Simulating land use changes, sediment yields, and pesticide use in the Upper Paraguay River Basin: implications for conservation of the Pantanal wetland

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Abstract

As a consequence of accelerated and excessive use of pesticides in tropical regions, wilderness areas are under threat; this includes the Pantanal wetlands in the Upper Paraguay River Basin (UPRB). Using a Land Cover Land Use Change (LCLUC) modelling approach, we estimated the expected pesticide load in the Pantanal and the surrounding highlands region for 2050 under three potential scenarios: i) business as usual (BAU), ii) acceleration of anthropogenic changes (ACC), and iii) use of buffer zones around protected areas (BPA). The quantity of pesticides used in the UPRB is predicted to vary depending on the scenario, from an overall increase by as much as 7.4% in the UPRB in the BAU scenario (increasing by 38.5% in the floodplain and 6.6% in the highlands), to an increase of 11.2% in the UPRB (over current use) under the AAC scenario (increasing by 53.8% in the floodplain and 7.5% in the highlands). Much higher usage of pesticides is predicted in sub-basins with greater agricultural areas within major hydrographic basins. Changing the current trajectory of land management in the UPRB is a complex challenge. It will require a substantial shift from current practices, and will involve the implementation of a number of strategies, ranging from the development of new technologies to achieve changes in land use policies, to increasing dialogue between farmers, ranchers, the scientific community, and local or traditional communities through participatory learning processes and outreach.

Keywords: Land Cover Land Use Change, sedimentation, agriculture, biodiversity, Paraguay River, agrochemical.

1. Introduction

Studies estimate that global agricultural expansion is expected to increase food production for more than nine billion people by 2050 (Foresight, 2011). This increase will further risk damaging environmental quality and food security (Phalan et al., 2011; Springmann et al., 2018). Expanding agricultural land use will likely accelerate the excessive use of existing pesticides as well as spurring the development and production of new pesticides (Popp et al., 2012). In response to the negative ecological and human health impacts surrounding the use of organophosphorus and organochlorine pesticides, new pesticides were developed in the 1990s, including neonicotinoids, which were rapidly adopted in agriculture (Thany, 2010; Morrissey et al., 2015; Hunt et al., 2016). Unfortunately, the use of these substances has increased globally in spite of compelling evidence of their detrimental ecological effects, including alarming declines in terrestrial insect pollinators, with potentially catastrophic implications for native vegetation and food crop production, and ultimately for animal and human health (Brittain et al., 2010; Sánchez-Bayo and Wyckhuys, 2019; Srivastava et al., 2020). Due to their ability to persist in the aquatic or terrestrial environment, pesticides can affect individuals through bioaccumulation, and may cause impacts throughout the trophic chain through biomagnification, affecting animal and potentially human health. There is evidence that some pesticide exposures are linked to acute (pesticide poisoning), and chronic (fetal malformations and cancer) effects on human health conditions (Bonner and Alavanja, 2017; Kim et al. 2017, Pignati et al., 2017).

In Brazil, pesticide use has increased dramatically since 1990. Indeed, in 2017, pesticide use in the country was three-times higher than the global average (Bombardi, 2019). The pesticide market in Brazil is currently worth US$10 billion per year (Gonzales, 2020). As a result of this massive pesticide use, wilderness areas are under threat, including the Amazonian frontier (Schiesari et al., 2013) and the Pantanal (Laabs et al., 2002). There are also additional human health implications, with one in four municipalities in Brazil having drinking water contaminated by pesticides (Aranha and Rocha, 2019), as well as threats from consumption of contaminated fish and shellfish (Alho and Reis, 2017).

