Natural and anthropogenic influences on the Nhecolândia wetlands, SE Pantanal, Brazil

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Abstract: The Nhecolândia region covers the southern wetlands of the Pantanal basin in Brazil. Characterized by myriad shallow freshwater and alkaline–saline lakes, the distinct natural features of the Nhecolândia wetland make it highly sensitive to climate change and the effects of human activities. This paper summarizes the natural and social aspects that have affected this delicate wetland and potential future impacts. We analysed the response of the wetland to historical changes in climate and human activity and used this understanding to forecast the response of the wetland to future changes. The data presented here show that this region is particularly sensitive to alterations in the flood regime, droughts and deforestation, which are intrinsically related to both global and local changes in climate and the intensification of cattle-ranching activities, which include deforestation and the introduction of cultivated pastures.

The Pantanal basin, located in central-west Brazil, is one of the world’s largest wetlands, covering >140 000 km². As a result of the low relief of the entire basin (from 80 to 200 m in elevation) and a complex hydrological network of rivers and lakes, large tracts of the basin are susceptible to seasonal floods that can last from 4 to 8 months in some areas (Assine 2015; Marengo et al. 2016b). The Pantanal basin acts as a wetland mosaic and is characterized by different climatic, hydrological and topographic gradients (Fig. 1; McGlue et al. 2017). During the dry season, from April to September, water is retained in perennial rivers and lakes, while extensive and continuous grasslands are exposed in between the islands of vegetation, where cerrado savannah-type forest predominates. As a result of its geomorphology and hydrology, the Pantanal basin acts as a natural reservoir for water, filling up during the rainy season and slowly draining during the dry season, helping to maintain the water balance of the south Paraguay and Paraná river basins (Paz et al. 2014; Marengo et al. 2016b).

The Nhecolândia region encompasses the southern wetlands of the Pantanal basin (Fig. 1). This region is located to the south of the Taquari megafan, where myriad shallow lakes have developed in an inactive lobe of the fan, with at least two distinct chemical compositions: freshwater and alkaline–saline (McGlue et al. 2017; Guerreiro et al. 2018). This leads to a unique environment, with cerrado forests, native pastures and herbaceous vegetation around the lakes (Bergier et al. 2016). The high rate of evapotranspiration, which exceeds the annual rainfall (Marengo et al. 2016b), contributes to an extended dry season that drastically reduces the number of filled lakes in the area and increases the salinity of the alkaline–saline lakes (McGlue et al. 2017). The presence of freshwater in the lakes of Nhecolândia, and the wider flood dynamics of the region, have a direct impact on the local economy. Not only do they determine the availability of freshwater for both humans and animals, but in so doing they define the biodiversity of the area and the land use,
affecting the distribution of areas suitable for cattle ranching (Batista et al. 2012).

The sensitivity of the region means that anthropogenic climate and land use changes could have a significant impact in the Nhecolândia region. Projections of changes in the occurrence of extreme floods and droughts may alter the ecological dynamics of the region. Human activities, predominantly cattle ranching, may also affect the natural environment, modifying the ecosystems both directly and indirectly. Bergier (2013) and Marengo et al. (2016a, b) concluded that natural or anthropogenic modification of the hydraulic conditions may threaten the ecological balance of the Pantanal basin.

This paper reviews current knowledge of the sensitive Nhecolândia region. The objectives of our study were: (1) to review the natural and social characteristics of the region; (2) to identify its potential sensitivity pinch-points; and (3) to assess future scenarios for the evolution of the Nhecolândia wetlands.
Nhecolândia wetland environment

Climate and hydrology

Palaeoclimate of the Nhecolândia wetlands. The sedimentary record of the Taquari megafan indicates that the Nhecolândia depositional system has been controlled by alternating humid and dry periods since the Late Pleistocene (Clapperton 1993; Bertaux et al. 2002; Assine & Soares 2004; Whitney et al. 2011; McGlue et al. 2017). Distinct cold and dry periods between 45 and 19.5 kyr BP have been described by Whitney et al. (2011), with periods that were arid relative to the present day climate remaining until 12.8 kyr BP and occurring again between 10 and 3 kyr BP. The strongest modification of the landscape, with exposure and reworking of the sediments under arid conditions, occurred during these dry periods and was related the associated changes in the amount of rainfall (McGlue et al. 2015, 2017).

