The Nhecolândia wetland: Natural and anthropogenic influences on south-east Pantanal, Brazil.

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Abstract: The Nhecolândia region covers the southern wetlands of the Pantanal basin in Brazil. Characterised by myriad shallow freshwater and alkaline-saline lakes,, the distinct natural features of the Nhecolândia wetland make it highly sensitive to climate change and human impact. This study summarises the natural and social aspects that have, and may potentially cause changes to this delicate wetland. Here, we analyse the response of the wetland to historical changes in climate and human activity and use this understanding to forecast responses 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 global and local climate changes and the intensification of the 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 more than 140,000 km^2. Due to the low relief of the entire basin (ranging 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). Acting as a wetland mosaic, the Pantanal is characterised by different climatic, hydrologic and topographic gradients (Fig. 1; McGlue *et al.* 2017). During the dry season, from April to September, the waters remain in perennial rivers and lakes, while extensive and continuous grasslands are exposed in between the "islands" of vegetation where *cerrado* savanna-type forest predominates (see *Biodiversity* section). Due to its geomorphology and hydrology, the Pantanal acts as a natural water reservoir, filled up during the rainy season and slowly being drained out during the dry season, helping to keep the water balance of the south Paraguay and Paraná rivers 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: fresh-water and alkaline-saline (McGlue *et al.* 2017; Gerreiro *et al.* 2017; *see The Nhecolândia region geomorphology* section). This leads to a unique environment, with *cerrado forests*, native pastures and herbaceous vegetation around the lakes (Bergier *et al.* 2016). The high evapotranspiration rate, 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 economy. Not only do they determine the availability of freshwater for humans and animals, but in so doing they define the biodiversity in the area and the land use, impacting the distribution of suitable areas for cattle ranching (Batista *et al*. 2012).

The sensitivity of the region means that anthropogenic climate and land use change could have a significant impact in the Nhecolândia region. Projections of changes in the occurrence of extreme floods and droughts may alter the ecological dynamic of the region. Human activities, predominantly cattle ranching, may also impact the natural environment, modifying the ecosystems directly and indirectly, with Bergier *et al.* (2013) and Marengo *et al.* (2016) concluding that natural or anthropic modification in the hydraulic conditions can threat the Pantanal ecological balance.

Here, we present a review of the knowledge about the sensitive Nhecolândia region. The objectives of this study are: (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.

The Nhecolândia environment

Climate and hydrology

Paleoclimate of Nhecolândia

The sedimentary record of the Taquari Megafan indicates that, since the Late Pleistocene, the depositional system was controlled by alternating humid and dry periods (Claperton 1993; Assine & Soares 2004; Whitney *et al.* 2011; McGlue *et al.* 2017). Distinct cold and dry periods, between 45 and 19.5 kyr BP are described by Whitney *et al.* (2011), with arid periods, in comparison with the present day climate, remaining until 12.8 kyr BP and occurring again in between 10 and 3 kyr BP. The strongest modification of the landscape, with exposure and reworking of the sediments in arid conditions, occurred during these dry periods, coupled to the associated changes on the rainfall amount (McGlue *et al.* 2016; 2017).

During the Early Holocene, the climate was predominantly dry when compared to present days (Whitney *et al.* 2011; McGlue *et al.* 2012; McGlue *et al.* 2017), including an intense drought episode (approx. 5,300-2,600 yr BP) interpreted from a hiatus in sedimentation that affected the region (McGlue *et al.* 2012). A later transgression coincided with increased flood and a more humid climate after that. The development of the Nhecolândia lakes (see *The Nhecolândia region geomorphology* section) is related to an abandoned lobe of the Taquari Megafan, with sediments reworked and morphology reshaped by enhanced wind conditions during more arid periods, leading to an aeolic and evaporative environment, with increasing salinity in the hydrological isolated lakes since ~910 yr BP (Guerreiro *et al.* 2017; McGlue *et al.* 2017).

Present 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 its climate is modulated by two phenomena: the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ; Lenters & Cook 1999; Marengo *et al.* 2001; Marengo et al. 2016a). Being modulated by both the ITCZ and the SACZ, the South American Monsoon System delivers concentrated rains from October to March (100 to 300 mm/month) and a dry period during the rest of the year (0 to 100 mm/month; Garcia 1984; Vera *et al.* 2006; Marengo et al. 2016a).

Despite the Pantanal's position within the tropical latitudes, its climate is closer to semi-arid than to tropical conditions (Marengo et al. 2016b). With an average air temperature of 24°C and an annual rainfall of 1,100 mm, the climate of Pantanal presents high evapotranspiration rates of 1,400 mm (Furian *et al.* 2013; Marengo et al. 2016b; McGlue *et al.* 2017), and an interannual variability that can cause intense dryness or drastic floods (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 Atlantic Ocean variability. Furthermore, regional scale phenomena, such as regional water balance, soil wetness and soil moisture storage influence the climate of the Pantanal (Bergier 2010; Marengo *et al.* 2016b*;* Bergier *et al.* 2018).