Many concerns have been raised about pesticide concentrations in the Upper Paraguay River Basin that provides a major input of flood waters to the Pantanal, the world's largest tropical wetland. Although concern is increasing about pesticide impacts on environmental and human health in the Brazilian portions of the Amazon and Cerrado (the Brazilian Savanna), the impacts on the Pantanal biome are still relatively unknown (Vieira et al., 2001). More than 474,000 inhabitants live in the 16 municipalities that make up the Pantanal (IBGE, 2010), and the region also hosts millions of visitors from all over the world each year. The Pantanal's biodiversity includes globally significant threatened wildlife species such as the jaguar (*Panthera onca*), giant armadillo (*Priodontes maximus*) and hyacinth macaw (*Anodorhynchus hyacinthinus)* (Harris et al., 2005; Tomas et al., 2010; Tomas et al., 2019). This extensive ecosystem also provides a wide range of ecosystem services (e.g., providing water and food, and controlling sediment dynamics, among others), which have been estimated to have a non-market monetary value greater than US$ 59 billion

(US$ 3,932.05 per ha/year) (Moraes et al., 2009; Bolzan et al., 2020). However, only around 10% of the Pantanal is formally designated as protected areas despite the extensive evidence showing that agricultural and other anthropogenic activities in the wetland and surrounding highland areas are negatively impacting ecosystem functions and wildlife health (Harris et al., 2005; Alho and Sabino, 2011; Schulz et al., 2019; Tomas et al., 2019).

Until recently, traditional production in the Upper Paraguay River Basin involved raising cattle, and little or no pesticides were used. Pesticide use apparently increased minimally after the introduction of exotic pasture grasses in the 1970s. Pesticides have increased with the introduction of large-scale soy bean and corn production from 2015 to 2020. As more of the land in the Upper Paraguay River Basin is brought into agricultural production and intensive cattle ranching, the impacts of pesticides and erosion are becoming more widespread, posing an increased threat to ecosystem functions as well as to animal and human health (Miranda et al., 2008; Hunt et al., 2016). Pesticides such as cypermethrin, endosulfan, 2,4-D, atrazine, L-cyhalothrin, permethrin and glyphosate are now widely applied in the highland drainage areas surrounding the Pantanal that broadly encompass the Upper Paraguay River Basin (UPRB) (Pignati et al., 2017). UPRB streams and rivers drain into the Pantanal floodplain, transporting both water and sediments (Laabs et al., 2002; Albuquerque et al., 2016). However, Rezende-Filho et al. (2015) highlighted an increase in SO_4^{2-} content that mainly affects areas developed on sandstone formations and some calcareous areas north of the Pantanal. The increase in SO_4^{2-} content (by approximately ten-fold) is likely from agricultural origin, and is reflected in the floodplain along the São Lourenço Basin down to its confluence with the Cuiaba River. There is very little information on the extent, magnitude or impact of contamination, making it challenging to implement policies to regulate pesticide use; this includes the development of policies for evaluation of environmental risks.

While pesticide transport mechanisms through the Pantanal are currently not well understood, relative to the surface- and below-ground flow paths, agriculture and cattle ranching are expected to continue to increase, mainly in the surround highlands, for the coming decades (Guerra et al., 2020a), with direct implications for increasing pesticide use and increased river bed sedimentation. Moreover, legally required buffer strips along streams (Permanent Protected Areas – "Áreas de Preservação Permanente" in Portuguese [APP]) are lacking around many streams in the highlands, due to the past conversion of native vegetation for use in agriculture and for cattle ranches. This process took place in the region primarily during the 1970s and 80s (Silva et al., 2011), and may increase the possibility of pesticide transport into the freshwater ecosystem. In addition, in the last 30 years in many areas of the Cerrado, land use conversion to croplands has affected soil hydraulic properties, soil pH and phosphorus content, as well as surface water nitrogen and pesticide contamination (Hunke et al., 2014). Many pesticides become bound to fine sediment (silt and clay), which readily erodes from agricultural land or from over-grazed pastures into the drainage network (Nowell et al., 1999). To identify strategies for reducing these impacts, it is essential to understand and predict the effects of pesticide contaminants on this unique ecosystem. Scenario modeling is an important tool for predicting how changes in land use influence different pathways of future human development and policy choices (Rosa et al., 2017). This is particularly true for land use scenarios which may be used to: (1) help evaluate the potential impacts of environmental resource mitigation measures, (2) more clearly delineate protected areas, and (3) more efficiently distribute financial incentives to farmers who implement alternative practices (Vernier et al., 2017).

