Physical, ecological and human dimensions of environmental change in Brazil's Pantanal wetland: Synthesis and research agenda

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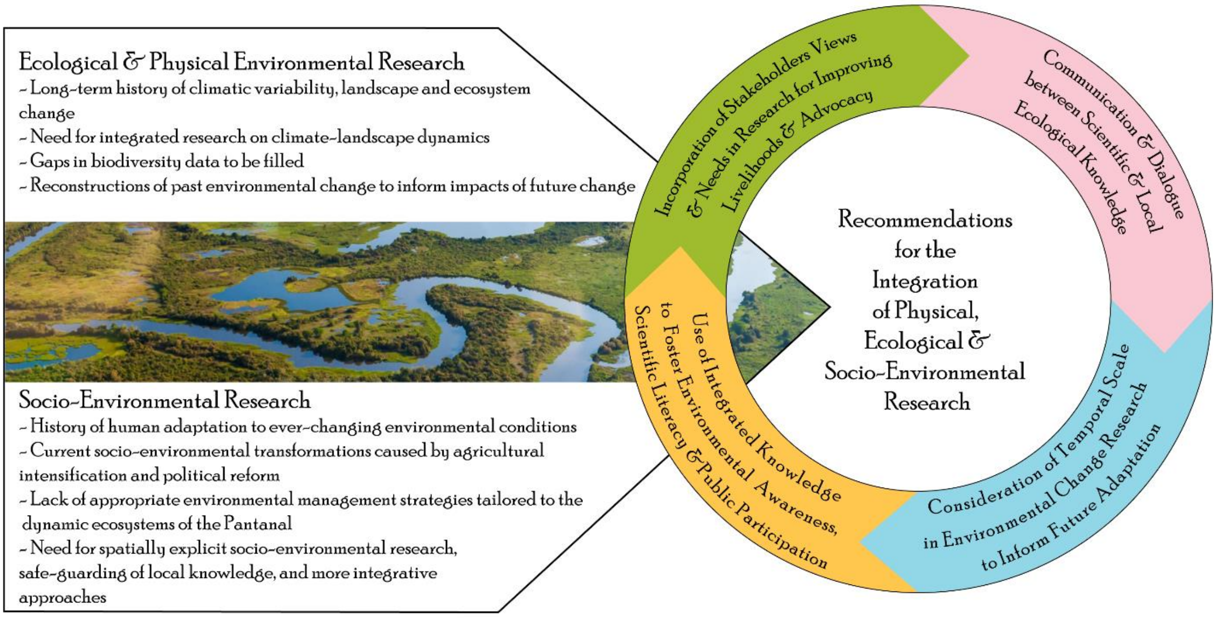
Graphical abstract



Highlights

- Pantanal with long-term history of climatic, physical geographical, and ecological change
- Need for integrated research on climate-landscape dynamics and socio-ecological systems
- Opportunity for dialogue between scientific and traditional ecological knowledge
- Reconstruction of past environmental change can inform adaptation to future anthropogenic change
- Recommendation to improve public participation and environmental education in and on Pantanal research

Abstract

The Pantanal is the world's largest freshwater wetland, located in the geographical centre of South America. It is relatively well conserved, and features unique landscapes, ecosystems, and traditional cultural practices, shaped by the dynamic interaction of climatological, hydrological, geological, ecological, and anthropogenic factors. Its ecological integrity is increasingly threatened by human activities, particularly, in the wider catchment area, for example, deforestation, agricultural intensification, and construction of hydropower plants, with implications for local people's livelihoods. We present a synthesis of current literature on physical, ecological, and human dimensions of environmental change in the wetland, outline key research gaps, and discuss environmental management implications. The literature review suggests that better integration of insights from multiple disciplines is needed and that environmental management could be improved through a better grounding in traditional practices and local perspectives. We conclude with four recommendations: First, future environmental change research should build more strongly on the positive example of a small number of case studies where traditional and local knowledge of the environment was put into a dialogue with scientific knowledge and techniques. Second, we recommend a more explicit consideration of longer temporal scales (>10 years) in environmental change research, making use of oral and written histories, as well as palaeoecological techniques, to understand system responses to different magnitudes of human and climatic pressures, and ultimately, to inform future adaptation activities. Third, we suggest that enhanced stakeholder participation in conceiving and implementing research projects in the

Pantanal would strengthen the practical relevance of research in addressing environmental management challenges, livelihood needs, and advocacy processes. Fourth, we call for a more systemic and integrative perspective on environmental education, which encompasses engagement activities between researchers, policy-makers, and citizens, to foster environmental awareness, scientific literacy, and public participation.

Keywords

Environmental change; climate-landscape dynamics; environmental education; Pantanal; Brazil

1 Introduction

The South American Pantanal is the world's largest freshwater wetland, located mostly in the Brazilian states of Mato Grosso and Mato Grosso do Sul (~80%), with minor shares in Bolivia (~19%) and Paraguay (~1%) (Calheiros et al. 2012: 33) (see Figure 1 below). It is often described as a relatively pristine and intact natural area that serves as an important biodiversity refuge within the South American continent (Assine 2015; Junk & Nunes da Cunha 2005; Junk et al. 2006) and has been recognised as a Brazilian National Heritage Site by the Brazilian Federal Constitution in 1988, and a World Heritage Site by UNESCO in 2000. One of its defining features is the Pantanal's specific flooding regime, characterised by a 'flood pulse' (Junk & Nunes da Cunha 2005), which propagates from north to south, due to the influence of the Amazonian rainfall regime on the northern Paraguay River (Bergier et al. 2018; Hamilton et al. 2002; Oliveira et al. 2018; Por 1995). Floods then reach the southern Pantanal during its dry season. This annual phenomenon shapes not only the ecology and hydrology of the area, but also the cultural traditions of the *Pantaneiros*, the people living in the Pantanal (Girard 2012). This hydrological phenomenon is defined by annual and multi-annual cycles of flooding which determine the extent of terrestrial and aquatic habitats, enable the migration of fish and other aquatic species, and influence biogeochemical cycling on the Pantanal's floodplains. These processes, in turn, have implications for traditional low density cattle ranching on the floodplains (Abreu et al. 2010) and the seasonality of inland fisheries (Alho & Reis 2017).

The Pantanal is a complex mosaic of many different ecosystems, which have been shaped by climatic, ecological, and anthropogenic factors, which are all closely interlinked (Pott et al. 2011). Located at the Brazilian development frontier, the Pantanal has always been considered as remote and inaccessible. This particular environment, including the Pantanal flood pulse, has shaped the subsistence lifestyle of the *Pantaneiros*. The *Pantaneiros* are the population who live with the Pantanal, and some have origins in indigenous groups in the region (Chiaravalloti 2019; Pacini 2015; Rossetto & Girardi 2015). Although the vast majority are cattle ranchers, riverine communities also form part of this group, as is sometimes overlooked or ignored (Chiaravalloti 2019; da Silva & Silva 1995), despite having existed in the area already at the time of the first European explorations in the 16th century (Teles de Ávila et al. 2018). Their identity comes from a close relationship to nature, their ecological knowledge, and knowledge of ancestral practices, which influence daily activities and shape material and immaterial aspects of *Pantaneiro* culture (Dalla Nora & Rossetto 2015; Diegues 2002; Rossetto 2009, 2015). It is important to note that these are different to the migrant populations who located to the Pantanal under government incentives relatively recently (Girard 2012; Silva & Passos 2018).

Whilst the *Pantaneiro* population density continues to be low, human activity from other groups, especially in the neighbouring uplands, has the potential to cause significant changes to the Pantanal's ecology and hydrology. One example is the construction of a large number of small hydroelectric power stations on its tributaries, which may affect the 'flood pulse', water quality and disrupt fish migratory routes (Calheiros et al. 2012; Coelho da Silva et al. 2019). Different authors differ with regards to their assessment in how far these impacts can be mitigated through careful reservoir management, also considering the variation in size among dams (Bergier 2013; Fantin-Cruz et al. 2015; Zeilhofer & de Moura 2009), and further research is thus warranted (Coelho da Silva et al. 2019; Silio-Calzada et al. 2017). Another example are the high levels of mercury in rivers polluted by gold mining activities, which then accumulate in fish and other animals of the local food chain, such as jaguars (May Júnior et al. 2018). The *Pantaneiros* have seen their relationship with the local environment challenged by these human activities that take place particularly in the upper and middle sections of the rivers that make up the catchment area (Bergier 2013; Coelho da Silva et al. 2019).

The Pantanal has taken a backseat in national environmental policy-making in the three countries of Brazil, Bolivia and Paraguay compared to other biomes, namely the Amazon, the Andes and Chaco (Ioris et al. 2014). Nevertheless, a step forward was given in March 2018, during the 8th World Water Forum, where representatives from Brazil, Bolivia, and Paraguay signed a landmark tri-national declaration through which the three countries are committed to develop coordinated plans and strategies to achieve the sustainable development of the Pantanal (WWF 2018). This renewed national and international attention may lead to novel attempts to improve environmental conservation and management in the Pantanal and neighbouring areas, which are currently characterised by extensive anthropogenic environmental change, but also have a long history of non-anthropogenic environmental change, as we discuss below. There is a need then to understand the current physical, ecological and social developments and issues in the Pantanal from an integrated perspective to inform management.