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

The drainage system of the Pantanal basin has approximately 500,000 km^2 of channels, with the main arteries being the Paraguay, Cuiabá, Piquiri, Taquari, Miranda and Negro rivers. The relief of the basin is minimal, which makes it susceptible to a seasonal flooding pulse (Hamilton *et al.* 2002; Paz *et al.* 2014), influenced by the Amazonian rainfall regime in the northern Pantanal rivers, which propagates from north to south, only reaching the southern regions of Pantanal 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 the rainfall in the Nhecolândia region display a non-uniform distribution, with an east-west gradient evident (92 mm/month in the east compared to 74 mm/month in the west). In the Paraguay river, west of Nhecolândia, the rainfall and the flood peak are disconnected, with the seasonal rainfall occurring ~ 4 months before the floods (Fig. 2; Por 1995; Hamilton *et al.* 2002; Fantin-Cruz *et al.* 2011) with notable influence of the Amazon rainforest in the moisture distribution (Bergier *et al.* 2018). There is, therefore, a very complex relationship at different scales between the hydrology of this region and the climatic patterns which drive it.

Geological context

The Pantanal basin is positioned in west-central Brazil (with some portions of the region extending into Bolivia and Paraguay) with a surface area of approximately 140,000 km^2 (Fig. 1; Almeida & Lima 1959; Assine 2015; Assine *et al.* 2015). The basin is elongated (north-south), with 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 (around 2.5 Ma ago, during the Early Pleistocene, Quaternary), 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 a regional epeirogenic uplift occurring during the Early Pleistocene, when the basin major faults were generated and when the basin depocenter started to subside (Almeida *et al* 2000; Assine 2015; Assine *et al.* 2015; Assine *et al.* 2016).

The infilling of the basin is characterised mainly by siliciclastic sediments (Weyler 1962; Assine *et al.* 2016). The main sequences show fining-upward 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 with the coarse portions (Weyler 1962; Assine 2015; Assine *et al.* 2015). Due to the process of subsidence, related to normal faults, alluvial sedimentary systems occur in the east border of the basin, grading to alluvial fans that occupy 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, comprising the São Lourenço, Aquidauana and Taquari megafans (Zani *et* al. 2012; Assine *et al.* 2015).

Geomorphology

The 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 km^2 alluvial fan deposits extending for ~250 km from apex (190 m a.s.l.) to toe (85 m a.s.l.), with a circular geometry suggests a multi-lobed evolutionary history (Assine & Soares 2004; Assine 2015; Assine *et al.* 2015; Zani *et al.* 2012). Characterised by low gradient slopes, a large number of meandering, single channel rivers extend across the fan surface. The high levels of fluvial activity across the fan, including frequent channel avulsions (Assine 2005; Assine 2015; Assine *et al.* 2015; Buehler *et al.* 2011), mean that relic paleo-channels are common-place. During the flood season these channels are activated and convey water and sediment across the fan, resulting in a highly-connected landscape which is less reliant on active channel systems to distribute sediment, nutrients and water.

The Taquari Megafan may be delineated into two distinct geomorphological zones (Souza *et al.* 2002; Assine & Soares 2004; Buehler *et al.* 2011; Assine *et al.* 2015); the upper fan displays a confined meander belt incised into abandoned depositional lobes, whilst in the lower fan the river is straighter 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 2008; Buehler *et al.* 2011) occurring across the lobe. Assine (2005) and Buehler *et al.* (2011) describes a complete avulsion that occurred between 1988 – 1999 at the fan toe, with the resulting distributary channel conveying 70% of the discharge between 1995 – 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 northern most side of the fan. Assine (2005) speculates that this rapid sedimentation may result in a major avulsion, potentially initiating a new depositionary lobe.

The Nhecolândia region geomorphology

The Nhecolândia region covers the southernmost 25,000 km^2 of the Taquari Megafan (Marengo et al. 2016b). Unique to the Nhecolândia region is the coexistence of thousands of fresh-water (‘*baías*’) and alkaline-saline (‘*salinas*’) lakes (Fig. 4; Furquim *et al.* 2008; Evans & Costa 2013; McGlue *et al.* 2017; Guerreiro *et al.* 2017). The *baías* may be up to two meters deep and are found in various areal extents. During the flood season *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 *baías*. The *salinas*, in contrast, are generally 500 – 1,000 m in diameter, 2 – 3 m deep (Barbiero *et al.* 2008; Furian *et al.* 2013; McGlue *et al.* 2017; Guerreiro *et al.* 2017) 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 so remain isolated from the flood waters. This maintains distinct geochemical signatures between different *salinas* (see *Soils and hydrochemistry of lakes* section). Costa and Telmer (2006; 2007) also distinguish an intermediate type of lake, ‘*doces*’, which they define as lakes in transition from the fresh-water '*baias*' to the more brackish '*salinas*'.

The origin of these different lake types is 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) associate the sand ridges, or '*cordilherias*', with relict aeolian lunette sand dunes, although they found no evidence of the longitudinal dunes interpreted by Klammer (1982). Barbiero *et al.* (2002) suggested that the *salinas* are, in fact, more recent products of the Pantanal ecosystem, forming over decades rather than centuries of millennia, highlighting their importance in the modern ecosystems of the Pantanal 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 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.* 2017; Guerreiro *et al.* 2017; 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

Much research has dealt with the chemical variability in the lakes of the Nhecolândia region and the related soils forming within and around those lakes (Barbiero *et al.* 2002, 2008; Soares *et al.* 2003; Furquim *et al.* 2008, 2010; Almeida *et al.* 2009; Barros Nogueira *et al.* 2011; Rezende Filho *et al.* 2012; Furian *et al.* 2013; Bergier *et al.* 2016; McGlue *et al.* 2012, 2017, among others). The co-existence of alkaline-saline and freshwater lakes is attributed by Barbiero *et al.* (2008) to a differential hydrological regime whereby water is lost from the saline lakes by evaporation, and an inflow coming 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 2007; Furquim *et al.* 2008; Rezende Filho *et al.* 2012, McGlue *et al.*, 2012, 2017), that in turn produces the precipitation of authigenic mineral phases (Furquim *et al.* 2010).