The climate during the Early Holocene was predominantly dry compared with the present day climate (Whitney et al. 2011; McGlue et al. 2012, 2017) and included an episode of intense drought (c. 5.3–2.6 kyr BP) interpreted from a hiatus in sedimentation that affected the region (McGlue et al. 2012). A later transgression coincided with increased flooding followed by a more humid climate. The development of the Nhecolândia lakes is related to an abandoned lobe of the Taquari megafan, with the sediments reworked and the morphology reshaped by increased winds during more arid periods, leading to an aeolian and evaporative environment with increasing salinity in the hydrological isolated lakes since c. 910 years BP (Guerreiro et al. 2018; McGlue et al. 2017).

Present day climate and hydrology of Nhecolândia.

The geographical position of the Pantanal basin – in the centre of the South American continent and south of the Amazonas basin – means that its climate is modulated by two phenomena: the Intertropical Convergence Zone and the South Atlantic Convergence Zone (Lenters & Cook 1999; Marengo et al. 2001, 2016a). The South American monsoon system is modulated by both the Intertropical Convergence Zone and the South Atlantic Convergence Zone and therefore delivers concentrated rains from October to March (100–300 mm per month) with a dry period (0–100 mm per month) during the rest of the year (Garcia 1984; Vera et al. 2006; Marengo et al. 2016a).

Despite the position of the Pantanal basin within the tropical latitudes, its climate is more semi-arid than tropical (Marengo et al. 2016b). With a mean air temperature of 24°C and an annual rainfall of 1100 mm, the Pantanal basin has an annual evapotranspiration rate of 1400 mm (Furian et al. 2013; Marengo et al. 2016b; McGlue et al. 2017) and an interannual variability that may cause either intense dryness or intense flooding (Marengo et al. 2016a). The annual monsoonal rainfall patterns are affected by large-scale climate phenomena, such as the El Niño–Southern Oscillation and the variability of the Atlantic Ocean. Regional-scale phenomena (e.g. the regional water balance, soil wetness and soil moisture storage capacity) also influence the climate of the Pantanal basin (Bergier 2013; Marengo et al. 2016b; Bergier et al. 2018).

The Pantanal basin undergoes a wide range of temperatures throughout the year, with daily contrasts between 1 and 40°C common in winter (June–August). This is partly due to the geomorphological interference of the Andes (to the west) and the Brazilian Central Plateau (to the east), with atmospheric weather patterns creating an air corridor capable of driving the southern polar air masses from northern Argentina directly to the Pantanal basin (Marengo et al. 2016a) in a phenomenon called friagem.

The drainage system of the Pantanal basin has c. 500 000 km² of channels, with the main arteries being the Paraguay, Cuiabá, Piquiri, Taquari, Miranda and Negro rivers. The relief of the basin is very low, which makes it susceptible to a seasonal flooding pulse (Hamilton et al. 2002; Paz et al. 2014). This flooding pulse is influenced by the Amazonian rainfall regime in the northern Pantanal rivers, which propagates from north to south and only reaches the southern regions of the Pantanal basin during the dry season (Por 1995; Hamilton et al. 2002; Fantin-Cruz et al. 2011; Paz et al. 2014; Bergier et al. 2018).

The patterns of rainfall in the Nhecolândia region show a non-uniform distribution, with a clear east–west gradient (92 mm per month in the east and 74 mm per month in the west). The rainfall and the flood peak are disconnected in the Paraguay river, west of Nhecolândia, with the seasonal rainfall occurring c. 4 months before the floods (Fig. 2; Por 1995; Hamilton et al. 2002; Fantin-Cruz et al. 2011) and with a notable influence of the Amazon rainforest on the distribution of moisture (Bergier et al. 2018). There is therefore a complex relationship on different scales between the hydrology of this region and the climatic patterns that drive it.

Geological context

The Pantanal basin is located in west-central Brazil (with some portions of the region extending into Bolivia and Paraguay) and has a surface area of c. 140 000 km² (Fig. 1; Almeida 1945; Almeida & Lima 1959; Assine 2015; Assine et al. 2015). The basin is elongated north–south, with its borders controlled by normal faults and a maximum sedimentary
thickness of 500 m (Weyler 1962; Assine 2015; Assine et al. 2015). The basement consists of low-grade Neoproterozoic metamorphic rocks of the Paraguay Belt (Alvarenga et al. 2009; Assine et al. 2015).