In the present article, we review physical and ecological as well as the human dimensions of environmental change in the Brazilian Pantanal (past, present, and future), propose an agenda for future research, and outline key environmental management implications of existing and future research. This article was conceived at an international academic workshop on environmental change in the Pantanal, attended by Brazilian and UK-based researchers with a diverse variety of disciplinary backgrounds. By combining a synthesis of existing research with a discussion of research gaps and environmental management implications, we are hoping to spark conversations on suitable pathways for improving environmental management and policy for the Pantanal in the medium to long term. We recognise that this article can only represent one small element within much larger societal processes that make up science-policy interfaces (van den Hove 2007), and that its immediate readership will mostly be limited to the national and international academic community. It is also clear that in practice, only a minority of science-policy interfaces can be described as linear processes in which policy-makers 'receive' or 'respond to' scientific input (Wyborn et al. 2017). Nevertheless, insights from academic discussions can eventually reach policy-makers or the general population, for example, via personal interactions, joint participation in official forums such as river basin committees, or public engagement activities.

Figure 1: Location and extent of the Pantanal wetland in South America; Outline of the Pantanal based on Assine et al. (2015)

2 The physical environment and ecosystem change in the Pantanal

The Pantanal is a sedimentary basin that occupies an Andean backbulge, where subsidence occurs due to tectonic activity associated with the last building phases of the Andes around 2.5 million years ago (Cohen et al. 2015; Ussami et al. 1999). The Pantanal is 135,000 km^2 and the Upper Paraguay Basin covers 356,000 km^2 when its catchment area, the surrounding plateaus and hills, are included. Due to the low topographical gradients, infiltration and retention in the sandy sediments that have eroded into the basin, the Pantanal floods annually and is slow to drain, resulting in the unique and dynamic nature of the floodplains (Alho 2005; Assine 2015; Assine et al. 2016; Hamilton 2002). This section demonstrates that the variability in the flood pulse over multiple timescales has determined the landscape evolution, ecology, and biogeography of the Pantanal since its inception.

2.1. Current research on the physical environment and ecosystem change in the Pantanal

The landscape of the Pantanal is defined by the annual flood pulse caused by seasonal rainfall. The key sources of precipitation are complex and spatially and temporally variable. Annual rainfall is linked to the annual migration of the Low Level Jet that brings monsoonal precipitation that is strongly modulated by the Amazonian forest (Berbery & Barros 2002; Bergier et al. 2018). The Chaco depression, a low pressure system located east of the Andes, is influenced by north-south and south-north atmospheric exchanges and by the performance of several atmospheric systems in the formation of the climatic system (Tarifa 1986). The Pantanal region is also influenced by the South Atlantic anticyclone (SAA), whose high pressure predominates in the dry season (autumn and winter), and by the Amazonian convection, which regulates the rainy season (Sette 2000; Zavattini 1990). The rainy season can also be influenced by rainfall systems, the Intertropical Convergence Zone (ITCZ) and the South Atlantic convergence zone (SACZ) (Marengo et al. 2016a). Zavattini (1990) points out that, depending on the cold frontal systems related to the flows of the polar mass in the eastern part of the Andes, there may be drier or rainy weather conditions.

The interaction of the aforementioned atmospheric systems, in association with the topography, phytogeography, hydrology and high solar incidence of the Pantanal, result in climatic conditions that typify the Pantanal subregions. Zavattini (1990, 2009) cites, as examples, the high annual rainfall indices of the northern region, which vary between 1,000-1,700 mm, where there is considerable variability in the distribution of rainfall; and the lowest indices recorded in the center-south, varying between 1,000-1,100mm, a region where the interannual variability is not very accentuated. The widespread flooding in the Pantanal associated with these annual rains in the (austral) summer, and its frequency, duration and amplitude interacts with the topography of the landscape to shape spatial and temporal distribution of terrestrial and aquatic ecosystems. The influence of climate and the flood regime on landscape structure and distribution is best described at macrohabitat scale (Junk et al. 2014, 2018a,b; Nunes da Cunha et al. 2015) and considerable advances in vegetation survey and mapping have produced macrohabitat classifications that incorporate the concept of the flood pulse within their definitions (Dubs 1992; Junk et al. 2018a). Classification of the diversity of Pantanal macrohabitats, from fully aquatic to fully terrestrial, has provided a basis on which to enable research into the influence of the flood pulse on species' distribution and interaction, and build a platform for sustainable management and conservation of the Pantanal.

Throughout the history of the Pantanal, however, there were significant changes to climate and the precipitation-driven flood regime which have impacted the biogeography and landscape evolution of the region. A proliferation of environmental reconstruction studies have improved our understanding of past climate-landscape dynamics in the Pantanal (Becker et al. 2018; Boin et al. 2019; Guerreiro et al. 2018; Rasbold et al. 2019). Direct indicators of palaeoclimate are inferred through cave deposits (Novello et al. 2017), and the majority of past landscape studies are derived from microfossil (Becker et al. 2018; Guerreiro et al. 2018; McGlue et al. 2012; Rasbold et al. 2019; Whitney et al. 2011) and geochemical signatures (Fornace et al., 2016; McGlue et al., 2017) in lake sediments, and relict geomorphological features of past landscape dynamics (Assine & Soares 2004). Most studies indicate that at the height of the Last Glacial Period (ca. 21,000 years ago), when the earth's climate system was considerably different from the present, there were high magnitude variations in climate, followed by a less variable period since the Younger Dryas (11,700 years ago) (Clapperton 1993; Stute et al. 1995).

These past climate fluctuations, specifically precipitation, have interacted in a complex and dynamic manner with the floodplain systems and controlled the distribution of aquatic and dryland ecosystems. Information on historical changes to the flood regime has been obtained from the large floodplain lakes associated with the course of the Paraguay River (McGlue et al. 2012; Power et al. 2016; Rasbold et al. 2019; Whitney et al. 2011) and from the alluvial fan landscapes in the higher, less flooded terrain of the Pantanal (Assine & Soares 2004; Guerreiro et al. 2018; McGlue et al. 2017). Vegetation and fire reconstructions from the large floodplain lake, Gaiva (Power et al. 2016; Whitney et al. 2011) imply that reduced flooding during the late Pleistocene was responsible for the higher abundance of dry land vegetation in the Pantanal from 21,000 years ago until near the beginning of the current global interglacial around 12,000 years ago. These interpretations were proposed by Assine and Soares (2004) who, using geomorphological evidence of relict dune systems, determined that climate must have been drier during the last global ice age. A strengthening monsoon through the transition into the modern warm interglacial (16,000 to 8,000 years ago) is interpreted from reconstructions at Gaiva (Metcalfe et al. 2014; Whitney et al. 2011).

In contrast, glacial-aged reconstructions from another floodplain lake (Rasbold et al. 2019) demonstrate a complex picture of precipitation change from the last glacial period until present, with alternating wet and dry phases, and evidence of higher fluvial activity in the glacial period. There are limited long-term data for the Pantanal subregions beyond the large riverine lakes, but studies of the evolution of Nhecolândia saline lakes also imply that there was higher fluvial activity during the last glacial period, linked to increased monsoon strength (Guerreiro et al. 2018). Taken together with precipitation inferred from cave deposits (Novello et al. 2017), these data show higher glacial-aged precipitation and a complex interaction between monsoon strength, river activity and lake dynamics. Some of these data from lake reconstructions are contradictory (e.g., Metcalfe et al. 2014; Rasbold et al. 2019; Whitney et al. 2011), which implies that the hydrological response to changing precipitation in the Pantanal might have been spatially heterogeneous.

There is strong evidence of lake lowstands (drought) and fluctuating water levels during the Holocene (the current global interglacial period) (Fornace et al. 2016; McGlue et al. 2012) among the floodplain lakes and lower precipitation inferred from speleothem records (Novello et al. 2017). Evidence shows lacustrine (lake) system evolution in Nhecolândia occurred during the Holocene (Assine et al. 2015; Furquim et al. 2010; Guerreiro et al. 2018; McGlue et al. 2017) and among the dry lake systems of the Pantanal do Miranda (Oliveira et al. 2017). The multitude of small water bodies in the southern Pantanal are relatively recent in origin, and are controlled by a complex interaction of topography, groundwater isolation or floods (McGlue et al. 2017). The situation shows that precipitation variability in the last few millennia was an important driver of landscape change in Nhecolândia and the Pantanal do Miranda, but their evolution also demonstrates a delicate balance between geology, geographic position and groundwater dynamics (McGlue et al. 2017; Oliveira et al. 2017).

The millennial-scale studies of Pantanal dynamics show a climatic influence on the flood regime of the basin which have exerted a strong control on the distribution and extent of terrestrial and aquatic habitats through time (Guerreiro et al. 2018; McGlue et al. 2012; Whitney et al. 2011). The variability in the flood regime, demonstrated over these longer timescales, is also manifested in decadal and annual changes albeit, to a lesser magnitude, as periods of higher flooding and drought have influenced the abundance and distribution of terrestrial and aquatic habitats over a human lifespan (Hamilton, 2002). Crucially, the long-term studies of Pantanal landscape change demonstrate that it is a highly dynamic system that has responded to frequent and high magnitude climate change in the past.

2.2. Remaining gaps in research on the physical environment and ecosystems of the Pantanal

The study of past climate and its dynamic relationship with ecosystem function, biodiversity, hydrology and geomorphology has proven crucial to understanding potential future impacts of climate change in regions throughout the globe (e.g., MacDonald et al. 2008; Macklin & Lewin 2019; Willis et al. 2010). Past climate-landscape interactions are most understudied in tropical regions, despite pending climate risk of rising temperatures and decreasing precipitation in some of the most vulnerable economies in the global south (IPCC 2013). In the Pantanal, landscape response to past high magnitude climate fluctuations can provide insights into how anthropogenic climate change will influence the future water security of the region, on which so many ecosystems and livelihoods are dependent.