Given that the quantity of pesticides used in an area is directly related to the area's land use, we first used Land Cover Land Use Change (LCLUC) to predict the amount of pesticides which will be used in the UPRB by 2050. We estimated the expected pesticide load in the Pantanal and the surrounding highlands region under three potential scenarios: i) business as usual (BAU), ii) acceleration of anthropogenic changes (ACC), and iii) use of buffer zones around protected areas (BPA). Because pesticides can be bound to fine sediments, we also modelled fine-sediment yields in the UPRB for the same three scenarios. We then explored different strategies to reduce the impact of pesticides in the region, with an emphasis on strategies applied at the landscape scale.

2. Methods

2.1 Study area

The Pantanal is a 150,880 km^2 floodplain that collects water and sediment from rivers originating in the UPRB highlands, which includes part of the Central Brazil Shield extensive wetlands (Harris et al., 2005; Assine et al., 2015) (Figure 1). As a result, there is a complete functional and ecological interdependence between the highlands and the floodplain (Harris et al., 2005; Assine et al., 2015; Roque et al., 2016). The highlands are mostly covered by the Cerrado, with portions of Amazon, Atlantic forest and Chaco vegetation in the northern, southeastern and southern regions, respectively (Figure 1). The UPRB and the Pantanal in Brazil are located in the states of Mato Grosso (MT) and Mato Grosso do Sul (MS), with 65% of the Pantanal located in MS (Boin et al., 2019; Schulz et al., 2019).

The region underwent a major intensification of land use over the last 30 years, mainly in the highlands, which by 2016 had 61% of the land under human use, in contrast to only 13% on the floodplain (SOS-Pantanal et al., 2017; Padovani, 2017). Vegetation loss, mainly in the highland, has resulted in large environmental impacts in the wetlands (Harris et al., 2005; Tomas et al., 2019), such as an increase in sediment loads of up to 191%, and water discharge of up to 82%, which can lead to significant changes in flood dynamics (Bergier, 2013). Natural sediment loads generally create complex habitats in sedimentary basins

(Assine, 2003, Zani et al., 2012); however, excessive sediment loads associated with human activity are highly detrimental to aquatic ecosystems, as they infill and bury microhabitats with fine sediments and silt (Assine et al., 2015). Increased sediment loads have had disastrous impacts in the Taquari River basin (which flows from the highlands into the Pantanal), with accumulation of sediments in some segments of the river and permanent flooding over a large area used for cattle ranching (Harris et al., 2005; Galdino et al., 2006; Bergier and Assine, 2016; Bergier et al., 2018).

2.2 Scenarios

To predict the amount of pesticides that will be used in the UPRB by 2050, we considered three possible scenarios, corresponding to different approaches towards management practices that affect land use and sustainability. We assumed that: i) the current environmental laws will be in force, ii) no new protected areas will be created, iii) the rate of land use conversion will not be higher than that experienced in the last 15 years, iv) levels of pesticide use will be the same as levels used today, and v) climate change will not affect the use of pesticides, land use changes or sedimentation processes. Clearly, these assumptions are simplistic and were adopted for pragmatic reasons; therefore, it is important to highlight that our scenarios represent conservative estimates of potential future outcomes, and that the amount of pesticides predicted should be seen as relative values used for comparative analysis between the three scenarios, rather than the actual quantities that will likely be used in the future.

In the BAU (business as usual) scenario, we projected native vegetation loss following the trend of recent years (between 0.5 – 1.5% per year; Figure A1), and assumed full implementation of the primary Brazilian environmental legislation (Native Vegetation Protection Law – NVPL; Law 12,651/2012). The NVPL aims to limit natural vegetation conversion and protect valuable ecosystems on all rural properties in Brazil. Revised in 2012 by law 12615/2012 (Soares-Filho et al., 2014), the NVPL requires landowners to maintain natural vegetation on at least 20% of their land under the conservation category, Legal Reserves (LR), in the Cerrado, Pantanal, Caatinga, Pampa and Atlantic Forest biomes (35% in MT state, and 80% in the Amazon rainforest) (Metzger et al. 2019). Additionally, riparian forest buffer strips with specified widths and specific vegetation types must be fully protected as Permanent Preservation Areas (PPA) along streams, rivers, springs, lakes and areas with >45% slope (Law 12,651/2012). These criteria were used in our BAU scenario.