However, Rezende Filho *et al.* (2012) question evaporation as the main factor in the salinisation of the ponds, given the current climatic conditions in the area. In fact, McGlue et al. (2012) describe a drought stage in the Holocene (5,300-2,600 yr BP) followed by a sudden increase in the flooding pulses, related to a more humid part of the Holocene. Therefore, it seems somehow contradictory to propose evaporation as the main reason for the presence of *salinas* in Pantanal (McGlue et al., 2017) as evaporation rates were likely lower during this formative period.

As a potential explanation, Furian *et al.* (2013) suggest that under poor drainage conditions, salinity can be maintained naturally in the landscape despite relatively humid mean climatic conditions, meaning that a past arid climate would not be necessary to produce the presently saline lakes in Nhecolândia area. They propose the ponds are filled by groundwater during the dry season, and the outflow would be prevented by the chemically cemented soils (Fig. 4). The results obtained by Guerreiro *et al.* (2017) fully support the idea of alkaline-saline lakes not being a relict of past aridity events. McGlue *et al*. (2012, 2017) also support Furian *et al.* (2013) explanation, adding the presence of *cordilheiras* as an important geomorphological feature acting as barriers 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. Affected by the highly variable water regime determined by the contrasts between the wet and the 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 Pantanal has been studied in detail by several authors (Pott & Pott 1996, 2009; Pott *et al.* 2011a, 2011b; Scremin-Dias *et al.* 2011), and is characterised 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 savanna (Alho 2005, 2011). In the Nhecolândia region there are more detailed studies on the forest vegetation (Ratter *et al.* 1988). These authors imply that the vegetation in Nhecolândia presents similarities to the deciduous and semideciduous forests of Central Brazil.

There are two main biomes in the Pantanal wetland (Alho *et al.* 2000; Alho 2005; Sabino & Prado 2006): the Cerrado and the Pantanal biomes. The Cerrado biome is a savanna-type forest, including open savanna (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 in the Brazilian Pantanal there are various degrees of Cerrado cover, in the region of Nhecolândia, it consists of between 40 and 50% of the total vegetation.

Regarding the wildlife, the feeding and breeding conditions are directly linked to the hydrological cycle and may be divided in four stages (Alho 2008, 2011): flooding, flood season, drainage season and dry season. The water availability affects not only the vegetation, but also the niches and the nutrient cycles for the animals that live in Pantanal. Moreover, many endangered species can be found in the Pantanal such as the jaguar and the marsh deer (Alho *et al.* 2003). Approximately 113 reptile species live in the Pantanal and 189 in the Cerrado biome. Specifically, amphibians show low diversity but high abundance in the area, with some 80 species occurring on the upper Paraguay Basin (Alho, 2008). 463 bird species have been recorded only for the floodplains, increasing to 665 species when the uplands are included, and 837 species when including the Cerrado biome (Alho *et al.* 2000, 2008; Alho 2005; Sabino & Prado 2006; Tubelis & Tomás 2002; Silva 1995). Mammals are also quite diverse, with up to 195 species identified so far (Alho *et al.* 2003, 2011; Alho & Gonçalves 2005; ANA 2004). Finally, Alho (2008) provides an estimation of 400 fish species living in the Pantanal region (including plateaus and plains). However, although there are many studies on the biodiversity of Pantanal as a whole, only a few show the close links between the annual floods and the wildlife and focus specifically on the Nhecolândia region. (e.g. Mamede & Alho 2006). Taking into account that floods directly influence the habitats of the Pantanal fauna and flora, it is important to fully understand the wetland evolution in order to predict changes that may affect its rich biodiversity in the future.

Anthropogenic influence on Nhecolândia

Prehistorical occupation

The human occupation in the Pantanal started around 27,000 years BP with a settlement located 100 km north of the basin (Oliveira 1994; Schimitz *et al.* 2009; Vialou *et al.* 2017). Archaeological evidence suggests the occupation of the rest of the basin began ~8,000 years ago in locations close to the Paraguay river (Schimitz *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 (4,400 years B. P.; Oliveira 1994; Schimitz *et al.* 2001; Oliveira *et al.* 2017) have been identified in a region called Pantanal do Miranda (Fig. 1).

Although there are no known archaeological sites in the centre of the Nhecolândia region, the west and south-west borders are full of archaeological sites, specially related to the Pantanal do Miranda mounds, geomorphological features resulting from the differential erosion of carbonate paleolakes and their surroundings (Oliveira *et al.* 2017). These mounds represent elevation highpoints on the Pantanal plain and are constantly exposed during flooding, forming "vegetation islands" that are rich in ceramic fragments of the Pantanal Tradition (Oliveira 1994; Schimitz *et al.* 2001, 2009). The people that occupied these mounds had a close relation with the surrounding floodplain environment, with small settlements and a fish based diet (Schimitz *et al.* 2001).