A synthesis of the studies about the past climate-landscape dynamics in the Pantanal, however, has not yet been attempted. This gap is likely due to the sparse spatial and temporal coverage of the datasets, the vast majority of which are derived from lake sediments, which causes a bias in sampling to more permanently wet regions of the Pantanal. Furthermore, there are contradictions inherent among the different types of datasets that are yet to be resolved. For example, recent speleothem (cave deposits) studies have postulated a different climatological history of the Pantanal (Novello et al. 2017) compared to some lake records (e.g., Whitney et al. 2011). These inferred differences, however, are potentially a consequence of the type of proxy used given that climate is only one of many possible drivers of vegetation and geomorphological changes recorded in lake sediments. These complexities demonstrate a need to reconcile the disparate lines of evidence for the region and/or quantify spatial variability in past hydrological change. Additionally, past interactions between hydrology and climate (and the ecosystems they support) have been shown to be linked to regional tectonics, geomorphology and sedimentology in this vast basin (Oliveira et al. 2018). More coordinated efforts in the calibration and development of proxy methods, retrieval of records from a wider variety of deposits and different sub-regions of the Pantanal, and the application of modelling (such as the interaction between the landscape, flood pulse and precipitation), will address most of these biases.

While the understanding of the longer term climate-landscape dynamics of the Pantanal is still rudimentary, the distribution of flood-tolerant and dryland ecosystems are clearly delineated by the modern flood regime and are well described in the literature (Alho 2005; Hamilton 2002; Junk et al. 2006; Pott et al. 2011). However, we still have little understanding of what controls biodiversity patterns across these highly variable landscapes. In fact, the few studies that assessed drivers of variation in landscape structure across climatic and edaphic (soil conditions) gradients in the Pantanal restricted their analyses to (i) macrohabitat classifications, which use multiple groups of higher plants (e.g., flowering plants) and point to the importance of hydrology, fires and human impacts for the differentiation of landscape units (Junk et al. 2014, 2018a,b; Nunes da Cunha et al. 2015); or (ii) assessed plant community turnover in forests (seasonally dry, Neves et al. 2015; riverine, Wittmann et al. 2017) and savannas (Bueno et al. 2018). Furthermore, these community turnover studies classified the Pantanal as an extension of the Cerrado biome, rather than a uniquely dynamic landscape combining elements of both. Notwithstanding, an important take-home message stemming from these studies is that distinct sets of environmental variables (e.g., the combined and independent effects of hydrology, climate, soils, topography) might shape the plant community composition across forest and savanna landscapes, suggesting that further studies are needed to explore the potential drivers of spatial and temporal variation in ecosystems, and the services they provide, across the High Pantanal landscapes to low wetlands.

At present, the Pantanal comprises one of the largest gaps of biodiversity knowledge for plants (along with the Amazon) and invertebrates (along with the Amazon and Caatinga) in Brazil (Oliveira et al. 2016). At the same time, the Pantanal also comprises the smallest gap of biodiversity knowledge for charismatic and economically valuable groups such as birds, mammals and fishes (Junk et al. 2006). The largest gap can be found across its central region (Oliveira et al. 2016), congruent with overall distance from access routes (see star in Fig. 1). This remote, under-sampled region comprises the alluvial fan of the Taquari River, which is often subdivided into Paiaguás (upper fan) and Nhecolândia (lower fan). Interestingly, one of the most collected areas in the Pantanal is also in the middle of Nhecolândia - the Nhumirim farm (Ferreira et al. 2017; Raizer et al. 2017). Sampling, however, only covers a tiny area, and is often focused in a few taxonomic groups. Therefore, we stress that these relatively 'oversampled' areas found across both Paiaguás and Nhecolândia could be used to guide priorities for new biological inventories of unsampled taxonomic groups, optimising resource use and significantly expanding the knowledge about biodiversity. We further suggest that sites distant from access routes, particularly those with poorly sampled environmental conditions, should be preferential targets for future biodiversity surveys, given the strong correlation between spatial variability in community composition and environmental variation across the Pantanal (Neves et al. 2015; Wittmann et al. 2017).

Among aquatic systems, fish diversity is best described, but there are gaps also due to lack of sampling (Junk et al. 2006). Fish life cycles are poorly described despite their value to the local economy (Junk et al. 2006). More than 70% of the total amount of fish caught is made up of five species only: *pacu* (*Piaractus mesopotamicus*), *pintado* (*Pseudoplatystoma corruscans*), *piavuçu* (*Leporinus macrocephalus*), *dourado* (*Salminus brasiliensis*) and *cachara* (*Pseudoplatystoma fasciatum*) (Catella 2003). The aquatic ecosystems are entirely dependent on the flood regime, which influences, for example, primary productivity, nutrient availability, water quality, food webs, population dynamics, and (sub)annual fluctuations in these, and related variables (Alho 2005; Hamilton 2002). Nonetheless, as for terrestrial ecosystems, there is an overall lack of studies aiming at assessing the impacts of such a flood regime on multiple dimensions of fish diversity (e.g., from genetic to within-population functional diversity). Furthermore, given the fluctuations of the hydrological regime as demonstrated from long-term studies (see section 2.1), there is no understanding of these effects on fish population variability, either from palaeo or historical reconstructions (e.g., Lenders et al. 2016; Selbie et al. 2007). This lack of long-term (i.e., centennial to millennial) fish population data limits understanding of the impact of changes in the extent and magnitude of annual flooding on aquatic ecosystems.

Of particular concern to fish populations are the frequency and magnitude of massive fish kills linked to the spread of anoxic waters that have been possibly caused by flooding of charred ground and linked to the expansion of invasive fire-tolerant grasses (i.e., Hamilton 2002), but requires long-term historical data on climate and fish populations to understand cause and possible management strategies. Participatory and integrative research on a limnological phenomenon locally known as 'dequada' has shown that local people may sometimes have a more advanced understanding of these issues, for example, with regards to the duration of fish kills (Calheiros et al. 2000), even if popular assumptions also benefit from testing with scientific methods. An improved understanding of the timing of fish kills may then be employed in environmental management, for example to regulate fishing activities in specific geographical areas. Insights from studies based on fish catch data have also shown great intra- and inter-annual variation in the geographical distribution of fish populations within the wider Paraguay River Basin (Mateus et al. 2004). Those authors attribute reduced fish catch rates to a complex set of factors, including environmental degradation associated with urbanisation, fishing restrictions, changes in market preferences, and overfishing. They particularly highlight that overfishing is unlikely to be the sole cause of reduced catches (see also Chiaravalloti 2017), and instead draw attention to the increased share of carnivorous species in fish landings.

2.3 Environmental management implications and a research agenda integrating landscapes, climate and ecosystems science in the Pantanal

The long-term studies reviewed above have demonstrated that variations in rainfall patterns will change the magnitude and seasonal distribution of the flood pulse, which directly determines the relative proportions of dryland and flooded terrain. Therefore, future climate change will have an impact on the provisioning (tourism, cattle ranching), regulating (water quality, soil preservation, fire frequency, flood control), supporting (biodiversity, habitats of rare or economically important taxa) and cultural services of both aquatic and terrestrial ecosystems of the Pantanal.

The study of long-term climate-landscape dynamics is patchy and underdeveloped in the Pantanal. Specific challenges requiring greater interdisciplinarity are to first generate better spatial coverage of environmental reconstructions across hydrological, topographical and geographical gradients and to calibrate proxy data so that the geochemical, geomorphological and biotic data are linked to better knowledge of the modern relationships between these proxy signatures and environmental processes (McGlue et al. 2011). To address the geographical biases in the study of past environmental change, there need to be more coordinated efforts in the retrieval of records from a wider variety of deposits and different sub-regions of the Pantanal, and the application of modelling to provide insight into future change (such as the interaction between the landscape, flood pulse and precipitation).

Reconstructions of past landscapes alone, however, are not sufficient to understanding the past dynamism of the Pantanal; improved model simulations of the monsoon over South America (Zhou & Lau 1998), and rainfall transmittance through the LLJ, are needed to produce accurate predictions of future climate scenarios for the Pantanal. Linked to the study of modern hydrology, these predictions will inform the influence of climate-landscape dynamics on water quality (e.g., dissolved oxygen concentrations, salinity, eutrophication, suspended sediments), the distribution and composition of terrestrial and aquatic ecosystems, and the adaptability and resilience of the system, as demonstrated in ecohydrological studies elsewhere in the globe (e.g., Brown 2002; Gillson & Willis 2004). There are also significant unknowns surrounding the influences on long-term changes to the strength, pathway and seasonality of the SALLJ. These external (and transboundary) influences (Bergier et al. 2018) on the climatic source of the Pantanal floodwaters require integrated water management strategies including multiple neighbouring countries.

Landscape diversity in terrestrial and aquatic ecosystems, and its relationship to modern climatic, geographic and edaphic gradients needs to be integrated to such a long-term temporal perspective in order to improve overall predictions of the impacts of climate change on ecosystem functioning. For instance, recent experiments brought support for the relationship between biodiversity and the functionality of important ecosystem services, such as primary productivity (Cadotte et. al 2008, 2009; Cadotte 2013). These studies build upon the assumption that lineages (of plants or animals) will often conserve their ancestral ecological niches over evolutionary time, a process known as phylogenetic niche conservatism. Thus, regions with more distantly related lineages (higher phylogenetic diversity) are more likely to exploit the full spectrum of available resources via higher niche complementarity. If this relationship holds at large scales in natural ecosystem such as the Pantanal, understanding the impact of biodiversity loss due to changes in the physical environment is imperative, given predictions of increased climate extremes all over the globe. Thus, here we argue that one of the greatest challenges in ecology and ecosystems science today is understanding how dynamic landscapes affect ecosystem services, ecosystem services' resilience to change (Lavergne et al. 2013) and, therefore, how ecosystem services respond to such change.

