Aspects of a unique natural limnological phenomenon in the Brazilian Pantanal

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ABSTRACT

This study compares physical and chemical parameters of water samples collected in a marginal lake (Castelo Bay) in the Paraguay River Basin in southern Pantanal during a significant natural phenomenon of hypoxia, locally called *decoada*, and shortly after it. Limnological parameters were analyzed from four sampling sites along the bay. Comparisons of the physical and chemical parameters between *decoada* and post-*decoada* periods were performed by Student's t-test, principal component analysis and multivariate permutational analysis of variance (permanova). During the period of the *decoada*, there was a significant reduction in mean values of water transparency and concentrations of dissolved oxygen, sodium and nitrite compared to the post-*decoada* period. On the other hand, water temperature and conductivity, and concentrations of orthophosphate, total nitrogen and total iron have all had higher values during the *decoada* period. An effect of connectivity between lake and river was found to generate a gradient of water characteristics at Castelo Bay. The limnological characteristics that differed the most between *decoada* and post-*decoada* periods are those associated with the reduction of dissolved oxygen that could cause natural death of fish and the increase in nutrients during the *decoada*, yet they vary on temporal and spatial scales.

Keywords: anoxia, dissolved oxygen, floodplain lakes.

Aspectos de um fenômeno limnológico natural único no Pantanal Brasileiro

RESUMO

Este estudo teve como objetivo comparar parâmetros físicos e químicos de amostras de água coletadas em um lago marginal (Baía do Castelo) na Bacia do Rio Paraguai no Pantanal Sul, durante um fenômeno natural significativo de hipóxia, localmente denominado decoada, e logo após. Parâmetros limnológicos foram analisados em quatro pontos de amostragem ao longo da baía. As comparações dos parâmetros físicos e químicos entre os períodos decoada e

pós-decoada foram realizadas pelo teste t de Student, análise de componentes principais e análise de variância permutacional multivariada (permanova). Durante o período da decoada, houve redução significativa nos valores médios de transparência da água e concentrações de oxigênio dissolvido, sódio e nitrito em relação ao período pós-decoada. Por outro lado, a temperatura e condutividade da água, e as concentrações de ortofosfato, nitrogênio total e ferro total apresentaram valores mais elevados durante o período de decoada. Um efeito de conectividade entre lago e rio foi encontrado para gerar um gradiente de características da água na Baía de Castelo. As características limnológicas que mais diferiram entre os períodos decoada e pós-decoada são aquelas associadas à redução do oxigênio dissolvido que pode causar a morte natural dos peixes e o aumento de nutrientes durante a decoada, porém variam em escalas temporais e espaciais.

Palavras-chave: anóxia, lagos de planícies alagadas, oxigênio dissolvido.

1. INTRODUCTION

The Pantanal is the largest wetland in the world, covering approximately 140,000 km^2 of the Upper Paraguay River Basin (Silva and Abdon, 1998). It is subjected to an annual flood pulse that causes the waters to "rise" and "fall", as annual floods and droughts, with extensive floodplain land-water interaction (Junk *et al.,* 1989; Calheiros *et al.,* 2012).

The changing water level of the floodplain profoundly affects the structure and functioning of this ecosystem, by favoring the occurrence of a natural phenomenon known locally as *decoada*. The term *decoada* is used to describe a change in the physical, chemical and biological aquatic environment that occurs as a result of rising water levels and their contact with the terrestrial environment during early flooding, which results in the decomposition of submerged vegetation biomass in lowland areas subject to flooding. At this stage of the summer hydrological cycle, temperatures are high, which contributes to the decomposition of the great mass of highly degradable plants, mostly grasses, submerged in the flooded fields.

In this context, *decoada* is a unique natural phenomenon; unique in the world in terms of coverage, duration and frequency, regardless of its magnitude (Calheiros *et al.,* 2000; Oliveira *et al.,* 2013). In the Brazilian Pantanal, *decoada* is perceptible through changes in various limnological parameters and its effects on the structure and dynamics of aquatic organisms (Oliveira and Calheiros, 2000; Oliveira *et al.,* 2010; 2011), such as significant fish kills (Calheiros *et al.*, 2000; Calheiros and Hamilton, 1998).

The change in water quality is characterized by the presence of a high amount of dissolved organic compounds from the decomposition of the submerged organic matter. During this period, there is an increase in electrical conductivity (approx. 40 to > 100 mS/cm^{-1}), alkalinity, dissolved carbon dioxide (6 mg.L^{-1} to > 100 mg.L^{-1}) and methane, and increased concentrations of nutrients such as nitrogen, phosphorus and carbon, as the result of decomposition. Ultimately there is a dramatic decrease in dissolved oxygen (from 8.0 to 0.0 mg.L^{-1}), as well as changes in pH (to about 5.0) and transparency (Hamilton *et al.,* 1995; 1997; Calheiros and Hamilton, 1998; Calheiros *et al.,* 2000; Bastviken *et al.,* 2010).

The first evidence of the formation of the water masses of a *decoada* occurs in February in some areas of the northern portion of the Pantanal, and move downriver as the flood pulse moves toward the southern portion of the Pantanal (Calheiros *et al.,* 2000; Hamilton *et al.,* 1997; Oliveira *et al.,* 2013).

Limnological studies of the *decoada* phenomenon and its relationship to fish kills in the Pantanal began in 1988 and have lasted for more than twenty years. From these studies, differences in limnological parameters between years without fish mortality and years with fish mortality have been observed.