In the AAC (acceleration of anthropogenic changes) scenario, we posited that political and institutional changes in Brazil related to global pressures for food production, and weakening of environmental protection, increase the amount of land lost to agricultural expansion. In this scenario, we assumed that the highest rates of native vegetation conversion to agriculture recorded among municipalities in the UPRB over the last 15 years would be the trend during the modelled period (according to IBGE, acronym in Portuguese for the Brazilian Institute of Geography and Statistics), while ensuring full implementation of the NVPL.

In the BPA (buffered protected areas) scenario, we considered the same trends assumed in the BAU scenario, with the addition of the creation of buffer zones (5 km in width in accordance to the NVPL) around protected areas and indigenous lands, considering that protected areas are a cornerstone of biodiversity conservation and uphold the rights of indigenous peoples. The rationale behind the implementation of buffer zones is that native vegetation in these areas of land can help prevent pollutants, including pesticides, fine sediment and nutrients, from being delivered to streams, and thus can decrease the exposure of wildlife, humans, and the wider ecosystem to pesticides (Hunt et al., 2017).

2.3 Native vegetation loss model

We used a validated spatially explicit model (Rosa et al. 2013; Guerra et al. 2020a) to generate a prediction of the loss of native vegetation by 2050 under the three scenarios. This model predicts the loss of vegetation by taking into account legal requirements, such as areas where land use is restricted by the presence of legal reserves and protected areas. The model involves two steps: the first step identifies the variables that explain vegetation loss in the past, and the second step involves projecting the loss through time based on a probability function (see all steps in Supplementary Methods). The key variables involved were previously identified by Guerra et al. (2020a) (see Table A1) for the same region. It is important to note that to be consistent with the previous models developed by Guerra et al. (2020a), we used the SOS Pantanal data set, which differs in some aspects (land use classification, Pantanal delineation) in relation to other land use data sets, such as IBGE and MapBiomas.

For all scenarios, we considered the LR required under the NVPL, specifically 20% for the Cerrado and 80% for Amazonia. For the floodplain region located in MS we considered the value of LR using the State decreed (#14,273/2015) level of 40%. The definition of LR values for the Pantanal wetland is still under debate, including in the context of the new Pantanal Law that is under discussion in the Brazilian Congress. Therefore, the level of 40% LR used in our study is only an indicative value. Previous scenario modelling (Guerra et al., 2020a) predicted that most properties in the Pantanal will not reduce native vegetation to the legislated threshold of having 20% LR (considering the LR of Cerrado in the Pantanal established in the NVPL; Law 12,651/2012) over the next 30 years. As such, we believe that using a value of 40% will not change the general outcomes of our study. For the BPA scenario, we used a 5 km buffer around protected areas and indigenous lands and assumed that within the buffer zones, the loss of native vegetation has been limited (Bellón et al., 2020), and that pesticides have not been (and will not be) applied on these lands, according to the Brazilian National System of Nature Conservation Units, or SNUC (Law #9,985/2000; Decree #4340/2002).

We did not include the possible conversion of pasture into crops in calculating the loss of vegetation probabilities. Although this is an important current trend, we were unable to reliably predict future conversion rates, because they depend largely on unpredictable trends in international demand for beef and/or crops. To characterize the pasture-crop mosaic, we further assumed that agriculture corresponded to 36.8% of the highlands and 6.4% of the Pantanal floodplain, following current trends (SOS-Pantanal et al., 2017). This assumption means that our model likely underestimates pesticide use in the BAU scenario, because there has been a trend of large areas of pasture being converted into agriculture in the UPRB over the last 15 years (MapBiomas, 2019)

2.4 Pesticides

To calculate the amount of pesticides used, we employed the average liters of pesticides per hectare applied to different crops in Brazil, based on the study by Pignati et al. (2017). We only considered soybean (17.7 L/ha) and corn (7.4 L/ha) crops, as they are the most common crops in the study area, representing 58% and 30%, respectively, of the region's land used for agriculture (IBGE, 2018). We then multiplied the average number of liters used per hectare (12.55 L/ha) by the total estimated agricultural area that resulted from each scenario. Thus, our estimates consider that the increase in the use of pesticides is proportional to the increase in agricultural areas. To build the scenarios, we developed a baseline estimation of the quantity of pesticide currently used (Pignati et al., 2017). This assumption is simplistic, and is likely a gross underestimate, because hundreds of new pesticide products have been approved recently in Brazil. However, because we have little information about the extent of use of these new products, or about future technological developments, we believe that our approach is sufficient to allow us, using the best information currently available, to increase our understanding of the potential scope of pesticide-related problems under the three different scenarios.

