Climate Change and the Pantanal: Comprehensive Summary of Existing Literature

Globally climate change has already affected every ecosystem on Earth, despite an average warming of only 1°C thus far. The impacts range from changes in species' distribution, physiology and phenology to ecosystem biodiversity and sustainability (Scheffers 2016). With respect to the Pantanal, the world's largest tropical wetland, the consequences of warmer temperatures vary, but the future is bleak. Temperatures will rise, perhaps as high as 7°C by 2100 (Marengo et al., "Climate Change Scenarios in the Pantanal," 2014). The hydrologic regime will shift though exactly how remains uncertain. Some studies, in fact, have shown that it already is.

But, at this point, climate change has impacted the Pantanal's wetlands far less compared to the damage from land use changes that stem from a lack of local land management (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). A growing body of research is looking at exactly how climate change has and will affect the Pantanal. The findings paint the story of an ecosystem at a fork in the road where warming temperatures, coupled with uncoordinated land management, infrastructure development, and native habitat conversion, could forever alter this natural gem. The need for a coordinated management framework for the Pantanal becomes evident when put in the context of the insurmountable challenges facing this ecosystem over the course of the coming decades. That is not to say, however, that the effects of global warming on the Pantanal's climate are well understood. In fact, Bergier et al. (2018) calls "the effects of global warming on the Pantanal … rather ambiguous" while "changes to rainfall remain remarkably uncertain."

Dr. Ivan Bergier of the Brazilian Agricultural Research Corporation explained via email that the uncertainty can be associated with a lack of data and model premises simplification. Even more important, though, is that climate change is associated with extreme events. Statistically speaking, extreme events have greater variability between max and min values, making statistical distribution larger and, therefore, more uncertain. In other words, climate change is largely uncertain due to the increase in frequency of extreme events, despite of the lack of data/model detailing (Bergier 2018).

It's important to remember as well that climate change works in conjunction with other anthropogenic factors, including deforestation and agricultural production, to influence the natural ecological processes in the Pantanal.

Presented below is an overview of how climate change has and may impact the Pantanal and the anticipated outcomes, divided into themes and the larger geographies into which the Pantanal resides.

Temperature

Though the Pantanal's air temperature currently averages 24°C, it can drop down to -1°C and climb to 41°C (Marengo et al., "Climate Change Scenarios in the Pantanal," 2014). The rise in temperature for the Pantanal for the end of the century was calculated using climatic projections data from the IPPC Fourth Assessment Report and other regional models. In one scenario, the projections displayed an increase in temperature by 3.5°C to 4.5°C with a decrease in the number of cold nights in winter and an increase in the number of consecutive dry days for the entire region. In the same study, three researchers ran a series of global climate models to project warming in the Pantanal and came up with different results, though all of them yield the same conclusion - more heat (Marengo et al., "Climate Change Scenarios in the Pantanal," 2014).

The Pantanal could warm between 3-4°C or 4-7°C in the summer and winter months while others predict this number to be as high as 10°C for the period between 2071-2100. Another 2015 study reflected the results of similar research, finding that there will be an annual mean warming from between 2.5-3.5°C in 2011-2040 up to above 5-7°C for 2071-2100 (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). Instead of using global climate models, this study depended on regional climate models because they play a key role in downscaling the global climate simulations to smaller grid sizes in the area of interest where the impact studies can be carried out (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

Moreover, a spike in warming is expected to increase maximum and minimum temperatures by about 5°C by 2071-2100 relative to 1986-2005. This also includes an increase in the number of days with warmer nights by about 70-90 days and an increase in the number of consecutive dry days by about twenty (Marengo et al., "Climate Change Scenarios in the Pantanal," 2014). There has been a clear increase in extremes—median maximum and minimum values—in the Brazilian Pantanal. This range in extremes may also fluctuate with the season, as a 2015 study indicates, with July potentially increasing by +6°C and by +8.5°C in December by the end of the twenty-first century (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

Cerrado-Pantanal bioregion

The Cerrado is a highly biodiverse but threatened tropical savanna that lies predominantly in Brazil. This immense ecoregion neighbors the Pantanal and provides additional habitat to the species that abide in the Pantanal, as well as forming part of the headwaters of the massive wetland. For the Cerrado-Pantanal bioregion, the present annual mean temperatures range between 16.1 and 27.7°C. For the region, the largest changes in temperature are predicted to be between 2.9 and 4.6°C in 2070 while the minimum is 1.2 and 2.3°C in 2050. The range of annual temperatures, currently between 13.8 and 24.7°C, is predicted to increase by up to 2.3°C in the western parts of the Cerrado-Pantanal and decrease by 0.4°C in the north-eastern and southern parts of the region. While the temperatures of the northeastern and central parts of the Cerrado-Pantanal are projected to remain relatively stable, the Upper Paraguay River Basin may witness a larger range of temperature changes (Raes 2015).