The carbonate mounds of Pantanal do Miranda are a more stable and elevated terrain, with denser vegetation, and closer to the river than the sand elevations (*cordilheiras*) of Nhecolândia, making them a more suitable place to live for ancient humans (Oliveira 1994; Schimitz *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 Pantanal, some native modern groups from the Amazon migrated to the region prior to the arrival of the Europeans (Oliveira 1996) in the fifteenth century. The discovery of this "New World" marked a step-change in the occupation of the Pantanal. European occupation was fast, with the north part of Pantanal being first occupied by the Europeans in the 1520s, as the rush for silver mining, earlier found in the nearby Andean region, spread to the Pantanal (Oliveira 1996). However, as the geological characteristics of Pantanal and its surroundings do not favour the development of abundant precious metals, with only some gold occurrences being discovered in the 1800's (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. Population in the region grew more consistently after the Brazilian government colonization programs between 1960 and 1980 (Coutininho 2005; Abreu 2010). During this period changes in land use were extensive, and cattle ranching became the main economic activity in Nhecolândia. The current estimated population of Nhecolândia region is ~3,000 people (Abreu 2010). Therefore, the habitation of this region is relatively new and conditioned to the hydrological and climatological characteristics of the past century. Inbuilt societal resilience to long term variations in hydrology and climate may therefore be lacking, meaning that the communities in this region are likely highly sensitive to potential future changes.

Cattle ranching in Nhecolândia

The main characteristic of the cattle ranching industry in the Nhecolândia region is the cattle graze system (transhumance), with the farmer driving the livestock through different farm lands during the year, to avoid the seasonal floods and to reduce the stress of 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 of native pastures, with approximately 8 pastures per farm (Rosa *et al.* 2007).

The land should include variations in relief, covering low lands, such as *baias* and *vazantes*, and high lands, 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, having a dramatic impact on the local ecosystems. Sometimes it is necessary to synchronize the movement of the cattle with other farms, in 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 past century, may not be resilient to future changes. It is a crucial component of Nhecolandia economical activity, and it depends mainly on the availability of pastures for the cattle to feed on. Thus, hydrological changes in the flood regime and in the extension of land affected by the floods are expected to have a direct impact on this activity, potentially reducing the primary food source for the animals and therefore forcing changes in the current transhumance patterns.

The impacts of human activity

There is no record of prehistorical alterations in the landscape, due to the hunter-gather character of all native groups that lived in or close to Nhecolândia (Schimitz *et al.* 2001; Bespalez 2015). The absence of economically valuable natural resources, such as minerals, prevented the area from human impact until the beginning of the cattle ranching activity (Oliveira 1996). The main modification is the removal of native vegetation and/or the native pastures in substitution for cultivated ones (Harris *et al.* 2005). In between 2003 and 2010, 12% of the forested area were replaced by cultivated pastures (Paranhos Filho *et al.* 2014). The deforestation of the region leads to desertification due to the changes in the local water cycle (i.e. humidity loss), especially around the saline lakes, where specialised vegetation has evolved (Sakamoto *et al.* 2012). The constant growth of the cattle ranching activity in recent years is also leading to an increase in stress of 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 anthropic modifications, such as unsustainable agriculture in river head waters, can be observed in distinct areas, inducing variations in water volume and affecting the sediments and nutrients carried by the rivers from the high lands of Pantanal to the low lands, such as Nhecolândia (Bergier *et al.* 2013). Although these impacts may be recent, they are likely to be major drivers of environmental and ecosystem change in the near future of this important wetland region.

Future perspectives

Nhecolândia's sensitivity to change

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

The waters that characterise Nhecolândia as a wetland are related to the water regimes of Negro and Paraguay rivers, both with distinct flooding cycles. The Negro river is directly related to regional rainfall and the water-table regime, acting as a tributary of Paraguay river. The Paraguay river has its origin in the Amazon basin and it is highly affected by the Amazon region climate (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 of 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-1970's to 2001) shows higher water levels. This can 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 is highlighted by Bergier *et al.* (2018) who show that the deforestation in the Amazon rainforest directly affects the distribution and intensity of the rainfall in Pantanal; 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) report the sensitivity of some animal groups in the Nhecolândia ecosystem to climatic variations, where variations in flooding frequency and prolonged periods of drought have been shown to impact upon community structure, breeding habits, population size and behavioural ecology of animals. This is due to the adaptation of these communities to the seasonal regime of the region (Mamede & Alho 2006). This adaptation means that future changes in the hydrological regime of the region may have devastating impacts on the ecology and biodiversity of the region. Potential future changes may be intensified by deforestation and/or substitution of native vegetation and pastures for cultivated pastures (see *Cattle ranching in Nhecolândia* and *The impacts of human activity* sections). Additionally, these changes will reduce habitats upon which many local food-webs rely (Sakamoto *et al.* 2012). The process of deforestation can be a direct anthropogenic action or a consequence of expanding cattle ranching activity, which induces modifications in the farms landscape, soil and vegetation that increases with the number of animals (Sakamoto *et al.* 2012; Rodela *et al.* 2007). From a social aspect, the modernisation of cattle ranching techniques and environments can negatively affect the cultural stability of the Pantanal population, changing the way they live in relation to the original environment (Rosseto 2003).

Lessons from other wetland environments

Given the sensitivity of the Pantanal wetland 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) in order to glean information as to how the Pantanal wetland may respond in the future. Looking at modern wetlands in the Ibera wetland, north Argentina, analysis of macro-fauna suggested that extensive dry periods provide refuges to animals with high dispersal ability, despite being a problem to animals with low dispersal ability (Ubeda *et al.* 2013). It has also been shown that the mortality of large mammals increased during dry periods due to pollution and cyanobacteria dominance in small water bodies (Ubeda *et al.* 2013).