The origin of the Pantanal basin is related to the tectonic reactivation of the forebulge of the Andean Orogeny during the Gelasian stage (c. 2.5 Ma ago, during the Early Pleistocene) as part of the Andean foreland system (Horton & DeCelles 1997; Ussami et al. 1999; Assine et al. 2016). However, the origins of the structural settings of the basin are related to regional epeirogenic uplift occurring during the Early Pleistocene, when the major basin faults were generated and when the basin depocentre started to subside (Almeida et al. 2000; Assine 2015; Assine et al. 2015, 2016).

The infilling of the basin is characterized mainly by siliciclastic sediments (Weyler 1962; Assine et al. 2016). The main sequences show fining-upwards trends, from conglomerates and coarse-grained sandstones at the base to fine and medium sands, locally coarse-grained, in the upper layers. The mineral composition is mainly quartz, with some fragments of metamorphic basement rocks related to the coarse portions (Weyler 1962; Assine 2015; Assine et al. 2015). As a result of subsidence related to normal faults, alluvial sedimentary systems occur on the eastern border of the basin, grading to the alluvial fans occupying the major part of the basin and to fluvio-lacustrine systems related to the Paraguay river (Assine et al. 2015). The alluvial fans are the most representative sedimentary systems and include the São Lourenço, Aquidauana and Taquari megafans (Zani et al. 2012; Assine et al. 2015).

**Geomorphology**

**Taquari megafan.** The Nhecolândia region forms the southernmost part of the Taquari megafan (Fig. 1), which has been depositing sediments in the Pantanal tectonic depression since the Early Pleistocene (Horton & DeCelles 1997; Ussami et al. 1999; Assine & Soares 2004; Assine 2015; Assine et al. 2015). The 49 000 km² of alluvial fan deposits extend for c. 250 km from the apex (190 m a.s.l.) to toe (85 m a.s.l.) with a circular geometry, suggesting a multi-lobed evolutionary history (Andrades Filho et al. 2016; Assine & Soares 2004; Zani et al. 2012; Assine 2015; Assine et al. 2015). A large number of meandering, single-channel rivers characterized by low gradient slopes extend across the fan surface. The high levels of fluvial activity across the fan, including frequent channel avulsions (Assine 2005, 2015; Buehler et al. 2011; Assine et al. 2015), mean that relict palaeochannels are common. These channels are activated during the flood season and convey water and sediment across the fan, resulting in a highly connected landscape that is less reliant on active channel systems to distribute sediment, nutrients and water.

The Taquari megafan may be delineated into two distinct geomorphological zones (Hamilton et al. 1998; Assine & Soares 2004; Buehler et al. 2011; Assine et al. 2015). The upper fan shows a confined...
meander belt incised into abandoned depositional lobes, whereas the river is straighter in the lower fan and is an active depositional environment (Fig. 3). The currently active depositional region is highly dynamic, with both partial crevasse splays and complete avulsions (Slingerland & Smith 2004; Buehler et al. 2011) occurring across the lobe. Assine (2005) and Buehler et al. (2011) describe a complete avulsion that occurred between 1988 and 1999 at the fan toe, with the resulting distributary channel conveying 70% of the discharge between 1995 and 1997 (Padovani et al. 2001). Recent sedimentation in the upper reaches of the depositional fan lobe has resulted in increasing overbank flow and the development of multiple crevasse splay deposits along the main channel on the northermmost side of the fan. Assine (2005) speculates that this rapid sedimentation may result in a major avulsion, potentially initiating a new depositional lobe.

**Geomorphology of the Nhecolândia region.** The Nhecolândia region covers the southernmost 25 000 km² of the Taquari megafan (Marengo et al. 2016b). The coexistence of thousands of freshwater (baías) and alkaline–saline (salinas) lakes is unique to the Nhecolândia region (Fig. 4; Almeida et al. 2007; Furquim et al. 2008; Evans & Costa 2009).

**Fig. 3.** Landsat 7 image of the Taquari megafan (acquired April 2000) showing historical and active lobes of the alluvial fan (numbered 1–7 and outlined by white dashed lines, modified from Makaske et al. 2012). The currently active depositional lobe is outlined by solid white lines. The location of the incised meander belt is highlighted, as is the Nhecolândia region. Scale bar in km.
The baías may be up to 2 m deep and are found at various areal extents. During the flood season, the baías may coalesce and form temporary flood channels or vazantes, which recede back to isolated ponds during the dry season. There is therefore much connectivity between the baías. The salinas, by contrast, are generally 500–1000 m in diameter, 2–3 m deep (Barbiéro et al. 2008; Furian et al. 2013; McGlue et al. 2017; Guerreiro et al. 2018) and often raised above the surrounding ground level. They are often enclosed by sand embankments or cordilheiras, which are covered by dense savannah vegetation and therefore remain isolated from the flood waters. This maintains distinct geochemical signatures between different salinas. Costa & Telmer (2006, 2007) also distinguish an intermediate type of lake, doces, which they define as lakes in transition from the freshwater baías to the more brackish salinas.