Spatial modelling of dynamic interactions between landscape features, ecosystem services and resilience may also have direct environmental management implications, where these give insights on vulnerability, for example with regards to biodiversity conservation and hydrological phenomena (Steinke & Saito 2013). Environmental changes are best observed at the macrohabitat level. Macrohabitats are already described and classified, but data regarding their extent across the Pantanal (e.g., georeferenced distribution maps) is still missing and requires strong efforts. With maps, environmental services can be better attributed spatially, and ecological changes resulting from human-induced global change, regional climatic extreme events and land-use change, can easily be detected, quantified and, if necessary, counteracted.

Nonetheless, progress has been limited in part by challenges associated with integrating disparate datasets to model the geographic distributions, functional traits, and phylogenetic relationships of multiple lineages (Violle et al. 2014), which is core to understanding ecosystem functions and the services they provide. We further argue that such integration is of paramount relevance for conservation strategies predicated on the protection of ecosystem services in the Pantanal wetland, especially under future climate scenarios. However, we currently lack not only comprehensive and standardised biodiversity datasets for the Pantanal, but also a complete understanding of the factors that control the distribution of biodiversity through its spatial and climatic gradients (section 2.1), even though important advances have been made with regards to macrohabitat classification more broadly (Junk et al. 2014; Nunes da Cunha et al. 2015; Junk et al. 2018a,b). Predicting climate-driven landscape shifts across the Pantanal wetland is, therefore, inherently uncertain.

Studies of environmental change show these delicate systems to be highly sensitive to precipitation change, but also they are highly responsive to anthropogenic impact. Deforestation to increase cattle ranching activities involves replacing natural pastures with cultivated ones, which is changing the environment (Paranhos Filho et al. 2014), leading to dessication due to the changes in the local water cycle (i.e. humidity loss), especially in Nhecolândia (Sakamoto et al. 2012). Deforestation for agribusiness activities in the eastern uplands of the wider catchment area, as well as in the more distant Amazon Basin may also contribute to a decrease in rainfall in the Pantanal (Bergier et al. 2018). Furthermore, it decreases soil permeability and increases sediment transport to the Pantanal basin, causing river avulsions and disruptions to the flood pulse (Bergier 2013). Additionally, the potential link between exotic grasses introduced for pasture and altered fire regimes has been highlighted (Williams & Baruch 2000), although competition with aquatic macrophytes in the floodplain may limit their spread in seasonally-flooded environments (Bao et al. 2019). Recent studies have demonstrated the potential of less environmentally impactful land use practices, such as the use of agroforestry systems to stem soil degradation in the uplands (Bergier 2013), certified organic, sustainable beef production, and traditional cattle ranching practices to limit carbon emissions (Bergier et al. 2019) (see also section 3.1). Historical data on the impacts of cattle ranching on Pantanal ecosystems over the past centuries, however, are limited and these observations could be based on shifted ecological baselines (Pauly 1995), where past human impact has altered managers' perceptions of what is natural. In addition to the development of sustainable land-use practices, however, is the need for accurate predictions of rainfall for the next century to enable a whole landscape approach to managing the future security of Pantanal environmental change and predict how climate change will interact with land-use practices in the future.

3 Socio-environmental change in the Pantanal

Following our overview and discussion of the literature on ecological and physical environmental change in the Pantanal, we now turn our attention to the human dimensions associated with environmental change in the Brazilian Pantanal. At the time of the last census, there were 474,000 inhabitants in the 16 municipalities that make up the Pantanal, of which 22.5% were living in rural areas (above the Brazilian average of 15.4%) (IBGE 2010). Major population centres within the Pantanal are Corumbá in the State of Mato Grosso do Sul (96,000 inhabitants), and Cáceres in the State of Mato Grosso (82,000 inhabitants), with the remainder of the Pantanal's population spread across smaller towns, rural communities, and farms. In this section, we first review current socio-environmental research on the Pantanal region, discuss remaining research gaps and needs, and outline potential implications for environmental management, policy, and research.

3.1 Current research on socio-environmental change in the Pantanal

The Pantanal has historically always had a sparse population. Human settlers arrived to the Pantanal area about 5,000 years ago, likely belonging to the Tupi-Guaraní (Arts et al. 2018), but it is possible that the area was inhabited by other hunter-gatherer societies prior to their arrival (Ab'Sáber 1988). Following European colonization of the Pantanal from the 16th century onwards (Schulz & Ioris 2017), the population then consisted of small riverine communities of subsistence fishers, large-scale low-intensity cattle ranching land owners and their workers, as well as a small number of indigenous communities (Girard 2012; Rossetto & Girardi 2015; Wantzen et al. 2008). Traditional livelihoods were well adapted to the characteristic flood pulse hydrological pattern of the Pantanal; for example, cattle numbers were such that they could roam free grazing on the rich Pantanal floodplains during dry season, and were moved to the much smaller patches of dry upland during rainy seasons (Abreu et al. 2010; Girard 2012). The *Pantaneiros* also hold significant local ecological knowledge, for example regarding edible and medicinal wild plants (Bortolotto et al. 2015; Ximenes de Melo et al. 2015), as well as the climate and floodplain dynamics (e.g. Calheiros et al. 2000; Da Silva et al. 2014; Girard & de Vargas 2008). Fishing, too, is an ancient activity in the area, having been practiced by indigenous people already at the time of European exploration in the 16th century (Teles de Ávila et al. 2018).

Livelihood strategies and socio-economic relations in the Pantanal have undergone significant changes in the last few decades, as well as in the recent past, which poses novel environmental management challenges and may also lead to new socio-environmental conflicts. While traditional livelihood strategies are still practiced to some extent, there has been a strong overall decline in such cultural practices, with an associated loss of traditional and local ecological knowledge (Girard 2012; Wantzen et al. 2008). This is significant, not least, because traditional knowledge enjoys a special legal status in Brazil, with regulations aiming to document and officially register it, and this way, safeguard Brazil's cultural heritage and prevent misappropriation by external commercial entities (Costa Eloy et al. 2014; Menuchi et al. 2016).

The loss of traditional and local ecological knowledge is particularly noteworthy during integration of cattle ranching into modern agribusiness systems. Traditional *Pantaneiro* ranchers have a specialised skillset and advanced knowledge about adapting cattle management to the seasonally flooded environment of the Pantanal (Abreu et al. 2010), which is increasingly being lost due to several factors (Ribeiro Lacerda & da Costa Lima 2015). One issue that constrains traditional ranchers is their comparative lack of economic competitiveness, especially in relation to the technologically advanced ranchers of the neighbouring uplands (Wantzen et al. 2008). This has led many traditional ranchers to move to different professions (Ribeiro Lacerda & da Costa Lima 2015). For example, a recent study conducted in the Pantanal town of Poconé found that the entire hospitality sector there is run by former traditional cattle ranchers (Oliveira Rabelo et al. 2017).

Nevertheless, more recent research has also highlighted the potential contribution of local knowledge and traditional practices to the conservation of the Pantanal and the global economy (Bergier et al. 2019; Guerreiro et al. 2019). This creates avenues for multi-stakeholder initiatives across geographical scales. For example, the Nhecolândia soda lakes in the Pantanal have been found to be carbon sinks. Maintaining these unusual environments then has important consequences for climate change mitigation, which opens the potential for Payment for Ecosystem Services (see also section 3.3). In addition, local knowledge of *Pantaneiro* ranchers could help develop practices that would allow for organic beef production and certification (Guerreiro et al. 2019). The traditional method of low-intensity cattle ranching has the potential to be carbon neutral in the floodplains of the Pantanal. This is, because biomass that cattle graze would otherwise decompose during the flooding phase, and the cattle carbon-recycle biomass for other species. Therefore the practices of *Pantaneiro* cattle ranching could be certified as carbon neutral, a potential niche market and conservation technique (Bergier et al. 2019).

Low-intensity cattle ranching is thus mostly considered to be an environmentally sustainable land use (Eaton et al. 2011; Junk & Nunes da Cunha 2005), but concerns arise about the ecological impact of the increasing intensification of both cattle ranching and soybean production in the Pantanal due to technological advances in adapting to the flood pulse (Rossetto and Girardi 2012). As can be seen in Table 1, more than 1,000,000 ha of soybean plantations were added to the Pantanal's municipalities between 2013 and 2017, even if the seasonal flood regime and comparatively poor soils have prevented more extensive land cover conversion. This intensification of land use has seen the introduction of exotic pasture grass, the use of agrochemicals to clear pastures (Rossetto 2004), as well as deforestation activities (Saito & Azevedo 2017), as noted in section 2.3. Some scholars have also pointed out the unequitable power relations between wealthy ranchers and their impoverished workers, which are based on economic exploitation, a problem that extends to traditional and modern cattle ranching practices alike (Ioris 2012).

