal Law (Stadual Law #6160/2023, forbidden soybean and sugarcane, for instance). Therefore, immense opportunities still need to be explored; for instance, a recent review showed that Pantanal, as well as Pampa, have no PES programs yet, while the Atlantic Forest biome has expanded on average 1.5 new PES projects per year on average (Mamedes et al., 2023; Taffarello et al., 2017).

Technological aspects and tools toward the sustainable intensification of food production in the Pantanal can also help toward the transition for S3. Clearly, we cannot anticipate all technologies and innovations for the next three decades, as well as the emergence of societal behaviors (e.g., food preferences and purchase of certificated goods) and interactions with climate change. However, considering that livestock plays a key role in the economy of the Pantanal and that animal protein demand is still increasing globally (Embrapa, 2020), it is reasonable to assume that beef production in the Pantanal will still be an important commodity in the next decades, and changes in technological aspects will be a key driver of change in the region. In the path of story line 3, agricultural digitization based on clean energy (Engler & Krarti, 2021) may play a crucial role in preserving and conserving benefits from ecosystem services. Currently, the fast digitization of agriculture may create new market models leaning toward sustainable food production systems (Tang et al., 2021), including improving the transparency of production processes, remote monitoring, and traceability, fundamental points to enable the origin certification for complex livestock chain systems (Bergier et al., 2021; Rajão et al., 2020). The increase in the overall efficiency in food production may leverage new business mechanisms that mutually protect the environment and climate, prevent the emergence of diseases driven by changes in land use, and suitably balance livestock stocking rate, deforestation, and enteric methane emissions (Bergier et al., 2019; Di Marco et al., 2020). However, it is important to note that the widespread use of digitization and traceability systems is still a challenge in the Pantanal, as well as in other parts of Brazil. Perhaps, the digitization of livestock production may take time, especially in some remote areas, where access to electricity and communication is a bottleneck. Solar energy generation in isolated areas of the Pantanal may represent a first step to improve this situation (the recently launched Ilumina Pantanal Program, which promotes the installation of solar panels in isolated properties and communities, is an important example). The popularization of the internet via a set of small satellites (Narayanasamy et al., 2017) may also contribute soon, with more affordable costs to promote more connectivity on a scale not yet experienced in the Pantanal. The tool Sustainable Pantanal Ranch (SPR) that evaluates the sustainability of beef cattle ranching (Santos et al., 2017) can contribute to the adoption of management best practices and promote positive effects on ecosystem services. The SPR diagnoses the production system in an individual way, helping to make decisions about the best management practices (management best practices or environmentally friendly management practices) that promote the conservation of ecosystems and ecosystem services. As an example, we can mention the landscape diversity index that is evaluated in each property to define which landscapes could be suppressed or replaced.

Recent studies have shown that cattle can be produced in native pastures with low impact on the local biodiversity and ecological services (Santos et al., 2020). However, it is critical to estimate the real carrying capacity of native pastures to support livestock by using clear criteria, such as grassland composition, available annual forage production, and spatial–temporal variation (Santos et al., 2017). Diversification and expansion of production chains based on native species can also aid in the sustainable intensification, including ecotourism, use of non-timber forest products, and fishing (Tomas et al., 2019). This is particularly valid for traditional communities whose livelihoods depend partly on non-timber forest products, such as honey, native rice, and fruits. For sustainable intensification, it is also essential to create consistent territorial management instruments and good governance practices, such as environmental certification schemes, financial incentives for sustainable agricultural practices, and integrated fire management initiatives (Libonati et al., 2020). Considering that many of the territorial management instruments involving ecosystem services occur through voluntary adherence (e.g., payments for ecosystem services and financial incentives for sustainable practices for meat production), special attention should be paid to the implementation process and adherence to novelties. Mato Grosso do Sul has subsidies for good practices, sustainable farming, for example, incentives for the production of calves in cattle breeding, the certification of organic meat, and more recently the certification of carbon-neutral meat that identifies producers that produce beef cattle in systems of integration cattle breeding, farming, and forest in a sustainable protocol (WWF, 2021). However, adherence to these programs is relatively low in relation to the total number of producers in the state. Reducing costs and bureaucracy without losing transparency and increasing disclosure can be important steps to improve adherence (Mascia & Mills, 2018; Mills et al., 2019), particularly by the widespread adoption of digital designs as those depicted by Bergier et al. (2021). Influencing patterns of consumption is also a pathway to change, by which interventions, such as sustainable food certification, influence consumer preferences for more sustainable products. In addition, trade barriers may arise, in both national and international markets, that restrict trade of products that are produced using unsustainable approaches.