The origins of these different types of lake are not overtly clear. Early hypotheses suggested an aeolian explanation, with the lakes forming in troughs and hollows produced by aeolian deflation (Tricart 1982). Klammer (1982) identified a series of longitudinal fossil dunes aligned in the NNE and NNW directions and concluded that the salinas formed as salt pans due to ponding in the interdune areas. Assine & Soares (2004) associated the sand ridges, or cordilheiras, with relict aeolian lunette sand dunes, although they found no evidence of the longitudinal dunes interpreted by Klammer (1982). Barbiéro et al. (2002) suggested that the salinas are, in fact, more recent products of the Pantanal ecosystem, forming over decades rather than centuries or millennia, highlighting their importance in the modern ecosystems of the Pantanal basin and their response to human and climatic pressures (Costa & Telmer 2006). The relatively inactive nature of this part of the Taquari megafan means that large-scale
geomorphic reworking of the sediments as a result of channel avulsion provides the lakes of the Nhecolândia region with the large timescales needed to form and maintain distinct geochemical signatures in the isolated salinas (Becker et al. 2018; Guerreiro et al. 2018; McGlue et al. 2017). This may help to explain why these landforms are not found on the more active northern and western areas of the Taquari megafan.

Soils and hydrochemistry of lakes

Many researchers have studied the chemical variability in the lakes of the Nhecolândia region and the related soils forming within and around these lakes (Barbiéro et al. 2002, 2008; Soares et al. 2003; Furquim et al. 2008, 2010; Almeida et al. 2009, 2011; Barros Nogueira et al. 2011; McGlue et al. 2012, 2017; Rezende Filho et al. 2012; Furian et al. 2013; Bergier et al. 2016). The coexistence of alkaline–saline and freshwater lakes is attributed by Barbiéro et al. (2008) to a differential hydrological regime, whereby water is lost from the saline lakes by evaporation and an inflow from the freshwater system is directed towards the depressions of the non-saline lakes, refilling them (Fig. 4). It is commonly agreed that a large part of the chemical variability of the Nhecolândia lakes is a direct product of the evaporation processes (Furquim et al. 2008; Rezende Filho et al. 2012; McGlue et al. 2012, 2017), which, in turn, lead to the precipitation of authigenic mineral phases (Furquim et al. 2010).

Rezende Filho et al. (2012) questioned evaporation as the main factor in the salinization of the ponds given the current climatic conditions in the area. In fact, McGlue et al. (2012) described a drought stage in the Holocene (5.3–2.6 kyr BP), followed by a sudden increase in flooding pulses, which was related to a more humid period in the Holocene. Therefore it seems contradictory to propose evaporation as the main reason for the presence of salinas in the Pantanal basin (McGlue et al. 2017) because the rates of evaporation were probably lower during this formative period.

As a potential explanation, Furian et al. (2013) suggested that, under poor drainage conditions, the salinity can be maintained naturally in the landscape despite the relatively humid mean climatic conditions, meaning that a past arid climate would not be necessary to produce the presently saline lakes in the Nhecolândia area. They propose that the ponds are filled by groundwater during the dry season and that outflow is prevented by chemically cemented soils (Fig. 4). The results obtained by Guerreiro et al. (2018) fully support the idea of the alkaline–saline lakes not being a relict of past aridity events. McGlue et al. (2012, 2017) also supported the explanation of Furian et al. (2013), adding the presence of cordilheiras as an important geomorphological feature acting as a barrier to the floods and contributing to the evaporation and high salinity of the water in the salinas.

Biodiversity

The biodiversity of Pantanal wetland secures its importance as one of the largest freshwater ecosystems in the world. As a result of the highly variable water regime determined by the contrasts between the wet and dry seasons, two very different styles of vegetation coexist (Alho 2008): mesic (related to a moderate amount of humidity) and xeric (needing a small amount of humidity to survive).