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

Sustainability in Nhecolândia

Projections of future climate change in the region show that temperature may increase up to 7°C in the next hundred years (Eta-HadGEM2 ES model; Marengo et al. 2016b), leading to an increase in evaporation and a decrease in rainfall values (Marengo et al. 2016a). The evolution of the current climate into a more arid one may affect all aspects in 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 are many studies in the literature discussing how aridification has been recorded in the fossil record and how it affects the morphology and sedimentation style of alluvial fans that were previously reflecting wetter conditions (Bull & Schick 1979; Wells *et al.* 1987; Harvey & Wells 1994; Pla-Pueyo *et al.* 2015). Blair and McPherson (1994) related alluvial fan aggradation in the Mojave Desert of the southern USA to transitions from a wetter to a dryer climate, helped by ephemeral processes such as storms. Sheets *et al.* (2002) demonstrated through an experiment that most of the deposition in an alluvial fan occurs as a result of short-lived flows caused mainly by overbank spills, flow expansions and failed avulsions. Highlighting the importance of discrete single events, rather than prolonged wet/dry cycles on alluvial fan evolution. Therefore, potential changes towards more infrequent, but more intense rainfall may be beneficial for the growth of the Taquari Megafan.

If the Taquari Megafan were to undergo an aridification process, a decrease in the effective soil moisture would reduce the vegetative cover on the hillslopes, which would in turn result in an increase in soil erosion and a concomitant increase in sediment supply donwnstream (Harvey & Wells 1994; Harvey *et al.* 1999; Silva *et al.* 2011) in the floodplain area. This area is currently occupied by cattle ranching pastures. Moreover, in such a sensitive system, the decrease of moisture in the soil, together with the change in temperatures, would result in the reduction and potential disappearance of the deciduous forests and most of the aquatic macrophytes in the area, highly impacting the wildlife depending on such vegetation. The landscape would change, as would the current ecological niches with it. Under these future environmental conditions, the flood regime would be expected to 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 channelised, less flashy floods. With an 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 ones concentrating; with, the freshwater ones becoming more saline, drastically reducing the amount of freshwater availability in the remaining lakes.

Given the above, climate change has the potential to be extremely damaging to the current biodiversity of the Nhecolândia region, and would be expected to have a destructive impact both on the wild ecosystems and human activities. In the meantime, the Pantanal is currently suffering anthropogenic modifications of its natural landscape, such as deforestation and/or substitution of the natural pastures by introduced cultivated species that leads to the competition of the native and exotic species, degradation of habitats and exposure of the sandy soil (Alho & Sabino 2011). The sandy soil is not suited for the growing of pastures and therefore, reduces the feeding areas for cattle. These modifications can accelerate the process of regional climate change, turning Nhecolândia into an arid place, with dramatic consequences for 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 ITCZ). Within the Pantanal, the Nhecolândia region remains one of the most understudied, yet sensitive area of the basin. The unique hydrological regime of this region, currently classified as semi-arid, means the sensitivity of the Nhecolândia sub—region to environmental modifications can be considered high. The water regimes of the main rivers are distinct; related to regional rainfall (Negro river) and Amazon region climate cycles (Paraguay river). In addition, human modifications and pressures also increase the sensitivity of the region to climate change. The main human impact in the region is deforestation in order to introduce cultivated pastures .The resultant changes in habitats, land cover and hydrological regimes mean that the entire Nhecolândia system is impacted. . Some native animal groups in the Nhecolândia ecosystem are highly sensitive to climatic variations, so any small climatic shift may produce an impact upon community structure, breeding habits, population size and behavioural ecology. Therefore, any future changes to the climate, land cover or ecosystem of the Nhecolândia region will result in complex reactions which will impact the society and ecology of the entire Pantanal basin.

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Figure captions

Fig.1. Location of the Pantanal basin. Circles highlighting Nhecolândia and Pantanal do Miranda regions, over a digital elevation model from Shuttle Radar Topographic Mission (SRTM).

Fig.2. Comparison between rainfall and Paraguay river levels in the same station (Porto Manga, Corumbá), without correlation (ANA 2017).

Fig.3. Landsat 7 image of the Taquari megafan (acquired April, 2000) displaying historical and active lobes of the alluvial fan (numbered 1 to 7 and outlined by white dashed lines, modified from Makaske et al. 2012). The currently active depositional lobe is outlined in solid white lines. The location of the incised meander belt is highlighted, as is the Nhecolândia region.

Fig.4. Aerial photographs showing a freshwater (*baía* or *lagoa*, depending on the authors describing them) and a saline lake (*salina*) in the Nhecolândia region (taken from Google Earth, 2017) and sketches showing their cross-section during the wet and dry seasons, following the descriptions by Barbiero et al. 2008 and Furiam et al. 2013. These authors propose the existence of chemically cemented soils below the saline lakes which prevent freshwater from reaching the *salinas* during the dry season, when evaporation is higher. On the other hand, during the flood events in the wet season, the salinity is reduced through the fresh groundwater reaching the lake.