Table 1: Area (ha) of new soybean plantations in the Brazilian Pantanal 2013-2017; (-) no data available; Source: IBGE, available online: https://cidades.ibge.gov.br/

Municipalities	2013	2014	2015	2016	2017	Total
Barão de Melgaço – MT	(-)	(-)	(-)	(-)	(-)	(-)
Cáceres – MT	3,570	4,150	4,722	5,517	6,085	24,044
Itiquira – MT	210,000	177,325	180,000	180,000	150,760	898,085
Lambari D'Oeste – MT	(-)	(-)	(-)	(-)	940	940
Nossa Senhora do Livramento – MT	0	300	1,700	1,950	1,950	5,900
Poconé – MT	1,035	2,420	5,302	7,130	8;450	24,337
Santo Antônio do Leverger – MT	20,821	21,732	22,950	22,860	18,000	106,363
Aquidauana – MS	(-)	70	(-)	80	(-)	150
Bodoquena – MS	1,020	450	1,180	960	2,540	6,150
Corumbá – MS	(-)	970	(-)	1,450	910	3,330
Coxim – MS	10,800	10,660	10,800	11,000	11,000	54,260
Ladário – MS	(-)	(-)	(-)	(-)	(-)	(-)
Miranda – MS	880	1,780	5,790	12,145	12,611	33,206
Sonora – MS	62,030	61,500	61,500	62,000	56,500	303,530
Porto Murtinho – MS	1,500	1,450	2,173	2,670	2,510	10,303
Rio Verde de Mato Grosso – MS	7,500	8,500	10,500	12,000	16,000	54,500
total	321,169	293,321	308,632	321,778	290,273	1,525,098

The Pantanal is also affected by intensive farming practices in the neighbouring uplands (probably more so than through farming inside the Pantanal), for example through pollution of its rivers with pesticides and fertiliser runoff from fields, with associated ecological and public health impacts (Campos de Magalhães et al. 2016; Ide et al. 2012; Miranda et al. 2008). Another socio-environmental issue that is caused by unsustainable farming practices, including deforestation and bank erosion in the uplands, is the sedimentation of rivers (Lisbôa Gazolla & Gonçalves 2017). This can lead to navigational and other hazards, divert rivers from their original channel, and impact on key ecosystem services such as nutrient cycling and provision of fish habitat (Bergier 2013). The environmental consequences of intensive farming have even led to the displacement of some local communities in the Pantanal, where avulsions caused the permanent flooding of land, including about 180 farms and the homes of about 1000 families in the Upper Taquari Basin (Assine et al. 2016; Ide et al. 2012). While Assine et al. (2016) clarify that such shifting of avulsive rivers is a natural geomorphological phenomenon caused by depositional mechanisms in fluvial megafans, it can be accelerated by cattle ranching and farming in the upper catchment area, as noted in section 2.3.

A further indirect driver of environmental change has been a land reform implemented under the National Programme of Agrarian Reform in 1985, in which large farms were transformed into smaller rural properties denominated as ‘rural settlements’ (Rossetto & Girardi 2012). These reforms were made without consideration of socio-environmental implications and the particular ecological conditions in the Pantanal. Traditional labour relations and social identities were disrupted; the new rural settlements were unable to provide basic necessities to local peasant families; and they were dependent on scarce and inadequate subsidies (provided via a ‘Settlement Development Plan’, PDA). Consequently, most areas were abandoned, that is, the agrarian reform did not accomplish its objectives. The *Pantaneiros* who left these rural areas and settled in urban centres were often faced with precarious living conditions and a lack of skills suited to urban living, thus challenging and shifting their identities (Ribeiro Lacerda 2017; Ribeiro Lacerda & da Costa Lima 2015; Rossetto & Girardi 2015).

Another human driver of environmental change is the significant increase of tourism in the Pantanal, which has developed into an important economic sector (Arts et al. 2018; da Silva Moraes 2015; Silva de Oliveira & Marques 2016). In the past, the Pantanal was primarily popular with Brazilian tourists for recreational fishing. More recently, it has also become a popular attraction for foreign ecotourists who visit the Pantanal for birdwatching and jaguar spotting, among others (Castro Pivatto et al. 2007; Tortato & Izzo 2017). Tourism in the region has been said to have some controversial effects, both from a social and environmental perspective (Arts et al. 2018; Girard & de Vargas 2008; Surubi Fernandes & Maluf-Souza 2013). For example, tourism companies are sometimes accused of monopolising economic benefits from tourism by providing fully organised tours in which no supplies are bought locally. New conflicts may also emerge where some community members earn an income in the hospitality sector, and others continue with a subsistence livelihood. Tourism has also been associated with child sexual exploitation and adult prostitution in regional towns, although no conclusive evidence on the topic exists (Pereira Vargas & Cavero Gonzáles 2016; Surubi Fernandes & Maluf-Souza 2013).

There is also continuing discontent about the competition between local subsistence fishers and fishing tourists who are both blamed for fish decline in the Pantanal (da Silva Moraes 2015; see Figure 2), even if the actual causes of fish decline are still poorly understood and impacts of fishing might be overstated (Chiaravalloti 2017; Mateus et al. 2004). Figure 2 shows that fish catch rates have declined considerably since the 1990s. The latest data indicates an annual total catch of 378 t in the entire Upper Paraguay River Basin of Mato Grosso do Sul, of which about 50% each was caught by professional and recreational fishers (Catella et al. 2017). Within the basin, most fish was caught in the Paraguay River (46%) and Miranda River (35.6%). Professional fishers typically spend 4 to 6 days on a fishing trip, with an average catch of 6.5 to 11.62 kg/day. These authors also find that numbers of recreational fishers have more than halved since the 1990s, reducing the share of recreational fishing in the total amount of fish caught. Yet it is important to recognise the inherent limitations to this type of data, given that much fish trade occurs informally or without intermediaries (Mateus et al. 2004; Rossetto & Tocantins 2015), and is thus not registered in statistics compiled on the basis of official inspections (Catella et al. 2017). In the (northern) state of Mato Grosso, no equivalent system for capturing fishing data exists, although individual studies have revealed roughly similar dynamics, with most fish being caught in the Cuiabá and Paraguay Rivers (Mateus et al. 2004).

Fish decline might also possibly be related to a regional climatic phenomenon known as *friagem* (cold front) that has been shown to kill large numbers of fish as well (Tundisi et al. 2010), affecting local fisheries and the ecology of the Pantanal, with potential long-term repercussions for livelihoods based on eco-tourism (Silva de Oliveira & Marques 2016). The decline in fish numbers has also led some local fishers to kill giant river otters (*Pteronura brasiliensis*), an endangered species, which they believed to compete for scarce fish resources (Saito 2006), this representing another example of a socio-environmental conflict, which connects ecological, climatological, and social aspects. Yet again, it is important to highlight that no conclusive evidence on the matter exists, and that some authors have attributed the reduction in fish landings to overly restrictive fishing regulations, rather than reduced availability of fish, among many other reasons (Chiaravalloti 2017; Mateus et al. 2004).

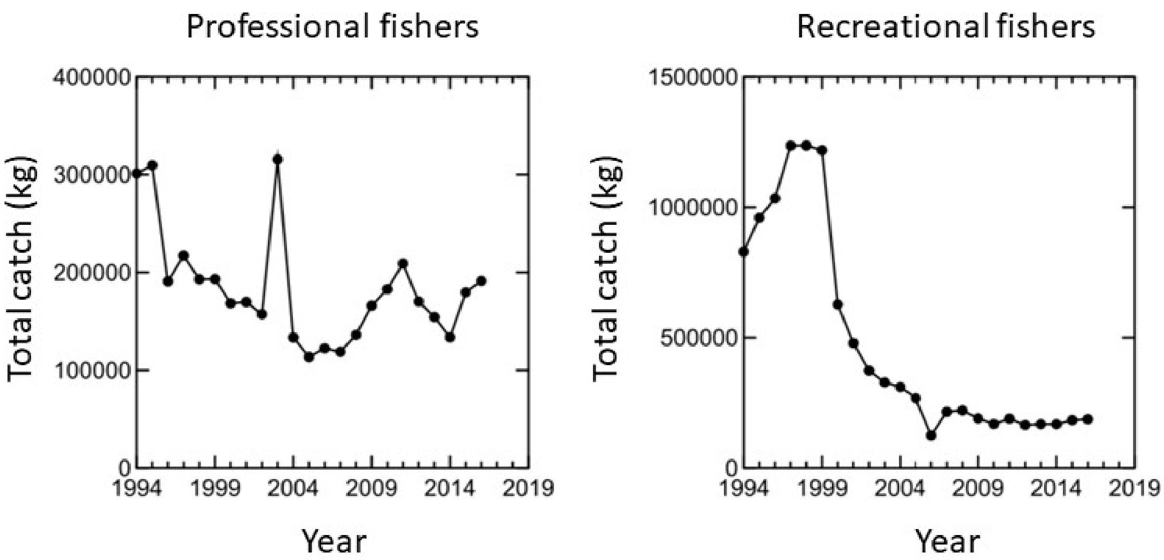


Figure 2: Fish catch rates of professional and recreational fishers in the Upper Paraguay River Basin (Mato Grosso do Sul only), based on official inspections by the environmental military police of Mato Grosso do Sul within the Fishing Control System (Sistema de Controle da Pesca de Mato Grosso do Sul, SCPESCA/MS). Source: Catella et al. (2017).

Another major anthropogenic driver of environmental change in the Pantanal are the rapidly growing numbers of hydroelectric power stations in its tributaries, which affect the hydrological regime and represent physical barriers for aquatic biodiversity, including a wide variety of migratory fish species (Alho & Reis 2017; Calheiros et al. 2012; Crabb et al. 2017; Junk & Nunes da Cunha 2005). According to Welcomme and Halls (2001), white fish species, which are very common in the Pantanal, are among the most impacted ones by dams, because their reproductive cycle is sensitive to flood patterns. Zeilhofer and Moura (2009) found that discharge of the Cuiabá River, one of the two major northern affluents of the Pantanal, was reduced by 20% at the beginning of the wet season and increased by an additional 1 meter during dry season, due to the construction of the large Manso Dam on one of the tributaries of the Cuiabá River, in the upper catchment area. The construction of dams has direct repercussions for the livelihoods of local communities who depend on fishing and the collection of other natural resources, as mentioned earlier, but also, for example, on nesting areas of shorebirds due to flooding during the dry season (Junk et al. 2006). There have also been warnings about increasing climate instability in the Pantanal due to climate change (Marengo et al. 2016b), which may have unknown impacts on the predicted operation of these dams and also on the vulnerability of the biodiversity and traditional communities already affected by the hydroelectric dams.