The flora of the Pantanal region has been studied in detail (Pott & Pott 1996, 2009; Pott et al. 2011a, b; Scrimin-Dias et al. 2011) and is characterized by its mosaic-like heterogeneity (Adámoli 1982), including inundated floating plants, seasonal flooding fields, gallery forests, scrub and semi-deciduous forests, and different kinds of cerrado savannah (Alho 2005; Alho & Sabino 2011). Ratter et al. (1988) carried out detailed studies of the forest vegetation in the Nhecolândia region and suggest that the vegetation in Nhecolândia is similar to the deciduous and semi-deciduous forests of central Brazil.

There are two main biomes in the Pantanal wetland (Alho et al. 2000; Alho 2005; Sabino & Prado 2006): the Cerrado biome and the Pantanal biome. The Cerrado biome is a savannah-type forest, including open savannah (grasslands) with sparse trees and closed woodlands with little grass. The Pantanal biome, restricted to the west of the region, corresponds to the floodplain areas with mainly wetland-type (Chaco and Amazonian) vegetation, including aquatic macrophytes among other plants. Although there are various degrees of cerrado in the Brazilian Pantanal cover, it comprises between 40 and 50% of the total vegetation in the Nhecolândia region.

The feeding and breeding conditions of wildlife are directly linked to the hydrological cycle, which may be divided into four stages (Alho 2008; Alho & Sabino 2011): flooding; flood season; drainage season; and dry season. The availability of water not only affects the vegetation, but also the niches and nutrient cycles of the animals that live in the Pantanal region. Many endangered species can be found here, such as jaguar and marsh deer (Alho et al. 2003). About 113 reptile species live in the Pantanal biome and 189 in the Cerrado biome. Amphibians have a low diversity, but high abundance, in this area, with 80 species occurring in the upper Paraguay Basin (Alho 2008). A total of 463 bird species has been recorded for the floodplains alone, increasing to 665 species when the uplands are included and 837 species when including the Cerrado biome (Silva & Abdon 1998; Alho et al. 2000; Alho
2008; Tubelis & Tomás 2002; Alho 2005; Sabino & Prado 2006). Mammals are also diverse, with up to 195 identified species (Alho et al. 2003; Alho & Sabino 2011; Agência Nacional de Águas 2004; Alho & Gonçalves 2005). Alho (2008) estimated that there are 400 fish species living in the Pantanal region (including the plateaus and plains). However, although there are many studies of the biodiversity of the Pantanal region as a whole, only a few have shown the close links between the annual floods and wildlife and few focus specifically on the Nhecolândia region (e.g. Mamede & Alho 2006). Taking into account the fact that floods directly influence the habitats of the Pantanal fauna and flora, it is important to fully understand the evolution of the wetland to be able to predict the changes that may affect its rich biodiversity in the future.

**Anthropogenic influences on the Nhecolândia wetlands**

**Prehistorical occupation**

Human occupation in the Pantanal region started at c. 27 kyr BP with a settlement located 100 km north of the basin (Oliveira 1994; Schmitz et al. 2009; Vialou et al. 2017). Archæological evidence suggests that the occupation of the rest of the basin began c. 8 kyr ago in locations close to the Paraguay river (Schmitz et al. 2009) and, later, in the western area of Nhecolândia, in a coincident period of a shift towards wetter conditions in the basin (McGlue et al. 2012). Some ceramic sites related to natural carbonate mounds (4.4 kyr BP; Oliveira 1994; Schmitz et al. 2001; Oliveira 2017) have been identified in a region called Pantanal do Miranda (Fig. 1).

Although there is no known archaeological site in the centre of the Nhecolândia region, the west and SW borders are full of archaeological sites, especially related to the Pantanal do Miranda mounds and geomorphological features resulting from the differential erosion of carbonate palaeolakes and their surroundings (Oliveira et al. 2017). These mounds represent elevation high points on the Pantanal plain and are constantly exposed during flooding, forming vegetation islands rich in ceramic fragments of the Pantanal tradition (Oliveira 1994; Schmitz et al. 2001, 2009). The people who occupied these mounds had a close relationship with the surrounding floodplain environment, with small settlements and a fish-based diet (Schmitz et al. 2001).

The carbonate mounds of Pantanal do Miranda are a more stable and elevated terrain, with denser vegetation, and are closer to the river than the sand elevations (cordilheiras) of Nhecolândia, making them a more suitable place for ancient humans to live (Oliveira 1994; Schmitz et al. 2001, 2009). This is probably the main reason for the differential preservation of human remains in these settings.