Rainfall

Rainfall underpins the very survival of the Pantanal, providing for the ecological processes that sustain this unique ecosystem. The average annual rainfall in the Pantanal is approximately 1,350 mm with about 70% falling in spring and summer (Bergier et al. 2018). For the Upper Paraguay River Basin in which the Pantanal resides, the rainy season starts in October and runs through April. The monthly range is between roughly 100 to 300 mm, but, during the dry period, the monthly precipitation drops to between 0 and 100 mm (Bravo et al. 2014).

Between the years 1968 and 2000, the annual average rainfall in the Upper Paraguay River Basin was between 920 and 1,540 mm, with a mean value of 1,320 mm (Bravo et al. 2014). However, this trend has been changing over the past 40 years. During that same period, the La Plata Basin, in which the Upper Paraguay River Basin is located, has seen an increase in annual precipitation (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). Even though the causes of these changes have been hard to discern, some researchers have linked them to climate change.

Some recent studies shed light on how precipitation has changed from the nineteenth into the twentieth century. Marcuzzo et al. (2010) found a moderate decrease in precipitation and a high inter-annual variability in the Brazilian Pantanal after studying the monthly trends in precipitation from 1977 to 2006 from 12 rain gauge stations. They also noticed a moderate decrease in precipitation and a high inter-annual variability in this region as well as a gradual decrease for precipitation from decade 1977 to 1986 to decade 1997 to 2006 (Marcuzzo et al. 2010). Using the same methodology of analyzing the monthly trends in precipitation from 1977 to 2006, Cardoso and Marcuzzo (2010) found that the Pantanal received less rainfall in every month except July and October, which witnessed an increase in the amount of precipitation. Another analysis of rainfall between 1926-2016 found an increase in the seasonal mean rate of rainy days (between 0.4-0.6 mm/day/year), while the average amount of precipitation in the Brazilian Pantanal has not changed significantly over the course of nine decades. In other words, the Brazilian Pantanal has experienced an increase in extreme rainfall events because rain in all four seasons has become more concentrated in time (Bergier et al. 2018).

Study after study warns that predicting future rainfall in the era of climate change in the Pantanal and the larger geographies in which it's situated is hard to predict. Scientists use cautionary language when qualifying their findings, including "ambiguous" and "uncertain" (Bergier et al. 2018; Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). This uncertainty is reflected in the results yielded from an array of models, each of which produce conflicting results. The one consistent factor is that the Pantanal will experience more climatic extremes, including droughts and floods.

A 2010 study found that the Pantanal will continue to experience declining rain levels while more rain will fall in July and October, based on a regression analysis of 30-years' worth of data (Cardoso and Marcuzzo 2010). Similarly, another study, using the model Eta-HadGEM2 ES, predicted that the mean annual rainfall would decrease by an order of 10-20% in 2010-2040 and 30% by 2071-2100 (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

On a larger scale, the La Plata Basin is projected to gain about 2-4 mm of rain per day in the summer. In the winter, the Basin experiences a smaller increase of about 1-3 mm per day, but this would be mostly concentrated over the coastal region. The Basin will also suffer an increase in rainfall extremes by the end of the century, mainly in summer (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). Another analysis, based on a set of models called CMIP5 models, found that 70% of the models showed an increase in the northern and central parts of the Basin in summer while between 60 and 80% of the models exhibited a decrease in precipitation. The rainfall reductions could be between 60 and 70%, but these findings come with a high degree of uncertainty (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

Hydrology

Pantanal

Precipitation is fundamentally linked to river flow.

The Pantanal is a 170,000 km2 floodplain whose depth and size fluctuate with the season. From October to March, floodwaters fill the Pantanal like a giant reservoir and drain out slowly between April and September, providing ideal aquatic habitat, nutrient renewal, and flood control for millions of people downstream (Alho and Silva 2012; Swarts 2000). In fact, peak flows on the 1,250 km. Paraguay River reach between Cáceres (just upstream of the Pantanal) and P. Murtinho (downstream of the wetland) are delayed by three to four months (Bravo et al. 2014). The overflow forms shallow lakes and innumerable swamps and marshes on the landscape and leaves island-like areas of higher ground that inundate as much as 70% of the floodplain until July. The depths range from a few centimeters to more than two meters (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