2.5 Sediment yield

Pesticides can contaminate the environment through direct application (Wauchope et al., 1994) or from movement through the landscape in association with runoff or, more likely, the transport of soils and sediment. Therefore, we estimated the amount of sediment that will be produced in the highland drainage basins and in the wetlands, through the SDR (Sediment Delivery Ratio) module of the InVEST 3.7.0 (The Natural Capital Project: Stanford, USA), which is based on the Universal Soil Loss Equation: (USLE) Eq. (1) (Wischmeier and Smith, 1978). The USLE is a widely used empirical modeling approach, with known limitations that have been addressed in several studies. In particular, the equation was not designed to erosion from concentrated flow, such as from gullies, and it simplifies the complex and highly heterogeneous hydrological and soil erosion processes that delivery sediment to rivers (Trimble and Crosson, 2000; Belyaev et al., 2005; Quinton, 2013; Evans and Boardman, 2016a, 2016b;). Despite these limitations, USLE is considered a good instrument for predicting soil losses due to laminar erosion, and it requires relatively little information when compared to more complex models (Amorim et al., 2009).

$$A=R*K*LS*C*P \tag{1}$$

where: A is the average soil loss per unit of 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 h MJ^{-1} mm^{-1}); *LS* is the topographic factor (dimensionless); *C* is the soil use and management factor (dimensionless) and *P* is the conservation dimension factor (dimensionless). A description of the variables used is presented in the Supplementary Methods. The sediment yield in the basin is indicative of the potential sediment that will reach the river network and potentially carry pesticides with them, increasing the capacity of pesticides to reach the Pantanal floodplain. Clearly, it is also a simplistic approach because the transport of pesticedes throught run off depend on the solubility, Kow, and other characteristics. Thus, our scenario modelling only provides an overview of the system.

3. Results

The agricultural area of UPRB currently represents 12% of its area (0.67% of the floodplain and 19.9% of the highlands) (Table 1). In the BAU scenario, this area is predicted to comprise 12.95% of the UPRB in 2050 (0.99% of the floodplain and 21.25% of the highlands), while in the ACC scenario it could cover 13.06% in 2050 (1.07% of the floodplain and 21.38% of the highlands). On the other hand, in the BPA scenario, the agricultural area in 2050 may reach 12.93% of the UPRB (0.98% of the floodplain and 21.23% of the highlands) (Table 1).

The quantity of pesticides used in the UPRB is predicted to increase overall by as much as 7.7% over current usage (directly proportional to predicted increases in agricultural area) under the BAU scenario (increasing by 46.0% in the Pantanal floodplain and 6.8% in the surrounding highlands) (Figure 2, Table 1). Under the AAC scenario, models predict there will be a further increase in pesticides of 8.6% in the UPRB over current use (increasing by 53.8% in the floodplain and 7.5% in the highlands), and the BPA scenario predicts an increase of 7.4% in the UPRB (increasing by 38.5% in the floodplain and 6.6% in the highlands) (Figure 2, Table 1).

For the AAC scenario, models predict increases in pesticide use (and agricultural land area) of up to 0.8% in the UPRB over and above the increases that are predicted for the BAU scenario (increasing to 7.0% in the floodplain and 0.6% in the highlands). For the BPA scenario a 0.2% decrease in agricultural land area and pesticide quantities used was predicted in the UPRB in relation to BAU (decrease to 1.3% in the Pantanal floodplain and 0.2% in the surrounding highlands) (Table 1 and Figure 2).

According to the BAU scenario, the watersheds of the UPRB with the greatest increase in agricultural area, and consequently, the greatest increase in pesticide use (Figure 3), will be Taquari 1 (46,892 ha), Miranda (41,343 ha), Paraguai Pant 01 (39,078 ha) and São Lourenço (30,405 ha) (see the values of increase of agriculture of each basin in Figure 4). However, in the BAU scenario, if we consider the proportional expansion of agriculture in relation to the area of each watersheds, those most affected will be Cuiabá 2, Miranda, Sepotuba, Paraguai 1 and Taquari 1 (considering the BAU scenario) (Figures 4 and 5).