The hydrological regime might also be affected by the construction of aquatic transport infrastructure. The construction of a waterway on the Paraguay River has been proposed, which would facilitate the large-scale exportation of soybeans to world markets (Schulz et al. 2017), but potentially go along with serious and irreversible socio-ecological impacts on the Pantanal's ecosystems (Hamilton 1999; Junk & Nunes da Cunha 2005) and further incentivise land use changes towards intensive soybean production. The proposed waterway thus represents another example in which elite decision-making in the upper parts of the wider catchment area might affect politically less influential *Pantaneiros* in the low-lying downstream areas. The general population in the Upper Paraguay River Basin is divided regarding the project's desirability, with a majority opposing it on environmental grounds (Schulz et al. 2018).

Finally, legal scholars, environmental social scientists and others have sought to understand the implications and shortcomings of (proposed) laws and regulations for socio-environmental dynamics in the Pantanal, which has been legally recognised as a Natural Heritage in Brazil's Federal Constitution of 1988 (Dias Cunha 2017). One basic issue that affects legal initiatives is imprecise or lacking legal terminology covering wetland areas, as opposed to, for example, forested areas (Junk et al. 2014; Maltchik et al. 2018). This impedes the design of effective laws for environmental protection in the Pantanal, as well as other wetland areas of Brazil. Whereas forests enjoy some (diminishing) legal protection under Brazil's Forest Code, including on private property (Soares-Filho et al. 2014), it is less clear how these laws may apply in the Pantanal, where about 95% of land is held in private ownership (Arts et al. 2018) and ecological classification for the purposes of legislation is not straightforward (Junk et al. 2018a; Maltchik et al. 2018).

But even where regulations explicitly target environmental management in the Pantanal, legal ambiguity may render them ineffective. For example, Mato Grosso's state law no. 038 art. 62 (1995) states that: "no type of deforestation will be permitted in the Pantanal's floodplain, except for subsistence agriculture and cleaning of native and artificial pastures" (cited in Rossetto & Girardi 2012: 142). Given that the term 'cleaning' is not further defined, this article may effectively accelerate the replacement of native vegetation with exotic grass species (Rossetto & Girardi 2012), which in turn may cause ecological problems and make the area more susceptible to fire, and thus, further deforestation (Alho 2005; Leite et al. 2018; Power et al. 2016; but see Bao et al. 2019). Such problems with legal loopholes are magnified, where existing sustainable cattle ranching techniques (Bergier et al. 2019) are not applied.

Mato Grosso's state law no. 8.830/2008 establishes that the management of the Upper Paraguay River Basin should be based on the principles of environmental sustainability, economic and social development, but fails to cover the large areas of the Pantanal located in the state of Mato Grosso do Sul, and does not address socio-environmental issues that originate in the neighbouring uplands (Dias Cunha 2017). A more recent legal proposal is the so-called 'Pantanal Law' (no. 750/2011), introduced to the Federal Senate by former governor of Mato Grosso Blairo Maggi. Yet it has been criticised for being almost identical to the existing law 8.830/2008 and thus offering little concrete guidance for sound environmental management (Dias Cunha 2017). More generally, critics suggest that environmental management laws are often undermined or weakened due to the strong influence of the politically powerful agribusiness sector in their formulation (de Souza & Hugueney Irigaray 2017; Saito & Azevedo 2017). Thus a continuing struggle between advocates of economic development and environmental conservation (see also Schulz et al. 2018) creates an impasse in developing appropriate legal structures.

3.2 Remaining gaps in research on socio-environmental change in the Pantanal

Overall, existing research covers almost all relevant substantial dimensions of socio-environmental change in the Pantanal, such as: agricultural transformation and its socio-economic and cultural implications (Bergier 2013; Calheiros et al. 2012; Ioris 2012; Ribeiro Lacerda 2017; Ribeiro Lacerda & da Costa Lima 2015; Rossetto 2004, 2009; Rossetto & Girardi 2012; Wantzen et al. 2008); conflicts around fishing (Alho & Reis 2017; Chiaravalloti 2017, 2019; da Silva Moraes 2015; Mateus et al. 2004; Rossetto & Tocantins 2015; Téles de Ávila et al. 2018) and tourism (Arts et al. 2018; Girard & de Vargas 2008; Oliveira Rabelo et al. 2017; Tortato & Izzo 2017); traditional and local ecological knowledge (Abreu et al. 2010; Bortolotto et al. 2015; Calheiros et al. 2000; Da Silva et al. 2014; Girard 2012; Ximenes de Melo et al. 2015); invasive species and biodiversity (Calheiros et al. 2012; Junk et al. 2006; Mamede et al. 2017); social implications of water infrastructure development, including dams and waterways (Bergier 2013; Calheiros et al. 2012; Crabb et al. 2017; Hamilton 1999; Junk & Nunes da Cunha 2005; Schulz et al. 2017, 2018); implications of climate change and variability (Araujo et al. 2018; Bergier et al. 2018, 2019; Da Silva et al. 2014; Ioris et al. 2014); laws, regulations and politics of the Pantanal (de Souza & Hugueney Irigaray 2017; Dias Cunha 2017; Duarte dos Santos et al. 2014; Oliveira 2002; Safford 2010, 2012; Sanches Ross 2006). Nevertheless, significant research gaps remain. These are not as much about novel topics of research, but rather about deepening our existing knowledge of processes of socio-environmental change and conflict, as well as about better understanding interlinkages between several factors.

First of all, while there is a relative wealth of individual qualitative case studies investigating social, economic, and cultural dynamics in the Pantanal, there is less research taking a quantitative methodological approach. This is not least due to the absence of basic socio-economic data (Junk & Nunes da Cunha 2005), beyond the census data of the Brazilian Institute of Geography and Statistics (IBGE 2010), which covers only some variables of interest and is collected only every 10 years. As a consequence, much socio-economic research relies on anecdotal evidence or smaller case studies, and it can be difficult to generalise findings, for example on the decline of traditional cattle ranching culture in the Pantanal. Due to the lack of reliable data on social issues within the Pantanal region, other sources of information, such as individual media reports have the potential to influence opinions of the general public and local decision-makers, for example on the issue of prostitution in the Pantanal, as highlighted earlier (Surubi Fernandes & Maluf-Souza 2013). Also, local popular opinion may remain unchallenged by a lack of reliable data, for example, misperceptions around the supposed problem of street children in the Pantanal town of Corumbá, which may obscure other serious issues such as child neglect (Oblak 2012). Both law authorities and criminal gangs perceive the Pantanal as an important location for illicit cross-border trade with illegal drugs, firearms, and protected wildlife, another issue which is (perhaps unsurprisingly) characterised by a lack of reliable data (Duarte dos Santos et al. 2014; Presti et al. 2015).

Quantitative data is also lacking as input into environmental planning as well as various types of socio-economic and socio-environmental modelling methods, which could be combined with ecological or hydrological data in integrated approaches to connect human systems with environmental indicators. Recent research has begun to report on the interrelationships between economic indicators, cattle ranching, and a changing climate (Araujo et al. 2018; Bergier et al. 2019), but socio-environmental issues beyond cattle ranching are still less well understood. There is also a considerable grey literature on environmental planning in the Pantanal, for example, a number of government reports outlining environmental conservation and economic development strategies (Oliveira 2002), of which the Conservation Plan for the Upper Paraguay Basin (PCBAP, in Portuguese), is likely the most relevant one (Brazil 1997). This report identified some of the major environmental management challenges with regards to the Pantanal, such as erosion or pollution of watercourses with sediments, and sought to recommend appropriate economic development strategies. In this sense, the report is considered a precursor to ecological-economic zoning, which has been recommended for data-driven spatial governance of the Pantanal (Sanches Ross 2006). Yet as our review suggests, many of the management challenges identified then continue to exist today, and further efforts to address them are needed.

Related to the issue of lacking quantitative socio-economic data, is the lack of spatially explicit socio-environmental data. Much research treats 'the Pantanal' as one spatial unit of analysis, despite significant ecological, social, economic, cultural, and legal differences between the different regions of the Pantanal. For example, as noted above, some laws may only extend to the Pantanal of Mato Grosso, but not of Mato Grosso do Sul (Dias Cunha 2017) or inhabitants of indigenous settlements may have little in common with *Pantaneiro* cattle ranchers. In comparison, the physical geography literature has put more emphasis on identifying and classifying intra-Pantanal differences. Boin et al. (2019) suggest that physical geography features may allow subdivision of the Pantanal into 6 to 25 sub-regions; Miranda et al. (2018) discuss the landscape complexity of the Pantanal based on vegetation heterogeneity and remote sensing data; and Assine et al. (2015) propose a subdivision of the Pantanal and catchment area into fans and inter-fan systems based on geomorphological characteristics. Yet no equivalent research on complexity and diversity has been conducted from an environmental social science perspective, for example addressing cultural or socio-economic variability between different regions of the Pantanal, even if institutional actors might in principle be aware of them. Thus, it is necessary to recognise that socio-environmental systems within the Pantanal are not homogenous, and more conscious consideration should be given to the selection of an appropriate scale of analysis. Related to the issue of appropriate scales for socio-environmental research, sometimes the administrative division of the Brazilian Pantanal into two federal states may also be unhelpful. For example, researchers from Mato Grosso and Mato Grosso do Sul may compete for research grants, leading to fragmented research, where a more collaborative approach would be more effective.