The rivers themselves are a critical part of this wetland's matrix. More than 1,200 rivers and streams flow into the Pantanal. These rivers bring nutrients and sediment from the headwaters into the floodplain, making possible the habitat value and high concentration of wildlife and aquatic plant species found in the world's largest tropical wetland. One critical feature of this landscape is river avulsion, which occurs when the course of a river changes position. This channel instability sustains and renovates the biodiversity and reconfigures the distribution of aquatic micro and macrohabitats on the floodplain, immensely benefiting biodiversity and renewing the landscape. Changing rainfall patterns associated with global warming, along with human land uses (including cattle ranching and deforestation of headwaters), can amplify river avulsions (Bergier et al. 2018).

How will climate change influence the Pantanal's hydrology? Has it already? Studies published over the past couple of decades have tackled these exact questions. The researchers emphasize two points: first, the impacts on hydrology are not well understood, but, second, the existing literature has shown that climate change has already impacted the Pantanal's hydrology as well as the larger basin in which it resides (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

The increase in extreme rain events due to climate change interacting with unsustainable land uses could lead to an increase in the frequency of river avulsions. In fact, this has already been seen with the Lower Taquari River Basin (Bergier et al. 2018). While there is a major gap in knowledge around how the Pantanal's hydrology specifically will alter with climate change, the rates of deforestation in and around the Pantanal are cause for alarm. An estimated 15% of the Pantanal has already been deforested, as has 60% of the surrounding plateau. At the current rate, the Pantanal's native vegetation will disappear by 2050 if no measures are taken to combat this trend (Alho and Silva 2012). Bergier et al. (2018) warns that river avulsions – natural or human caused – disrupt the livelihoods of people who depend on this landscape for their income, whether it be fishing, ranching, tourism or agriculture. Water security and conservation will have to be major priorities for basin stewardship efforts in the Pantanal.

Upper Paraguay River Basin

The Pantanal plays an integral role in regulating the Upper Paraguay River Basin's drainage system. A 2014 study found that, just as precipitation is projected to either increase or decrease, river discharge could experience the same. Half of the results from a series of models in a 2014 study found river discharge increasing and the other half decreasing. Depending on the factors selected, future streamflow projects changed. These factors included the degree of temperature rise, the amount of precipitation change, and the offset (or lack thereof) of precipitation and evapotranspiration, among others (Bravo et al. 2014). However, a 2015 study found that discharge, along with precipitation, will increase in the austral (southern) summer while both will decrease through the rest of year (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). Since river flow is dependent on rainfall, it makes sense that projecting streamflow is also difficult and contingent. As Bravo et al. (2014) states, "There are several factors influencing the rainfall-runoff transformation, which is a non-linear process, making the response of the basin in terms of river flow regime for the prescribed climate change not directly deductible, unless a specific methodology is employed."

Rio de la Plata Basin

A 1998 study sheds light on the evidence for how climate change has already impacted the Rio de la Plata Basin, which includes the rivers influencing and influenced by the Pantanal. Analyzing the temporal variability of the Basin, they found that the period around the year 1970 marked a shift in flows in the watershed. Take, for instance, the Paraná River whose flow history can be divided into two distinct time zones for the 20th century: the period 1943–1970, which was characterized as the driest, and the one that began in 1971 with its hyperhumid characteristics. What makes the year 1971 stand out is that these surprising characteristics seemed to endure without reverting to the previous climatic patterns. The period beginning in the year 1971 saw a 22% increase in streamflow in comparison to the historical average except in March, where the monthly mean streamflow was a little lower than 4% of the historical average. The authors note that the Paraguay River, which flows through and out the Pantanal, has similar temporal behaviors to the Paraná. Prior to 1971, the Paraguay had sharply defined low waters between September and January but starting that year the low waters now occur between November and December (García and Vargas 1998).

The changes in river flow took place through the entire Rio de la Plata Basin beginning in the early 1970s. Since the changes remained constant since that time marker – or did "not seem to revert but [become] symptomatic," as the authors write - this pattern suggests climate change is the culprit (García and Vargas 1998).

Wildlife

Climate change has already impacted species across the world. A 2017 study found that climate change has harmed at least part of the distribution of 47% of terrestrial non-volant threatened mammals and threatened birds, out of 873 species and out of 1272 species, respectively (Pacifici et al. 2017). While the research concurs that the Pantanal will experience more extreme storm events, including floods and droughts, the impacts of warming temperatures on wildlife density and population parameters remain understudied. A 2012 review of the effects of severe floods and droughts on wildlife in the Brazilian Pantanal concluded that the "seasonal hydrological changes have their greatest impact on the region's wildlife when the regime of floods and droughts is unusually severe" (Alho and Silva 2012).