994

Figure 1

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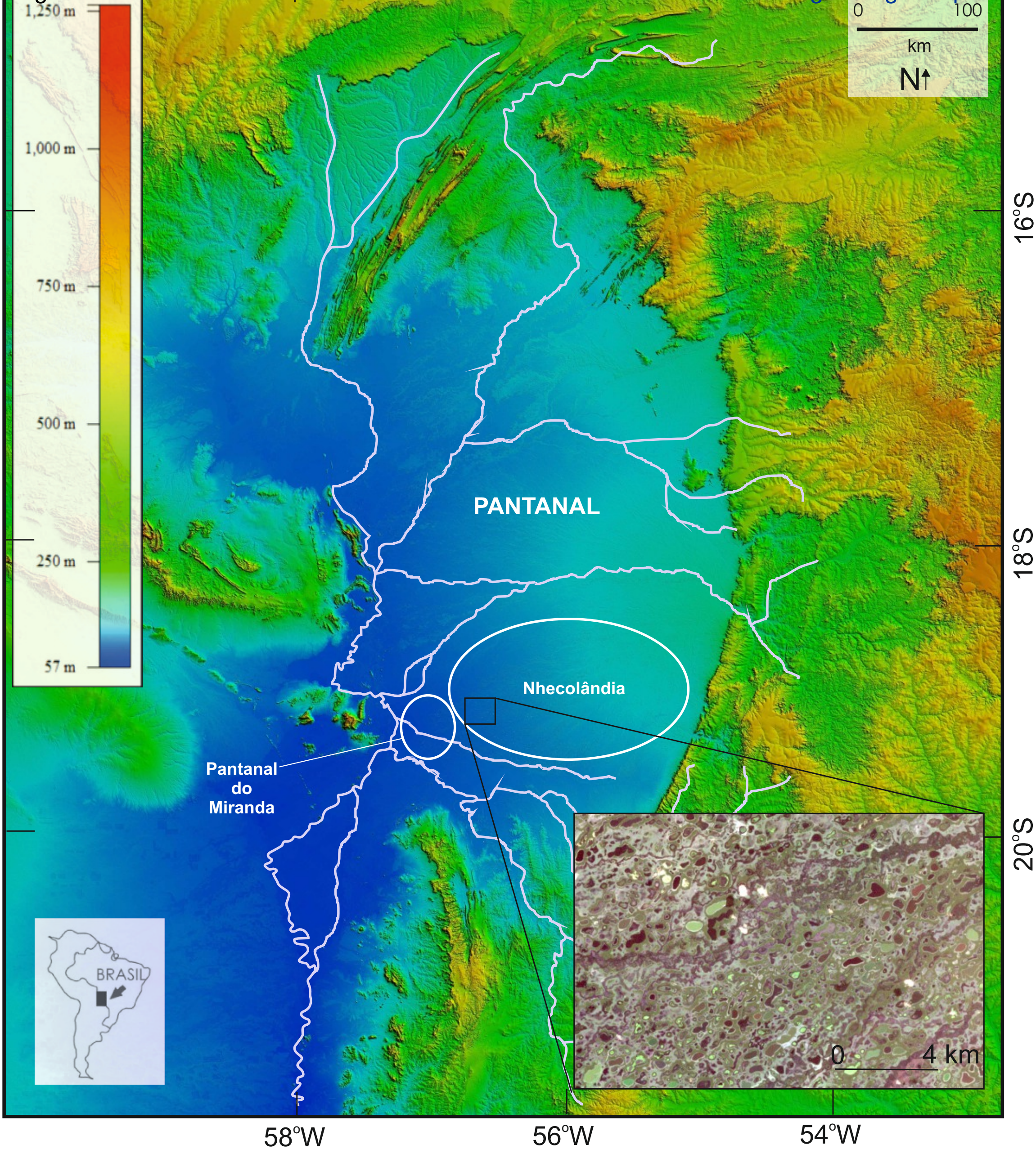
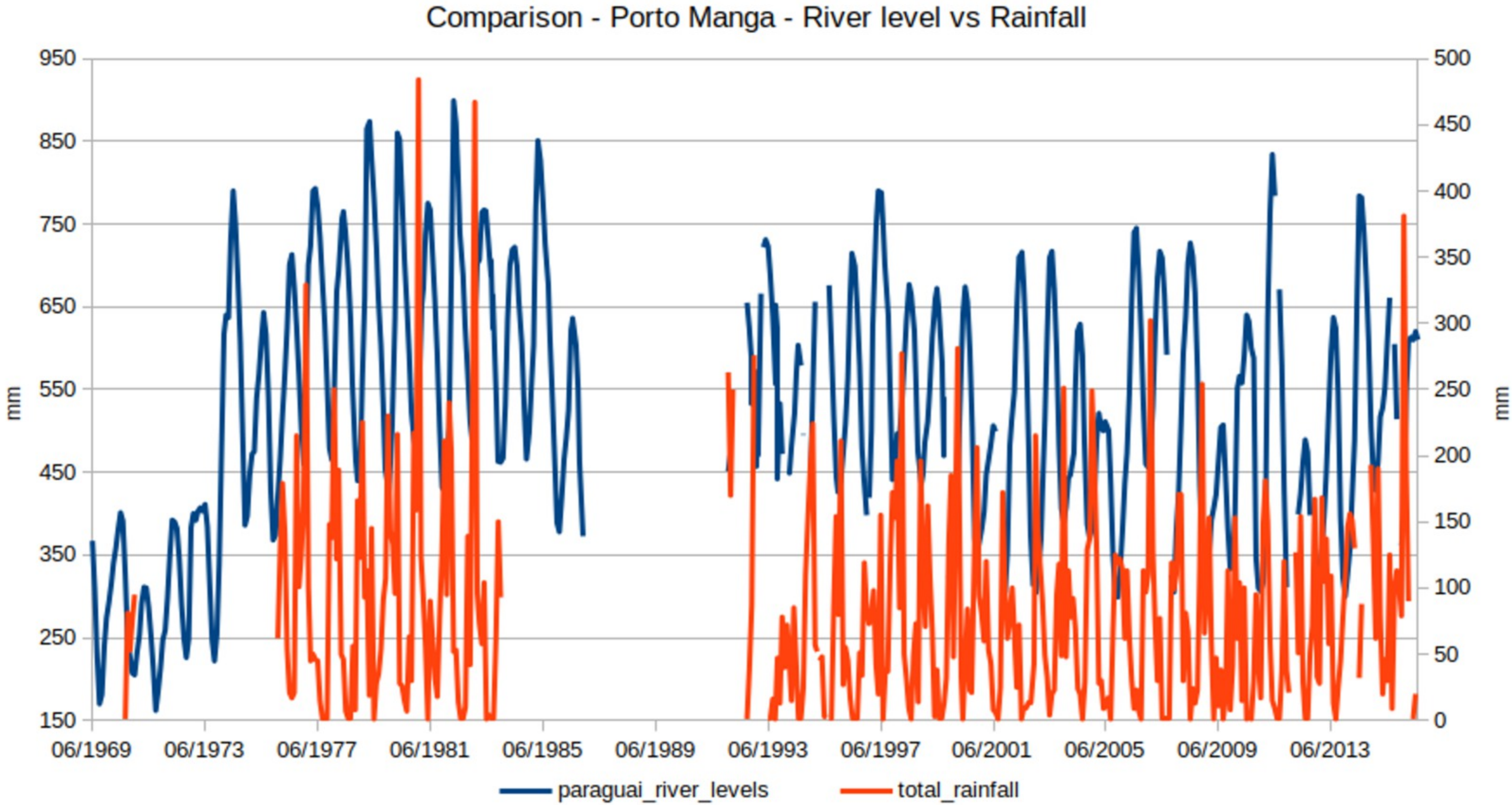