Many socio-environmental processes may also have geographical links that could extend far beyond the Pantanal floodplain. For example, the proposed waterway on the Paraguay River across the Pantanal is ultimately connected to demand for soybean in China and Europe (Schulz et al. 2017). Few studies have sought to address transboundary management issues, taking into account similarities and differences between the Pantanal of Brazil, Bolivia, and Paraguay (but see e.g. Ioris et al. 2014). Deforestation and human-induced land use change in the Amazon biome may threaten water security in the Pantanal (Bergier et al. 2018). Many other issues are linked at a relatively smaller scale to the neighbouring uplands within Brazil, such as pollution of rivers with pesticides and fertiliser runoff (Campos de Magalhães et al. 2016; Ide et al. 2012; Miranda et al. 2008), sediments from upland erosion (Bergier 2013; Godoy et al. 2002; Ide et al. 2012; Lisbôa Gazolla & Gonçalves 2017) or the impacts of hydropower dams (Bergier 2013; Calheiros et al. 2012; Coelho da Silva et al. 2019), which may all have socio-environmental implications. Thus, research on the Pantanal does not necessarily have to be conducted within its borders.

Another gap concerns better integration of findings from various disciplines, as well as taking a more holistic approach towards socio-environmental research. While cattle ranching in the Pantanal is now relatively well explored from multiple perspectives (Abreu et al. 2010; Araujo et al. 2018; Bergier et al. 2019), other topics still lack such integration. For example, fish decline in the Pantanal is still often interpreted as the simple result of overfishing, despite emerging evidence that it is the result of a complex set of factors, including the hydrological impacts of dams (Alho & Reis 2017; Chiaravalloti 2017). Not least, the amount of fish caught depends on the economic dynamics around recreational and commercial fishing (Catella et al. 2017). Moreover, subsistence fishing is an important part of traditional *Pantaneiro* culture, yet cultural aspects of changing fish numbers are commonly overlooked. An integrated perspective would also consider the complex consequences of a decrease in fish populations, which may have implications for seed dispersal, and this way, vegetation and landscape patterns (Correa et al. 2015).

There is also scope to better understand local perspectives and traditional ecological knowledge for example, regarding fishers' knowledge of fish species, habitats, and seasonal migratory trends, and to integrate this knowledge with more conventional biological and ecological research. An example of such integration of knowledge systems can be found in a case study on local knowledge and perceptions of climate change in relation to scientific climate scenarios (Da Silva et al. 2014). Another example is research on the Pantanal's *dequada* phenomenon, that is, periodic fish kills which occur as the result of reduced oxygen and increased carbon dioxide contents following high levels of organic decomposition processes during flood events, which are well understood by local people living in the Pantanal (Calheiros et al. 2000), as also mentioned in section 2.2. The more general benefits and risks associated with the integration of insights from multiple knowledge systems have been extensively documented in the literature (Berkes et al. 2000; Persson et al. 2018; Puri 2007; Robbins 2003). Such integrated studies may help to 'safeguard' the cultural heritage of traditional and indigenous populations in the face of cultural assimilation into mainstream societies; they may serve as a 'short-cut' for the development of conventional science, especially in newly emerging research fields; they may improve communication and dialogue between scientists and local partners, this way facilitating more effective environmental management and conservation; and they may give insights on underlying worldviews and cultural perspectives associated with specific traditions and cultural practices (Schulz et al. 2019).

Yet, due to the uneven power dynamics between researchers and researched, there is always the risk that traditional or local knowledge will be incorrectly or selectively represented, based on the preferences of conventional scientists. It may also be challenging to identify a precise, if any, boundary between traditional and more conventional scientific knowledge (Löfmarck & Lidskog 2017). In Brazil, there is also strong local concern about biopiracy, i.e. the use of traditional knowledge on the country's genetic heritage for commercial applications without due compensation to traditional knowledge holders, which is regulated by the national Law 13.123/2015 (Costa Eloy et al. 2014; Menuchi et al. 2016). Yet the desire to document and promote traditional knowledge via academic research is equally strong (Campos 2018; Tiriba & Fischer 2015).

Finally, there is a need to better understand political processes and dynamics shaping socio-environmental change in the Pantanal. Some research has explored for example, the interests and lobbying power of the agribusiness sector (Ioris 2012; Safford 2012), political dynamics in local multi-stakeholder watershed institutions (Safford 2010) or the opportunities of various stakeholder groups to participate in the formulation of laws concerning the Pantanal (de Souza & Huguney Irigaray 2017). Yet, there are also many obvious gaps in research on the politics of environmental change and stakeholder analysis. For example, no social science research has explored the motivations of political decision-makers or financial investors enabling the current hydropower boom in the tributaries to the Pantanal, as well as the complex decision-making networks of various actors involved in this more generally. Another example for a research gap concerns the social implications of safeguarding the Pantanal's biodiversity heritage. While there is a general consensus among relevant stakeholders and the general population that better environmental conservation is needed (Ioris 2013), little research has explored how to implement it in practice, and how to avoid negative social impacts on traditional *Pantaneiro* communities (see e.g. Chiaravalloti 2019; Chiaravalloti et al. 2017).

3.3 Environmental management implications and a research agenda for the environmental social sciences

Addressing the above-mentioned research gaps to obtain a better understanding of socio-environmental dynamics of change in the Pantanal is the precondition for numerous follow-up activities, ranging from better environmental planning and management to improved environmental education and subsequent research (see also Bergier et al. 2019; Guerreiro et al. 2019). Generally, to achieve such impact beyond academia, environmental social science research will need to produce information that is relevant and timely, credible and authoritative, and legitimate, that is, developed in a process that considers the perspectives of all relevant actors (Cook et al. 2013).

First of all, environmental planners would benefit from a better understanding of socio-environmental trends in the Pantanal and in neighbouring regions where activities may have direct impacts on the Pantanal's socio-ecological systems. This could be used for more targeted environmental management interventions and design of environmental legislation and regulations. Due to the current lack of basic socio-environmental information, many environmental management policies are based on widespread assumptions and hypotheses, but not scientific evidence, which may have adverse consequences and unintended side effects. An example (noted in section 3.2) which illustrates this problem well are fishing restrictions imposed on subsistence fishers in the Pantanal, which have led to significant hardships, despite lacking evidence that overfishing is indeed the primary cause of fish decline (Chiaravalloti 2017). This is an ongoing problem, as evidenced by the recent introduction of the Law no. 5.321 in Mato Grosso do Sul, which forbids any fishing of the *dourado* (*Salminus brasiliensis*) during the next five years (Andrade 2019). Another example could be the siting of dams, which have complex socio-environmental impacts, yet are often not comprehensively assessed before a decision is taken.

On a more positive note, environmental policy-makers may also use research findings to inform the design of financial incentives such as Payments for Ecosystem Services (PES) programmes, which could compensate land owners for environmentally beneficial behaviour (Schulz et al. 2015). Considering that the territory of the Pantanal is almost entirely in private hands, PES schemes could be designed to reward plantation of native vegetation or low impact cattle ranching. As Schulz et al. (2015) note, PES schemes targeting the Pantanal would also need to be implemented in the neighbouring uplands where many threats originate. For example, farmers could be rewarded for planting buffer strips delimiting their fields to avoid sedimentation of rivers and watercourses, possibly paid for by the hydropower sector, which benefits from lower sediment loads in rivers (Fu et al. 2014). Better socio-environmental research would facilitate the identification of appropriate payment amounts and beneficial management interventions.

Beyond enabling better top-down environmental management, locally grounded environmental social science research could also empower local people living in the Pantanal; there is no need to focus exclusively on financial incentives for environmental management. For example, some researchers have suggested adapting policies to address justice-related concerns via a climate justice capabilities approach (e.g. Ioris et al. 2014), which would involve mapping vulnerabilities to climate change, enhancing social recognition of marginalised groups, improving distributional equity, and strengthening public participation in environmental policy-making. Calheiros et al. (2000), too, call for participatory research methodologies to be implemented for successful ecological research and the sustainable management of natural systems. Findings could potentially be used as input for the work of multi-stakeholder forums (such as river basin committees) as envisioned in the Brazilian water governance system (Safford 2010) or 'dialogical-posing problem approaches', that is, multi-stakeholder processes which serve an emancipatory and educational function while addressing a specific joint management problem (Saito 2013). Such educational activities would benefit from taking an integrative view of environmental management problems and enhance scientific literacy, which we suggest is needed not only in socio-environmental research on the Pantanal, but also in engagement between scientists, stakeholder groups, and wider society. Political analyses, for example, within a political ecology framework, may also help to understand locally viable management alternatives as opposed to centrally prescribed institutions and processes, and this way, reduce conflicts around water and other natural resources (Rodríguez-Labajos & Martínez-Alier 2015). They may also give insights on the barriers for improved environmental management, where it emerges that improved knowledge integration and exchange is insufficient to address socio-environmental problems on the ground. From a legal perspective, it would be desirable to investigate the interactions, synergies, and conflicts between the entirety of laws, projects, and programmes that affect the Pantanal. This could be based on network or matrix analysis and could lead to a more coordinated and effective management system.

4 Integrating physical, ecological and socio-environmental research on the Pantanal: recommendations

In this article, we sought to present the state of the art of research on physical, ecological, and human dimensions of environmental change in the Pantanal wetland, identify relevant research gaps, and explain their implications for improving environmental management. Nevertheless, it is also important to take a broader and more systemic perspective towards the multiple processes that shape environmental change in the Pantanal, and here we suggest a number of pathways for future integrative research.