The sediment yield within the UPRB will increase 402% by 2050 according to the BAU scenario to over 75 t ha^{-1} $year^{-1}$ (increase of 458% in the floodplain and 398% in the highlands). The AAC scenario predicts an increase of 460% in the UPRB (increase of 608% in the floodplain and 449% in the highlands), while the BPA scenario predicts an increase of 223% in the UPRB by 2050 (increase of 191% in the floodplain and 226% in the highlands) (Figure 6). For the AAC scenario, models predict an increase of 12% in the UPRB in relation to BAU (increase of 26% in the floodplain and 10% in the highlands), and the BPA scenario may decrease sediment yields to the UPRB by 36% in relation to BAU (decrease of 47% in the floodplain and 34% on the highlands) (Figures 6 and 7).

4. Discussion

4.1 Estimation and spatial heterogeneity of pesticide increase

Transformation towards sustainability is needed to address many of the current and future environmental and societal challenges that we are facing, and moving toward decreasing pesticide use is clearly one of those challenges. Our analyses indicate that if the current trajectory of land use change continues in the Pantanal and surrounding highland regions, the level of pesticide use will increase by 8% (4.3 million liters) in the UPRB by 2050. Modeling predictions have shown that if current trends continue, it is expected that in the next 30 years, 14,000 km² of native vegetation will be converted, primarily into agricultural use, in the UPRB (Guerra et al., 2020a). In the Pantanal, the main motivation to replace the native vegetation is the development of pastures containing African grasses, in order to increase cattle production (Tomas et al., 2019).

Even taking into account the uncertainties associated with the global food market in the aftermath of the coronavirus pandemic, it is expected that Brazilian commodity production (e.g., soy bean, cattle, and corn) will continue to rise in response to international demands for food production, particularly from China (CEPEA, 2020). In addition, even in the face of the pandemic, the Brazilian government recently approved new pesticides (Ato Nº 31, de 4 de maio de 2020, Diário Oficial da União). This situation makes our scenario “acceleration of anthropogenic changes” the most likely one. Therefore, it is critical to promote and implement a range of policies and practices geared towards the reduction of pesticide use.

BAU and ACC are similar in terms of predicted quantity of land/pesticide, and sediment produced and their general spatial pattern. However, BAU and ACC are markedly different in their implications for specific hydrographic basins. Much higher usage of pesticides is predicted in the sub-basins with greater agricultural area within major hydrographic basins such as the Taquari 1, Miranda, Paraguai Pant 01 and São Lourenço. In particular, the floodplain is projected to see a 46% increase in pesticide application based on the BAU scenario; however, this value is uncertain and dependent on the potential expansion of agriculture in this region.

In addition to the increase in pesticide use that will occur in critical regions of the floodplain, modelling also indicates that sediment production on the surrounding highlands will increase substantially, but with marked spatial heterogeneities depending on the slopes, and soil types. Areas with high potential for sediment production such as the Taquari River basin also have high sediment yield. The passage of river water through the floodplains results in sedimentation, accounting for the observed 43-69% losses observed among the tributaries of the Paraguay River (Oliveira et al., 2019). High sediment production areas (> 200 t/ha/yr) are spatially clustered; this is concerning, as these sediments will likely move downstream into the floodplain, causing river channel changes, such as that observed in the Taquari River. Because many contaminants in aquatic systems become bound to sediments, this increase in sediment load entering these waterways will likely be linked to increased contaminants (including pesticides) in the Pantanal floodplain, thus compounding pesticide impacts. These effects may be particularly the case in the Pantanal Vegetation Loss Arc (Guerra et al., 2020a), a critical transitional region between the highlands and the Pantanal floodplain, where less extensive flooding allows conversion of native habitat and pasturelands into crops. Another important consideration is that despite being one of the largest continuous wetlands on the planet (Alho, 2008) which hosts the most intact contemporary mammal fauna in South America (Bogoni et al., 2020), less than 10% of the Pantanal comprises formally protected areas, such as indigenous lands and national parks (Tomas et al., 2019). Thus, as a result of increased, direct application of pesticides in the floodplain, coupled with increased sedimentation derived from UPRB highland pesticide application, pesticide levels in the region are substantial and continue to increase. More pesticide exposure in the floodplain is of particular concern, given the global ecological significance of the Pantanal wetlands.