**Modern occupation**

Despite the presence of some native ancient human groups in the Pantanal region, some native modern groups from the Amazon migrated to the region prior to the arrival of Europeans (Oliveira 1996) in the fifteenth century. The discovery of the New World marked a step change in the occupation of the Pantanal region. European occupation was fast, with the north part of the Pantanal basin being first occupied by the Europeans in the 1520s when the rush for silver mining, found earlier in the nearby Andean region, spread to the Pantanal (Oliveira 1996). However, because the geological characteristics of the Pantanal region and its surroundings do not favour the development of abundant precious metals, with only a few occurrences of gold being discovered in the 1800s (Oliveira 1996), this occupational period was short lived.

The region became permanently occupied in the early 1900s, with an extensive cattle-ranching industry expanding to fill the demand for dry beef. The population in the region increased more consistently after the Brazilian government colonization programmes between 1960 and 1980 (Coutininho 2005; Abreu et al. 2010). Changes in land use were extensive during this period and cattle ranching became the main economic activity in Nhecolândia. The current estimated population of Nhecolândia region is c. 3000 people (Abreu et al. 2010). Therefore, habitation of this region is relatively new and is conditioned to the hydrological and climatological characteristics of the past century. In-built societal resilience to long-term variations in the hydrology and climate may therefore be lacking, meaning that the communities in this region are likely to be highly sensitive to potential future changes.

**Cattle ranching in the Nhecolândia wetlands**

The main characteristic of the cattle-ranching industry in the Nhecolândia region is the cattle graze system (transhumance), with the farmer driving livestock through different farmlands during the year to avoid seasonal floods and reduce stress on the grazing lands in the dry season (Rosa et al. 2007). The production is focused on calf-rearing, independent of the environmental conditions, and the total number of animals is around 1 million (Batista et al. 2012).

The cattle production in this region occurs in extensive farms due to the need for native pastures, with about eight pastures per farm (Rosa et al. 2007). The land should include variations in relief, covering lowlands, such as baias and
vazantes, and highlands, such as cordilheiras. The pastures are essentially native, but due to production limits, some cultivated pastures are being introduced, especially in the flood-free areas (Pott 1982). This involves the removal of native vegetation and the introduction of some invasive and non-native species, which is having a dramatic impact on the local ecosystem. Sometimes it is necessary to synchronize the movement of cattle with other farms, such as in the case of intense floods or drought, in an integrated management system that involves the farmers (Rosa et al. 2007; Abreu et al. 2010). Transhumance, a practice inherited from the last century, may not be resilient to future changes. It is a crucial component of economic activity in the Nhecolândia region and depends mainly on the availability of pastures for the cattle to feed on. Thus hydrological changes in the flood regime and in the amount of land affected by floods are expected to have a direct impact on this activity, potentially reducing the primary food source for the animals and forcing changes in the current transhumance patterns.

**Impacts of human activity**

There is no record of prehistorical alterations in the landscape due to the hunter–gather character of all the groups of native people who lived in or close to the Nhecolândia wetlands (Schmitz et al. 2001; Bespalez 2015). The absence of economically valuable natural resources, such as minerals, prevented human impacts on the area until the beginning of cattle ranching (Oliveira 1996). The main modification of the landscape is the removal of native vegetation and/or the native pastures and their substitution by cultivated species (Harris et al. 2005). Between 2003 and 2010, 12% of the forested area was replaced by cultivated pastures (Paranhos Filho et al. 2014). The deforestation of the region has led to desertification due to the changes in the local water cycle (i.e. humidity loss), especially around the saline lakes, where specialized vegetation has evolved (Sakamoto et al. 2012). The constant growth of cattle ranching in recent years has also lead to increasing stress in the native vegetation due to the use of pesticides and herbicides and the burning of weeds in some areas (Harris et al. 2005). The influence of some anthropogenic modifications, such as unsustainable agriculture in the river headwaters, can be observed in distinct areas, inducing variations in the water volume and affecting the sediments and nutrients carried by the rivers from the highlands of Pantanal to the lowlands, such as the Nhecolândia wetlands (Bergier 2013). Although these impacts may be recent, they are likely to be major drivers of changes in the environment and ecosystems in this important wetland region in the near future.