Figure 2



Comparison - Porto Manga - River level vs Rainfall
950
850
750
650
550
450
350
250
150
mm
500
450
400
350
300
250
200
150
100
50
0
mm
06/1969
06/1973
06/1977
06/1981
06/1985
06/1989
06/1993
06/1997
06/2001
06/2005
06/2009
06/2013
paraguai_river_levels
total_rainfall

Figure 3

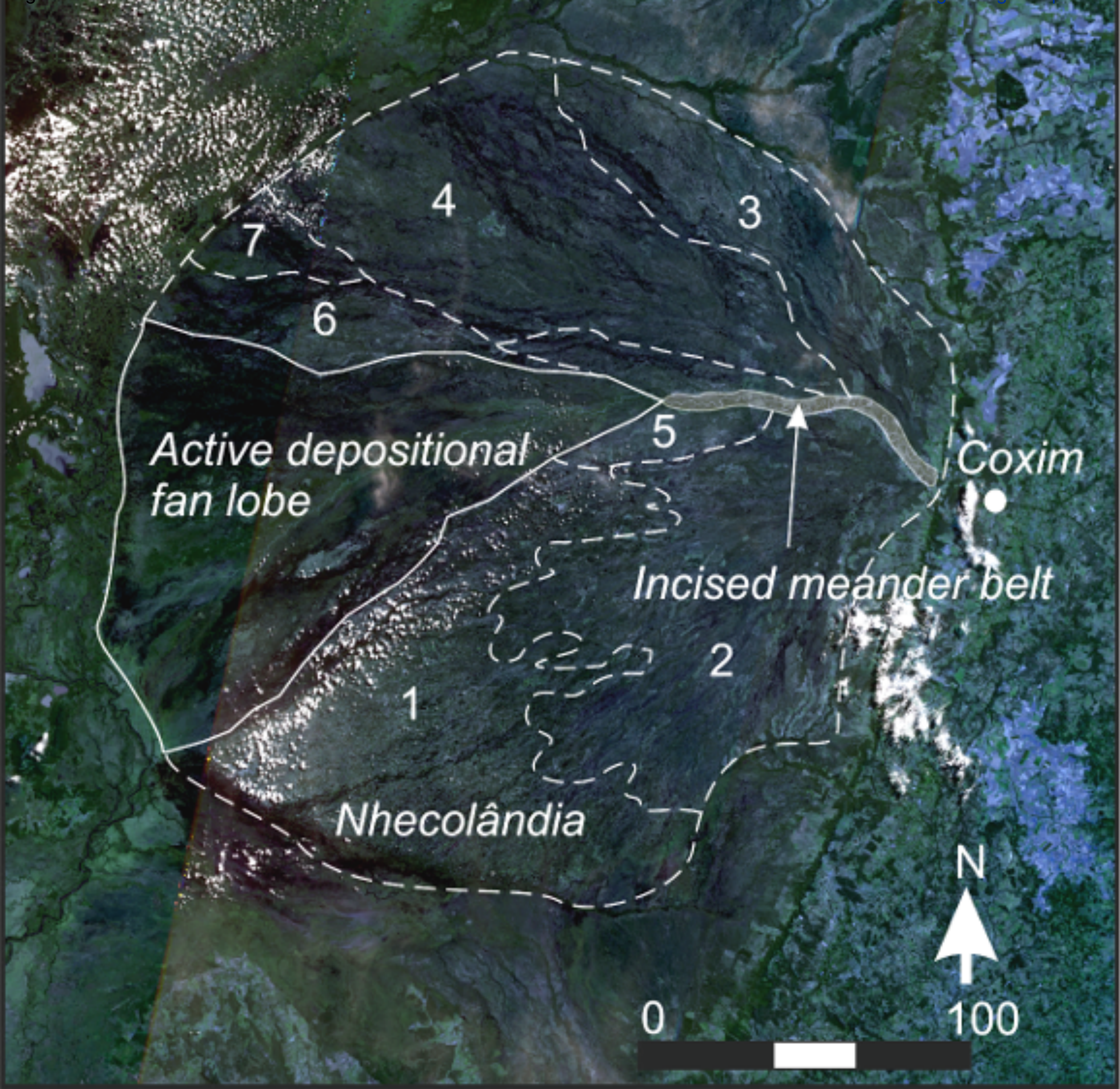
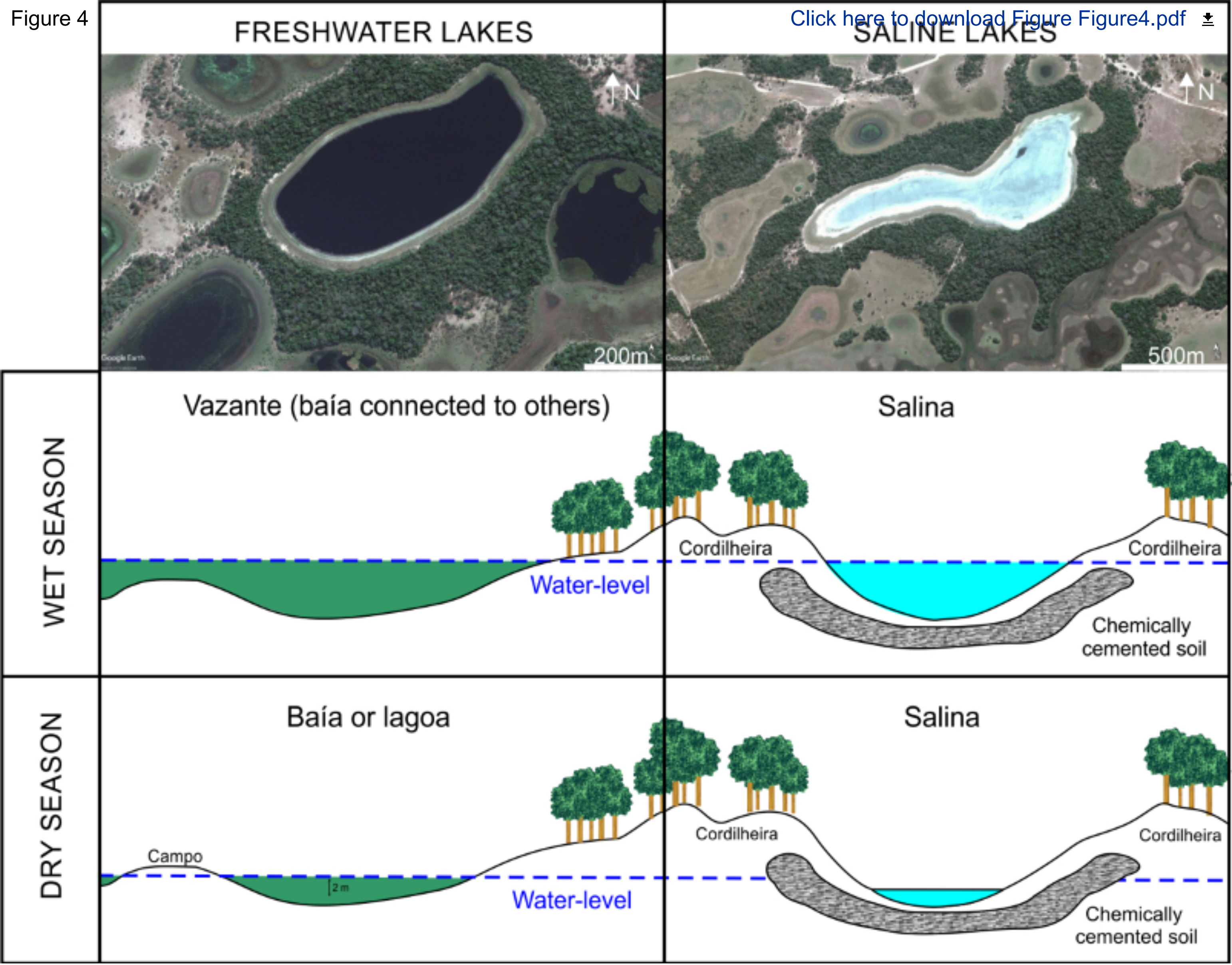

4
3
7
6
5
Active depositional
fan lobe
Coxim
Incised meander belt
2
1
Nhecolândia
N
0
100

Figure 4


FRESHWATER LAKES
SALINE LAKES
N
200m
500m
Google Earth
WET SEASON
DRY SEASON
Vazante (baía connected to others)
Water-level
Salina
Cordilheira
Cordilheira
Chemically cemented soil
Baía or lagoa
Campo
2 m
Water-level
Salina
Cordilheira
Cordilheira
Chemically cemented soil