The great loss of vegetation, especially in the highlands, is directly linked to impacts on the Pantanal floodplain, particularly the movement and deposition of large quantities of sediment. More than 90% of the sediment input onto the floodplain is produced in the highlands (Guerra et al. 2020b), with a large proportion transported to the Taquari alluvial megafan. Our study shows that some specific watersheds are more likely than others to experience rapid land use changes, and they may be more affected by sediment transportation in the coming years.

Areas with high potential for sediment production, such as the Taquari River basin, also have high sediment yield. The sediment load of the Taquari River at the entrance to the Pantanal is around 7.5 t/d and represents 50% of the sediment transported by the UPRB rivers (Oliveira et al., 2019). The São Lourenço basin carries 20% of sediments, and the Miranda and Aquidauana rivers around 10%. Although not all sediments produced in the highlands reach the Paraguay River and its floodplain, most accumulate in the up-stream portions of alluvial fans where inundation begins. This highlights the urgent need to improve land use practices in all watersheds of the UPRB, including the Taquari watershed, which has a large-scale influence on hydrological and sedimentological processes in the Pantanal (Assine et al., 2015).

Our results showing the percent increase in agriculture in relation to basin area should be evaluated by the heads of river basin committees, because they provide information on how much native vegetation still exists and how much will be lost in the future in each possible scenario, enabling prioritization of actions for the basins that avoid worst case scenarios.

4.2 Implications for land use management and policy

Changing the current trajectory of land management in the UPRB is a complex challenge. It will require abandoning current practices, and introducing best practice, by developing new technologies to improve land use, and increasing dialogue between farmers, ranchers, the scientific community, and local or traditional communities through participatory learning processes and outreach activities. Alongside these activities, many authors have already identified that the first and crucial steps are stricter pesticide regulations and stronger enforcement measures to decrease the illegal use of pesticides in Brazil. Moreover, given that i) some municipalities in the highlands already use high levels of pesticides (up to 10^7 L/ha/year) (Pignati et al., 2017); and ii) agrochemicals currently used on soy bean crops in Brazil include 457 separate chemical formulations registered for use as pesticides, of which 219 are considered “extremely toxic” or “highly toxic” to humans, and 235 are “highly dangerous” or “very dangerous” to the environment (Schiesari and Grillitsch, 2010), it is essential that there is immediate implementation of Health Surveillance of Populations Exposed to Pesticides (VSPEA), which involves applying the guidelines of the National Worker Health Policy (Pignati et al., 2017).

The high agricultural productivity of Brazilian agribusiness underpins the high levels of pesticide use in the UPRB; specifically, combined soybean, corn and cotton crops account for more than 88% of all pesticides used in the region (Pignati et al., 2017). Therefore, any solution which moves towards decreasing pesticide use must involve adoption of new production strategies for these crops. Indeed, a number of recent studies have provided evidence that lower use of pesticides has not resulted in any decreases in productivity or profitability in arable farms in the temperate region (Lechenete et al., 2017); however, this needs to be tested in tropical regions, such as the UPRB, to confirm that it is equally applicable. Moreover, as land use changes in the UPRB are at least partially driven by international demands for increased food production, there is a window of opportunity for introducing international food safety management standards, involving global food supply chains, and encouraging consumer-driven actions to support reduced pesticide use in the UPRB.

Nature-based solutions at the landscape scale could contribute to the reduction of sediment loads and pesticide impacts in the UPRB. As this study shows, buffer zones around protected areas and streams, as well as proper soil management, can reduce the rate of sedimentation, and consequently the amount of pesticides that would move from the highlands into the Pantanal wetlands. Moreover, protecting native vegetation on private lands beyond the minimum Legal Reserve requirements, and restoring non-compliance areas, as specified by the NVPL would enhance ecological services provided by agricultural lands in the Pantanal and UPRB highlands. This would help to decrease the rate of sediment production (Guerra et al., 2020b) and promote greater ecological resilience (Stefanes et al., 2016). These kinds of nature-based solutions can be particularly useful for this region, because they can provide multiple benefits, such as food and water security, carbon sequestration, protection of biodiversity and provision of space for recreation.