The fact of the matter is that there are few studies on how climate change will affect the estimated 4,700 plant and animal species that thrive in the Pantanal (Ministério do Meio Ambiente). WWF has identified the Cerrado-Pantanal region as a priority conservation area. Dr. Niels Raes in 2015 conducted a study that looked at how climate change would affect seven priority conservation areas, including the Cerrado-Pantanal (Raes 2015). For the following, I am summarizing Raes' findings on how changing bioclimatic conditions in the Cerrado-Pantanal will likely impact the range of three animal species – Marsh deer, Maned wolf, and hyacinth macaw – of the Cerrado-Pantanal conservation area. He provides results for impacts on the three species in terms of extrapolation and no extrapolation. The results with extrapolation give the future predicted distributions for a couple of climate change scenarios for the years 2050 and 2070 when the model is allowed to project to novel bioclimatic conditions; no extrapolation gives the future predicted distribution when no extrapolation is allowed (see Raes 2015 p. 57).

For more information than what is below and a thorough explanation of the models used, please see Raes' full paper.

Marsh deer

Climate change is expected to dramatically impact the Marsh deer population. The deers' population could reduce by up to 75% by 2100 ("Mudanças climáticas," 2016). This species' abundance is linked to the climate. Specifically, between 1903-2004, the marsh deer's population size has varied between 4,500 and 31,000. During a period of high rain between 1991-1993, the population rose to between an estimated 40,000 and 45,000. Then, during the middle of a drought, the population dropped to around 20,000 ("Mudanças climáticas," 2016).

A study by Dr. Niels Raes ended with contrary results for the Marsh deer's future occurrence in the Pantanal. The deer's range is restricted to the southwestern part of the Cerrado-Pantanal region and is predicted to expand towards the West and East if the model is allowed to extrapolate into novel future bioclimatic conditions. However, if the model is refrained from projections into novel future bioclimatic conditions, then it renders unsuitable future bioclimatic conditions at the core of its present distribution model. The results also found that the Marsh deer has "an increasing probability of occurrence with increasing annual mean temperatures," which means that it's unlikely that the core part of the deer's distribution will become unsuitable in the future. Moreover, Dr. Raes also noticed that large seasonal precipitation differences have a negative impact on the distribution of the deer (Raes 2015). This is supported by Dr. Pereira's findings. Dr. Guellity Marcel Fonseca Pereira of the Federal University of Mato Grosso do Sul asserts that the eventual impact of climate change on deer can be reduced by guaranteeing the quality and availability of land for this specie ("Mudanças climáticas," 2016).

According to Dr. Raes, the Marsh deer will fare better than the Maned wolf. The deer is more likely to sustain higher mean annual temperatures and thus is less threatened by future bioclimatic change (Raes 2015).

Maned wolf

The Maned wolf has a niche: moderate temperatures and continuous dry conditions with considerable seasonal ranges of temperatures. The wolf is limited in some parts of its range. It has an optimum response at 21°C, which means that, because the southwestern part of the Cerrado-Pantanal region has temperatures higher than that, it forms the northern range limit of the Maned wolf. Under a scenario of extrapolation, the range of the Maned wolf is predicted to expand to the North and East of the Cerrado-Pantanal region. If not, the core of the wolf's present distribution range is predicted to become unsuitable (Raes 2015).

Dr. Raes found that "the Maned wolf does not occur where seasonal changes in precipitation are large, as is the case for large parts of the Cerrado-Pantanal region" (Raes 2015).

Hyacinth macaw

Different models resulted in disparate outcomes for the world's largest parrot, predicting that its current habitat could become uninhabitable or its range could expand, depending on whether extrapolation is taken into account or not. It is predicted that the Hyacinth macaw, too, will occur in the dry Chaco and Pantanal parts of the Cerrado-Pantanal region. Dr. Raes warns that these predictions, therefore, should be interpreted with caution (Raes 2015).

Other Pantanal species

There is little available research on how climate change will affect the thousands of other species in the Pantanal.

Take, for instance, fish. Dr. Pereira warns that if the floodplain size of the Pantanal is reduced or the duration of floods is altered, then fish productivity in this major wetland could be altered ("Mudanças climáticas," 2016).

At the end of the day, global warming will affect every specie in the Pantanal and the globe. As Dr. Raes points out, some species potentially benefit from this anthropogenic phenomenon while others may virtually go extinct (Raes 2015). Ultimately, the future habitat suitability under climate change is dependent on species' ability to adapt, so any predictions should be taken with caution.