Improving the balance between cattle production and maintenance of ecosystem services in the highland has some special challenges. The region is marked by overgrazing, inefficient pasture divisions, animal access to water in permanent protected areas (PPA), low investment in nutrient replacement and pasture correction, and low productivity (Galdino et al., 2013). As a result, there is a strong degradation process, evidenced above all by the gullies in the pasture areas of the Taquari basin (Louzada, Roque, & Bergier, 2021). A transition between BAU and the *Economy based on sustainable principles*' scenarios may be viable if the current and recently new approved laws mentioned before in the text (e.g., Payments for Ecosystem Service [PES]) become in fact priorities of the current governments, at the same time, to the *Acceleration of anthropogenic changes*' scenario being prevented depending on the public policies and public pressure to avoid legal setbacks. Here, the advances would be in the expansion of the adoption of more sustainable ICLS, involving pasture and PPA restoration, improvements in soil fertility, and the nutrition, reproduction, and stocking rate of livestock (Buller et al., 2015). Other important examples of success have been the ATeG (Technical and Management Assistance) program of SENAR-MS (National Service for Rural Learning/Training) and SEBRAE-MS (Brazilian Micro and Small Enterprises' Support Service). Public policies to encourage the dissemination of knowledge in these regions will be fundamental. Given the rapid expansion of soy production in the highland (MapBiomas, 2020), the adoption of integrated systems is a promising avenue toward the transition for S3. Public policies that are in line with these premises and can help to improve the region as a whole would be the National Plan for Low Carbon Emissions in Agriculture (ABC) and the differentiated financing lines in the Constitutional Financing Fund for the Center-West (FCO).

In the case of the Pantanal, as in other regions across the world, opportunities and constraints for new land uses are created by local as well as national and international markets and policies. Considering that about 80% of the Pantanal is reportedly managed as cattle ranches, international demands for cattle beef are determinants of land-use changes, and they amplify or attenuate local factors. Cattle produced in the Pantanal are part of a complex value chain, including exportation to Asia, the EU, and the UK (Embrapa, 2020; Greenpeace, 2021). Therefore, it is important to improve transparency, traceability, dropping commodities linked to forest and ecosystem destruction, ensuring trade policy aligns with climate, biodiversity, and social justice goals, making full transparency a condition of trade. Moreover, it is imperative to consider a better balance between regulating and provisioning services toward a more sustainable beef cattle value chains in the long term, including the possibility of national and international monetary incentives from the main beneficiaries for payment of ecosystem services in the Pantanal. The Pantanal State Program for Sustainable and Organic Beef, in Mato Grosso do Sul, has increased the volume of certified animals since its launch. From 2021 to 2022, the area of organic and sustainable beef production in the Pantanal increased by 55% (from just over 713 thousand certified ha in 2021 to over 1 million ha in 2022) and the number of producers doubled (Canal Rural, 2023). This fiscal incentive program for sustainable production in the Pantanal ends up being a payment mechanism for environmental services since the certification process brings some advances to the conservation of the Pantanal. The protocols can certainly improve, thanks to the gradual improvement and integration with the concepts of the Sustainable Pantaneira Farm

(Embrapa Pantanal), but the results point to the effectiveness of an incentive system as a mechanism for payments for environmental services, even if indirect.

Despite currently negligible positive signals for the future under the storyline S3 is achievable, though it might demand wide societal changes. Studies about futures and the implementation of policies associated with ecosystem services in the Pantanal, as exercised here, although have a number of methodological limitations (see Guerra, Oliveira, et al., 2020; Guerra, Roque, et al., 2020; Roque et al., 2021) and societal challenges (Schulz et al., 2019), have also great potential to support the development of policy options or, at least, start the dialogs (IPBES, 2016). In the UPRB, previous initiatives have already been done to use studies about land use futures to support policy decisions, particularly in the context of land use instruments and planning, such as Ecological and Economic Zoning. In this way, we believe that the first step toward improving the connections between future fields and policymaking is incorporating this kind of analysis into land use policy instruments that already exist in the context of regional planning, such as the ecological and economic zoning, payments for ecosystem services, and restoration planning.

It is important to recognize that our scenario 3 is only one among several different potential "sustainable" scenarios for the region. Moreover, we focused on the environmental dimension of the sustainable challenges (particularly in terms of land use). New studies are clearly needed to address what the trade-offs and synergies of this scenario are compared to other potential sustainable scenarios and evaluate environmental, social, and economic issues in a more integrated way in the context of the United Nations' Sustainable Development Goals of the 2030 Agenda (Nilsson et al., 2016).

This study is based on the Forest Code legislation that highlights the particular case of wetlands as Restrict Use Areas, in which an intermediate state level can rule and execute specific land-use policies grounded on up-to-date scientific knowledge (see https://www.embrapa.br/en/codigo-florestal/entenda-o-codigo-florestal/area-de-uso-restrito). For that case, rather than sparing, land sharing is more appropriate, in which intensification can be limited by law to guarantee the maintenance of pristine basic ecological functionalities of the landscape (see Mato Grosso do Sul, 2015). Evidently, that is presumably accomplished in scenario 1 and improved in scenario 3, so both contrast with scenario 2 with unlimited or unsustainable intensification.