**Future perspectives**

**Sensitivity of the Nhecolândia wetlands to environmental change**

The sensitivity of the Nhecolândia region to environmental modifications is considered to be high because it is now often classified as a semi-arid region (Marengo et al. 2016b), where the annual rainfall is lower than the annual rate of evapotranspiration. These factors, combined with the concentration of rain (October–April), can leave the region without rainfall for 5–7 months of the year (Marengo et al. 2016b).

The waters that characterize the Nhecolândia as a wetland are related to the water regimes of the Negro and Paraguay rivers, both of which have distinct flooding cycles. The Negro river is directly related to the regional rainfall and the water table regime, acting as a tributary of the Paraguay river. The Paraguay river has its origin in the Amazon basin and it is strongly affected by the regional climate of the Amazon (Por 1995; Hamilton et al. 2002; Fantin-Cruz et al. 2011; Bergier et al. 2018), which, by extension, affects the Nhecolândia region. Therefore the hydrological regime of the region may be greatly affected by modifications to the hydrological regime of the Negro and Paraguay rivers as well as by changes to the precipitation regime in the Nhecolândia region itself. The sensitivity in the variation of the water level of the Paraguay river, observed by Collischonn et al. (2001), shows that some droughts can last as long as a decade, as observed between 1962 and 1973. Conversely, the subsequent period (from the mid-1970s to 2001) showed higher water levels. This may be related to the increased river discharge due to deforestation for new pasture areas (Silva et al. 2011).

The connection between the Amazonian and Pantanal environments was highlighted by Bergier et al. (2018), who showed that deforestation in the Amazon rainforest directly affects the distribution and intensity of rainfall in the Pantanal basin, which can cause natural disasters such as severe floods and droughts. Human alterations, as well as changes in climate, in these basins are likely to be compounded in the Nhecolândia region, where complex interactions between multiple source zones create a dynamic ecological hotspot.

With respect to the ecosystems supported by the Nhecolândia region, Alho & Silva (2012) reported the sensitivity of some animal groups in the Nhecolândia ecosystem to variations in climate. Variations in the frequency of floods and prolonged periods of drought have been shown to affect the community structure, breeding habits, population size and behavioural ecology of animals. This is due to the adaptation of these communities to the seasonal
regime in the region (Mamede & Alho 2006). This adaptation means that future changes in the hydrological regime may have devastating impacts on the ecology and biodiversity of the region. Potential future changes may be intensified by deforestation and/or the substitution of native vegetation and pastures for cultivated pastures. These changes will also reduce the habitats relied on by many local food webs (Sakamoto et al. 2012). The process of deforestation may be a direct anthropogenic action or a consequence of expanding cattle-ranching activities, which induces modifications in the landscape, soil and vegetation of the farm that increases with the number of animals (Rodela et al. 2007; Sakamoto et al. 2012). From a social aspect, the modernization of cattle-ranching techniques and environments can negatively affect the cultural stability of the Pantanal population, changing the way in which they live in relation to the original environment (Rossetto & Brasil 2003).

Lessons from other wetland environments

Given the sensitivity of the Pantanal wetlands to changes in climate and the relatively limited anthropogenic influence in the region, it may be pertinent to assess records of change from other ancient and modern wetland environments around the world (e.g. Pla-Pueyo et al. 2015) to glean information about how the Pantanal wetlands may respond in the future. Analysis of the macro-fauna in the modern wetlands in Ibera, north Argentina, suggests that extensive dry periods provide refuge for animals with a high dispersal ability, but are a problem for animals with a low dispersal ability (Úbeda et al. 2013). It has also been shown that the mortality of large mammals increases during dry periods due to pollution and the dominance of cyanobacteria in small water bodies (Úbeda et al. 2013).

More locally, Barros & Albernaz (2014) have shown that modifications in climate in an Amazonian wetland can cause intense droughts or inundations, which both lead to environmental changes, causing losses within the specific environment of the wetland. They highlighted the fact that sensitivity to climate change is intrinsic to wetlands due to their relationship with both dry and wet environments. The results of these modifications will challenge the adaptability of species (their composition and distribution), with consequences for the human population (Barros & Albernaz 2014).

Sustainability in the Nhecolândia wetlands

Projections of future climate change in the region show that temperatures may increase by up to 7°C in the next 100 years (Eta-HadGEM2 ES model; Marengo et al. 2016b), leading to an increase in evaporation and a decrease in rainfall (Marengo et al. 2016a). The evolution of the current climate into a more arid climate could affect all aspects of the Nhecolândia region, from the rainfall and flood frequency to the sedimentation rates of the Taquari megafan, leading to drastic changes in the landscape, water availability and ecosystems.