Environmental Impacts

Climate change will also affect several ecological functions and processes in the Pantanal and the larger geographic area with cascading impacts throughout the rest of the ecosystem. As temperatures rise in the Pantanal, evapotranspiration rates will also, which would have implications for streamflow (Bravo et al. 2014). Bravo et al. (2014) points out that future anomalies in streamflow will in part depend on whether changes in rainfall will or will not counterbalance the increase in evapotranspiration. Changes in climate conditions could also disturb ecosystem functioning, mostly by altering precipitation and evapotranspiration rates, and impact floodplain inundation dynamics (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). Warming temperatures and changes in seasonal and interannual weather extremes (droughts, heat waves, floods, etc.) could also favor harmful cyanobacterial blooms in eutrophic waters and enhanced vertical stratification of aquatic ecosystems (Bravo et al. 2014).

Connection to the Amazon

The Pantanal as an ecosystem fits into a much larger geographic puzzle. The deforestation of the Amazon influences the precipitation levels in the Pantanal. This is how: deforestation leads to a reduction in moisture fluxes from the Amazon's surface – essentially, there is less water evapotranspiring off the thick foliage of the Amazonian rainforest and, therefore, less moisture to condense into precipitation elsewhere. For that reason, deforestation has the capacity to delay summer rainfall and lengthen the dry season. This means that, for neighboring geographies in central South America like the Pantanal, the transfer of atmospheric vapor between regional climates will change. With a reduction in the tropospheric transfer of moisture, water security could also decrease (Bergier et al. 2017).

The authors of the 2018 paper, "Amazon rainforest modulation of water security in the Pantanal wetland," were the first scientists to tackle the intersection of climate change, the Amazon and the Pantanal (Bergier et al. 2018), Though they did not give explicit outcomes for how sustained deforestation of the Amazon would alter the Pantanal, they did lay out the concerns going forward.

Changes in water security would have drastic consequences for a multitude of ecosystem services, ecological processes, economic activities, and floral and faunal behaviors that are dependent on rainfall. Flooding by rain and river overflow create the habitats, food availability and reproductive niches that sustain the biodiversity of the Pantanal. The seasonal fluctuations of water and sediment also make possible the recycling of nutrients in the Pantanal, which supports the region's highly complex and diverse food web. These natural hydrologic processes also maintain the region's diverse, abundant fishery that local fishermen depend on for subsistence and business, and tourists for sport (Bergier et al. 2018).

It's for all these reasons and many more that Bergier et al. (2018) writes "water security for ecosystem services provided by the Pantanal for human activities and ecosystems resilience is critically attached to the state and conservation of the Amazon rainforest."

Limits of Current Research and Future Opportunities

The existing literature lays the groundwork for understanding a unique global resource that is under threat by inevitable, impending climatic forces. The Pantanal will get hotter. The rainfall patterns will modify. And, consequently, regional hydrology and environmental functions will change in unexpected ways. The impacts on wildlife, the local communities, and the regional economies also remain unclear.

Informed science and studies of climate change impacts on the Pantanal is at the root of being able to understand the ripple effects of these changing climatic patterns. The current major impediments to realizing these impacts scientifically are the following: the projections of impacts on wetlands (including the Pantanal) remain too divergent; the uncertainty of rainfall projections; and the need to identify existing stressors and their future role and impacts on the Pantanal's ecosystem (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015). A 2012 *Ecological Risk Assessment for the Paraguay River Basin* identified the current stressors as livestock, mining, deforestation, hydroelectric plants, and gas pipelines, to name a few (WWF-Brazil and The Nature Conservancy 2012). An updated ecological risk assessment that incorporates climate change would help to fill that gap as well as inform policymakers, who hold the future of the Pantanal in their hands. As Jose Marengo and his co-authors put it, filling these knowledge gaps "is fundamental for wildlife management and nature conservation for the Pantanal … [and] makes it possible to design and implement effective adaptation actions" (Marengo et al., "Regional Climate Change Scenarios in the Brazilian Pantanal watershed," 2015).

The *Declaration for the Conservation, Integrated and Sustainable Development of the Pantanal*, signed March 22, 2018 by ministers from Bolivia, Brazil and Paraguay, calls for the growth of "scientific knowledge on the Pantanal and the integrated and sustainable management of the wetland … so that the system can remain healthy and can continue conserving its natural ecological functions" for future generations. Funding research that studies the impacts of climate change on the Pantanal would be an affirmative action toward fulfilling this trinational objective.

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