Our simplified model is a data-based biophysical prediction system that does not take into account changes in: (a) policy, (b) trade in agricultural crops, such as import, export, or changing intra-and international consumer demand, (c) human behavior, (d) technology innovation, (e) regeneration and restoration, and (f) climate conditions. In addition, another model pitfall has been recognized for the Pantanal plains, where a river can eventually change its course in the active lobe and then inundate large plain areas over the scale of decades (Assine, 2005). In addition, we highlight livestock as the main activity in the Pantanal, and we do not consider other economic activities such as fishing, ecotourism, intensive agriculture (soy production), and family farming because we do not have enough data to include them in the modeling. Therefore, new model approaches might be considered in future predictions for the lowlands by considering ecological succession toward river restoration with corresponding changes in landscape ecosystem services (Louzada et al., 2020; Louzada, Bergier, et al., 2021). Moreover, it was also assumed that the distribution of protected areas is a static feature in the landscapes. Despite the possible limitations herein pointed out, the S3 scenario (Economy based on sustainable principles) points to significant effects in the reduction of anthropogenic impacts on future ecosystem services provided by the UPRB.

With a few large properties collectively surpassing the total area of all small farms in the Pantanal, it becomes imperative for sustainability policies to account for this disparity, echoing recommendations made for the Cerrado region (Colman et al., 2024; Stefanes et al., 2018). Central to our approach is the prioritization of large farms in the implementation of public policies aimed at curbing land conversion and mitigating major drivers of landscape transformations, such as wildfires that, to be avoided, need interventions based on fire management. By targeting these entities, we stand to achieve substantial gains in total landscape conservation swiftly.

However, this emphasis on large farms should not overshadow the importance of small farms. We firmly recommend that small farms play a pivotal role in bioeconomy initiatives, particularly in fostering food systems based on native species. Moreover, they are crucial in advancing policies related to carbon markets and incentivizing conservation efforts through mechanisms like payments for ecological services. Moreover, by new law, family farmers are priority groups for environmental services payment policies. Nevertheless, it is essential to underscore the need for supporting and mobilizing groups of small farms to consolidate their presence in emerging markets and scale up their sustainable initiatives effectively. This collaborative approach, involving both large and small farming enterprises, is pivotal in driving holistic and inclusive sustainability strategies across the Pantanal landscape.

AFFILIATIONS

[1]Programa de Pós-Graduação em Ecologia e Conservação, Universidade Federal de Mato Grosso do Sul, Campo Grande, Brazil
[2]Instituto Terra Brasilis de Desenvolvimento Socioambiental (ITB), Brasília, DF, Brazil
[3]International Institute for Sustainability (IIS), Rio de Janeiro, RJ, Brazil
[4]Rio de Janeiro State University (UERJ), Rio de Janeiro, RJ, Brazil
[5]Empresa Brasileira de Pesquisa Agropecuária (Embrapa Pantanal), Corumbá, MS, Brazil
[6]Empresa Brasileira de Pesquisa Agropecuária (Embrapa Informática Agropecuária), Campinas, SP, Brazil
[7]Institute for Sustainable Resources, University College London, London, UK
[8]World Wildlife Fund – Brazil (WWF-Brasil), Programa Pantanal, Campo Grande, MS, Brazil
[9]Universidade Estadual do Mato Grosso do Sul (UEMS), Campo Grande, MS, Brazil
[10]Ecosev Consultoria Ambiental, Campo Grande, MS, Brazil
[11]School of Natural Sciences, Bangor University, Bangor, UK
[12]Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Brasília, DF, Brazil
[13]Instituto Homem Pantaneiro (IHP), Corumbá, MS, Brazil
[14]Programa de Pós-Graduação em Tecnologias Ambientais, Universidade Federal de Mato Grosso do Sul, Campo Grande, Brazil
[15]Anthropology Department, University College London, London, UK
[16]Smithsonian Conservation Biology Institute, Front Royal, Virginia, USA
[17]Instituto Taquari Vivo (ITV), Campo Grande, MS, Brazil
[18]Knowledge Centre on Biodiversity, Belo Horizonte, MG, Brazil
[19]IPÊ - Institute of Ecological Research, Nazaré Paulista, SP, Brazil
[20]Centre for Tropical Environmental and Sustainability Science (TESS) and College of Science and Engineering, James Cook University, Cairns, Queensland, Australia

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ORCID

Angélica Guerra https://orcid.org/0000-0001-6399-8507
Ivan Bergier https://orcid.org/0000-0002-1076-8617
Alison Fairbrass https://orcid.org/0000-0002-4907-9683
Rafael Morais Chiaravalloti https://orcid.org/0000-0003-4271-3749
Walfrido Moraes Tomas https://orcid.org/0000-0001-9395-7415
Fabio de Oliveira Roque https://orcid.org/0000-0001-5635-0622

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SUPPORTING INFORMATION

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