First of all, we suggest that a better integration of scientific and local ecological knowledge constitutes a promising way forward for research on environmental change in the Pantanal. At present, there are mostly parallel strands of research on climatic, ecological, and hydrological change from natural sciences and social sciences perspectives (with a few notable exceptions, see

Calheiros et al. 2000; Da Silva et al. 2014; Guerreiro et al. 2019). Yet, traditional or local ecological knowledge may often be a valuable source of information that could guide scientific research, and in this way, enhance its quality and efficiency (Medeiros Prado et al. 2013; Melo & Saito 2013; Silvano & Valbo-Jørgensen 2008), for example via cross-validation or ground-truthing. In the Pantanal, subsistence fishers are one example of a group that holds extensive knowledge on local biodiversity, hydrology, and ecological processes (Chiaravalloti 2017), but whose knowledge is only just beginning to be appreciated by conventional scientists. NGOs working within the Pantanal have started to address this issue: Ecologia e Ação (ECOA) are one example of an NGO, which has been working to align local ecological knowledge and biodiversity conservation (da Silva 2012). Another example is the Jatobazinho School, run by the Acaia Pantanal Institute, which gives children in remote areas of the Pantanal access to education, and also aims to raise environmental awareness (Porfirio et al. 2014). However, it is also important to recognise the limitations and risks of relying on local NGOs only to deliver such synergies. Not all projects are successful; and a weak civil society combined with a lack of public accountability may mean that some local NGOs are captured by local elites, thus furthering elite interests primarily (Crabb 2016). A more holistic approach to conservation, involving multiple stakeholders, may therefore help to ensure more sustainable outcomes.

Local ecological knowledge holders may also support research by collecting data, for example on species abundance and diversity, which helps scientists but also creates a shared sense of ownership and can be the basis for positive social change (Van Rijsoort & Zhang 2005). Not least, partnering with local *Pantaneiros* to conduct scientific research would also establish a dialogue between scientists and people living in the area, which could inform socially appropriate environmental management interventions. These might also be based on existing, relatively sustainable land use practices, such as rotational grazing of native pastures (Eaton et al. 2011) or clearing of invasive woody plants, which enables a greater diversity of habitats and ecosystems in the Pantanal (Junk & Nunes da Cunha 2012). These practices have existed in the Pantanal over centuries and continue to exist, even if significant socio-environmental change is currently taking place.

Second, we recommend a better consideration of temporal scale in integrative research on environmental change in the Pantanal, especially longer-term time frames covering periods beyond 10 years in the past. As the world is beginning to experience profound anthropogenic environmental change, it would be highly desirable to understand how the Pantanal's ecosystems have responded to human pressures and climate change in the past, which may offer rare positive insights on the adaptation capacity of natural systems and the degree to which past management practices have shaped the modern environment. The insights of palaeoecology would also be useful for ecologists, and dialogue between palaeoecology and ecology is still surprisingly rare (Mercuri & Florenzano 2019), although recent investigations elsewhere in South America have demonstrated the value of historical perspectives in understanding the legacies of changing land use on ecosystem structure and function, and implications for what might be termed 'natural' (e.g., Loughlin et al. 2018; Rull et al. 2015). Yet, even making use of local ecological knowledge or consulting people's memories about environmental change since the times of their parents or grandparents would already significantly extend the time frames typically used for ecological research. For example, older *Pantaneiros* may remember how a severe drought in the 1960s affected landscapes and ecosystems. A better understanding of the distant past (i.e. thousands of years) and the more recent past (i.e. the last 100 years) would not only be an interesting question for basic research. Such research may also help make predictions for the future, which can then inform environmental policy-making and management. For example, Lenders et al. (2016) have shown how the historical collapse of salmon stocks in Europe during the Middle Ages coincides with the expansion of watermill technology, with direct management implications for the ecological restoration of rivers and streams today.

The Pantanal would be a highly suitable geographical area for similar interdisciplinary research on the past, given its history of strong climatic and environmental variability. The absence of written sources prior to the arrival of European settlers would present a challenge, however, giving more importance to safeguarding orally held traditional knowledge. Beyond using such knowledge for future projections, it would also be interesting to understand how traditional sustainable land management practices have been adapted to changing climates and environments in the past. Present environmental conditions may no longer match the original conditions in which these practices were developed, yet they continue to be applied successfully, as the example of traditional fire management strategies of the Xavante Indians of Northern Mato Grosso demonstrates (Melo & Saito 2013). Such positive examples of successful adaptation to a changing environment are sorely needed in the face of current and future anthropogenic climate change. It would also be desirable to combine such analysis of specific time frames with corresponding spatial analysis, leading to more systematic integrated spatial-temporal research.

Third, it is necessary to achieve better stakeholder participation in research. At present, research agendas are mostly shaped by researchers themselves and/or their funders, but this rarely takes into account the needs and priorities of local people living in the Pantanal, which may differ significantly (de Souza & Hugueney Irigaray 2017). It would especially be necessary to consider the needs of poor and marginalised local people in the Pantanal, given the power dynamics that have been identified in previous political ecology research on the Pantanal (Arts et al. 2018; Ioris 2013; Saito & Azevedo 2017; Schulz et al. 2017). That is, powerful economic and political elites from the neighbouring uplands directly or indirectly control traditional *Pantaneiros*, for example through the imposition of national parks, fishing bans, or replacement of their economic system with modernised agriculture (Chiaravalloti et al. 2017; Wantzen et al. 2008). This can be particularly important in assessing contemporary impacts such as hydroelectric dams (Crabb et al. 2017), because they may cause landscape fragmentation, disruption of the natural flood pulse and isolation of populations, besides the social impacts associated with the loss of traditional lands, displacement and livelihood impacts of a changing environment. The need for better stakeholder participation in research has also been recognised in the global sustainability literature. Proponents view such participation as a means to ensure that research is well grounded in real-world issues and of practical relevance, to produce higher quality research through an integrated perspective, and to implement conceptual advancements in the context of social-ecological systems thinking (e.g. Kliskey et al. 2017; Olsson et al. 2004). Nevertheless, practical challenges also need to be overcome, for example the translation of local knowledge into scientific knowledge and vice versa (Persson et al. 2018) or time and budget constraints (Kliskey et al. 2017; Tress et al. 2007).

Beyond improving livelihoods, more participatory research is also important from a process perspective, that is, it challenges the extractive dynamics and relationship between researcher and research participant that is a feature of much conventional socio-environmental research, and may instead lead to mutual respect and more appreciation of the value of research (Wentz Diver & Higgins 2014). Better stakeholder participation in research may also strengthen advocacy processes. For example, many ecologists and others are motivated by their desire to contribute to environmental conservation of the Pantanal (see e.g. Junk & Nunes da Cunha 2005), but this will not be achieved in isolation, and it would be necessary to form strong alliances with non-academic actors. Finally, formal pathways for such stakeholder engagement processes are emerging in Mato Grosso and Mato Grosso do Sul, that is, via river basin committees. These committees are supposed to facilitate stakeholder dialogue, particularly between water users, government, and civil society (Safford 2010; Schulz & Ioris 2017), and could be used to distribute findings of integrative research.

Fourth, mainstreaming environmental education as scientific literacy and the development of an integrated cross-disciplinary view is fundamental. Currently, this challenge is focused on school education to transmit basic understandings of climate science, hydrology, ecology, soil sciences, and others (Felipin et al. 2013; Lopes Nogueira et al. 2015). Here, however, we are proposing to expand this perspective and defend the idea that a lack of a holistic vision of interdependencies is present among scientists, research agendas, and policy-makers. Ultimately, such a process needs to start with adopting an integrated perspective within scientific knowledge production, and it would also be highly desirable to link scientific knowledge with traditional and local ecological knowledge of sustainable land management practices in environmental education to connect specific problems (socio-environmental conflict) with ongoing solutions (positive local actions) (Saito 2013). This would help society to value and gain respect for local knowledge generated in the Pantanal, and this way, create a better sense of community. It would also be necessary to target not just the area of the Pantanal itself, but those areas where major threats to its ecological integrity originate (see e.g. Bergier 2013; Bergier et al. 2018; Ide et al. 2012). To enable such integration of scientific and local ecological knowledge in environmental education, more detailed research is also necessary to identify further synergies between the two (Da Silva et al. 2014).

Beyond focusing on school education and curriculum development only, the systemic rationality of multiple stakeholders could be increased by taking an integrated perspective, especially those interacting with its environment on a daily basis, such as farmers, cattle ranchers, fishers, and those working in the tourism sector (de Souza & Montagnini Logarezzi 2018; Mamede et al. 2017). Conceptual models (see e.g. Bergier 2013), especially those developed for educational activities such as concept maps, can be valuable tools for this purpose (Saito 2017). If such activities are implemented, an opportunity for incremental improvements may exist, including increased environmental awareness, scientific literacy and engagement in participatory processes. This in turn would empower *Pantaneiros* to develop skills and knowledge to face the challenges associated with environmental change and to lobby for environmental justice with decision-makers. Nevertheless, such conceptual modelling activities can not only increase stakeholder knowledge about Pantanal ecosystem dynamics, but the models themselves can be improved by local knowledge, as evidenced by the example of Calheiros et al. (2000), discussed above. Finally, by taking a systemic view towards education (Gattie et al. 2007), we can integrate physical, ecological, and human dimensions of environmental change in the Pantanal to explain the complex interdependencies between the many drivers of change that were discussed in the present article.

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Conflict of interests

The authors declare that they have no conflict of interests.

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