New technologies, and new and more efficient methods for carrying out organic agriculture can also be utilized to help decrease pesticide use. For example, rather than applying the same amount of pesticides over an entire agricultural field, precision agriculture helps by measuring specific pest control needs and adapting pesticide use accordingly. Precision farming and biological control have already been implemented on some farms in the region, particularly those that are large, highly productive and financially well established (Silva et al., 2007). Providing financial incentives for organic food production throughout the UPRB will also be important, and will encourage sustainable production approaches across the entire watershed, although achieving scale and creating a market will be significant challenges. At the federal level, the National Policy on Agroecology and Organic Production (Pnapo, Decree #7,794/2012) could serve to stimulate more organic production. Complementary state policies are also important for improving sustainable production in the Pantanal. The state of Mato Grosso do Sul also has specific legislation to encourage agroecological and organic production initiatives (Law #5279/2018), and in Mato Grosso, a similar law is under discussion. Local policies and incentives should also be developed at the municipal level, particularly in those watersheds that are expected to suffer the most pronounced land use changes. Although it has been poorly documented, hundreds of small and medium sized properties in the UPRB have already been involved in some initiatives for organic production and agro-forestry systems. Therefore, it is important to avoid unsupportive or conflicting incentives or regulations that could hinder ongoing efforts to reduce pesticides in the UPRB, for example avoiding policies that promote substantial use of pesticides (e.g. by reducing importation taxes), while simultaneously seeking to promote organic food production in the same region.

In summary, among potential sustainability strategies to reduce sediment loads and pesticide impacts, we highlight: 1) promotion of agroecology and sustainable cattle production in the UPRB, using clear diagnostic systems based on indicators as those developed by the Fazenda Sustentavel Program (Tomas et al., 2019); 2) increasing the conservation of native riparian vegetation along streams and rivers in the highlands, which will reduce fine sediments being washed into drainage networks (Guerra et al., 2020b); 3) the introduction of buffer zones around protected areas, in order to specifically protect them from increased agricultural activities and deposition of contaminated sediments (Hunt et al., 2017); and 4) reducing the use of pesticides per hectare by using new technologies.

4.3 Limitations of our models and windows of opportunity for improvements

Models cannot incorporate the full complexity of natural systems. We made a number of necessary assumptions during the modeling process that could lead to differences between model predictions and reality. However, our model and the resulting projected scenarios are the first attempt to take this kind of approach and apply it to the decision making process in the UPRB and, as such, provides an important basis for future work and management. It has also highlighted a number of challenges for future studies. First, a finer scale quantification of pesticide use, and understanding of the different pesticide routes of contamination and spread, are needed for the UPRB. Second, new models should consider the species specific impacts of different pesticides in terms of their toxicological effects (in this paper we simply considered the total amount utilized without considering possible impacts on different species). Third, better land use classification is critical to improve the outcomes of LCLUC models; for example, a better discrimination between native and exotic pastures. Fourth, our modelling approach, although very useful to forecast general land use trends, is purely a data-driven biophysical model. Consequently, the model is unable to consider or quantify changes in: (a) policy, (b) trade in agricultural crops, such as import, export or changing intra-and international consumer demand, (c) human behavior and (d) technological innovation. Furthermore, the magnitude of effects of the estimated drivers may not remain constant in upcoming decades. Finally, we need studies that consider the nexus between climate change and land use change, which can then predict the current and future consequences of increased pesticide use, as well as the introduction of new pesticides, on biodiversity, health of human and animal populations, the economy, and ecosystem services provided by the Pantanal. This integrated model will be particularly important for identifying those human populations which are at risk of exposure to potentially hazardous levels of pesticides.

Despite the current limitations, the information derived from the model provides a useful comparison among the different scenarios considered, and an indication of general trajectories of change. This comparison can be used to inform the development and ongoing monitoring of more sustainable land use policies, and influence decision makers and other stakeholders to consider necessary changes in land use policies. Future scenarios can be included in regional planning strategies, such as ecological-economic zoning of the UPRB, and analyses of the cost-effectiveness of reductions in pesticide use, which should include different long term landscape-level approaches for different types of pesticides.

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