There have been many studies of aridification in the fossil record and how it affects the morphology and sedimentation style of alluvial fans that previously reflected wetter conditions (Bull & Schick 1979; Wells & Dorr Jr 1987; Harvey & Wells 1994; Pla-Pueyo et al. 2015). Blair & McPherson (1994) related alluvial fan aggradation in the Mojave Desert of the southern USA to transitions from a wetter to a drier climate, helped by ephemeral processes such as storms. Sheets et al. (2002) showed experimentally that most of the deposition in an alluvial fan occurs as a result of short-lived flows, mainly caused by overbank spills, flow expansions and failed avulsions. This highlights the importance of discrete single events, rather than prolonged wet–dry cycles, on the evolution of alluvial fans. Therefore potential changes towards more infrequent, but more intense, rainfall may be beneficial to the growth of the Taquari megafan.

If the Taquari megafan were to undergo an aridification process, a decrease in the effective soil moisture content would reduce the vegetation cover on the hillslopes, which would, in turn, result in an increase in soil erosion and a concomitant increase in sediment supply downstream (Harvey & Wells 1994; Harvey et al. 1999; Silva et al. 2011) in the floodplain area. This area is currently occupied by cattle-ranching pastures. In such a sensitive system, a decrease in the moisture content of soil, together with a change in temperature, would result in the reduction and potential disappearance of deciduous forests and most of the aquatic macrophytes in the area, affecting the wildlife dependent on such vegetation. The landscape would change, as would the current ecological niches within it. Under these future environmental conditions, the flood regime would change according to the reduced rainfall and the changes in the watershed soil cover, leading to a shortening of the wet season and more frequent flash flood events substituting for channelized, less flashy floods. With increased evapotranspiration, a decreased rainfall and floods more concentrated in certain periods of the year, periods of drought are more likely to occur. This would result in some of the lakes drying out permanently and the remaining lakes becoming concentrated, with the freshwater lakes becoming more saline, drastically reducing the amount of freshwater available in the remaining lakes.

Climate change therefore has the potential to be extremely damaging to the current biodiversity of
the Nhecolândia region and would be expected to have a destructive impact on both the wild ecosystems and human activities. The Pantanal region is currently affected by anthropogenic modifications of its natural landscape, such as deforestation and/or the substitution of natural pastures by introduced cultivated species. This has led to competition between native and exotic species, the degradation of habitats and the exposure of the sandy soil (Alho & Sabino 2011). The sandy soil is not suitable for pastures and therefore reduces the feeding area available for cattle. These modifications could accelerate the process of regional climate change, turning the Nhecolândia wetlands into an arid place, with dramatic consequences for the flora, fauna and human occupation.

Conclusions

The Pantanal region is a mosaic representing millennia of climatic changes, displaying a landscape that is the result of multiple shifts from humid to more arid environments. As such, the current landscape geomorphology, ecology and productivity of this composite landscape reflects its unique position at the boundary of several key atmospheric circulatory patterns (e.g. the Intertropical Convergence Zone). The Nhecolândia region remains one of the most understood, yet sensitive, areas of the Pantanal basin. The unique hydrological regime, currently classified as semi-arid, means that the sensitivity of the Nhecolândia sub-region to environmental modification is high. The water regimes of the main rivers are distinct and are related to regional rainfall (Negro river) and the climate cycles in the Amazon region (Paraguay river). Human modifications and pressures also increase the sensitivity of the region to climate change. The main human impact in the region is deforestation to introduce cultivated pastures. The resultant changes in habitats, land cover and hydrological regimes mean that the entire Nhecolândia system is affected. Some native animal groups in the Nhecolândia ecosystem are distinct and are related to regional rainfall (Negro river) and the climate cycles in the Amazon region (Paraguay river). Human modifications and pressures also increase the sensitivity of the region to climate change. The main human impact in the region is deforestation to introduce cultivated pastures. The resultant changes in habitats, land cover and hydrological regimes mean that the entire Nhecolândia system is affected. Some native animal groups in the Nhecolândia ecosystem are highly sensitive to climatic variations, so any small shift in climate may affect the community structure, breeding habits, population size and behavioural ecology of the wild-life present. Therefore any future changes in climate, land cover or the ecosystems of the Nhecolândia region will result in complex reactions affecting both human society and the ecology of the entire Pantanal basin.

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