The complexity and unpredictability of this phenomenon, both spatially and temporally, require ongoing analysis based on a lengthy time series of data collection. For these reasons, this study aimed to compare the physical and chemical parameters of water samples collected from an marginal lake of Paraguay River, called Castelo Bay, in the Paraguay River Basin of the southern portion of the Pantanal, during a significant *decoada* event and soon thereafter, with the goal of understanding how limnological parameters vary between *decoada* and post-*decoada* periods.

2. MATERIALS AND METHODS

2.1. Study Area

Castelo Bay is located in the Paraguay River floodplain of the Upper Paraguay River Basin (UPRB) in the southern portion of the Pantanal in western Brazil (18°35'28" S and 57°31'56.6" W) (Figure 1). The UPRB is formed of other sub-basins that drain into the Paraguay River. Each sub-basin drains different geological regions of varying rainfall regimes and have distinct hydrological and limnological characteristics. The climate is tropical seasonal, characterized by dry and rainy seasons. In the Southern Pantanal the flood peak of the Paraguay River occurs between May to July, a few months after the peak of the rainy season (November to March) due to the "floodplain effects" of delaying water mass displacements. The lowland vegetation around Castelo Bay is a mixture of flooded savannah, predominantly covered by grasses, and forests in the higher areas.

Analyzing a historical data set of hydrological level of the Paraguay River at Ladário Station, Soares *et al.* (2008), considered the 2007/2008 hydrological year as normal floods; however, rainfall was above mean values, and generated a significant *decoada* phenomenon in March 2008, which is evaluated in the present study.

2.2. Sampling

Limnological parameters were analyzed at four sampling sites along Castelo Bay (Figure 1), and distributed along a gradient of connectivity with the Paraguay River. The first sampling point was located near (approximately 2 km) the Paraguay River and the last point was located approximately 14.8 km from the Paraguay River in the extreme far portion of the lake. Castelo Bay was chosen for this study because it experiences *decoada* events every year (to a lesser or greater extent and magnitude) and because it is a large area, thereby allowing the evaluation of the role of flood dynamics in the *decoada* phenomenon.

Despite the existence of other studies about the *decoada* phenomenon in the Pantanal, none of them considered an *event* of such magnitude as the one in 2008, which demonstrated the full extent of the changes caused by the processes of decomposition. Results of the analysis of water samples collected in March 2008 (*decoada* period - D) and July 2008 (post-*decoada* period - PD) are presented, with those of the post-*decoada* period sampled after the "recovery" of the system.

The variables analyzed were temperature, hydrogen potential (pH), electrical conductivity, depth, water flow and water transparency, plus the concentration of dissolved oxygen, sulfate, orthophosphate, sodium, ammonia, nitrite, nitrate, total suspended solids, total nitrogen, total phosphorus, total iron and chlorophyll-*a* (Table 1).
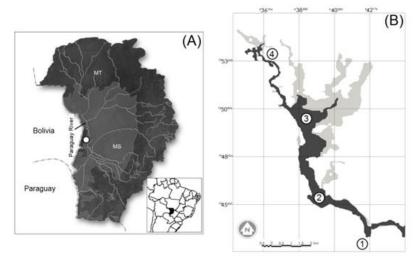
Figure 1. (A) Study area (white dot) located in the Upper Paraguay River Basin, Brazilian Pantanal. (B) Area occupied by Castelo Bay during dry (dark gray) and rainy (light gray) seasons in the Pantanal. Circled numbers indicate the sampling points (Brazil). Abbreviations: MT-Mato Grosso, MS-Mato Grosso do Sul.

Table 1. Evaluated limnological variables and the method of analysis used for characterizing the water during *decoada* and non-*decoada* periods in Castelo Bay, southern Pantanal.

Variables	Methods	References
Dissolved oxygen (mg.L^1)	Equipment electronic Hanna HI 9828	---
pH	Equipment electronic Hanna HI 9828	---
Total nitrogen (mg.L^{-1})	Potassium Persulfate digestion/colorimetric flow injection (FIA)	Wetzel and Likens, 2001; Zagatto, 1981;
Total phosphorus (μg.L^{-1})	Potassium Persulfate digestion/colorimetric flow injection (FIA)	Wetzel and Likens, 2001; Zagatto, 1981; Mackereth *et al.*, 1978
Alkalinity (mg.L^{-1})	Titulometric	Wetzel and Likens, 2001; Gran,1952
Water temperature (°C)	Equipment electronic Hanna HI 9828	---
Total Suspended Solids (TSS) (mg.L^{-1})	Gravimetric method (cellulose filters)	APHA*et al.*, 1998
Water transparency (m)	Secchi disk	APHA *et al.*, 1998
Electric Conductivity (μ.S.cm^{-1})	Equipment electronic Hanna HI 9828	---
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Water flow	Flow meter model Marsh-McBirney 2000	---
Sulfate (μeq.L^{-1})	Turbidimetric method	APHA *et al.*, 1998; 2005
Orthophosphate (μM)	Colorimetric method	Wetzel and Likens, 2001; Mackereth *et al.,* 1978
Sodium (μeq.L^{-1})	Flame spectrophotometry	APHA *et al.*, 1998; 2005
Fe total (μeq.L^{-1})	Atomic absorption spectrometry	APHA *et al.*, 1998; 2005
Chlorophyll-a (mg.L^{-1})	Atomic absorption spectrometry	Wetzel and Likens, 2001
Nitrate, Nitrite, Ammonia	Colorimetric method	Zagatto, 1981; Krug *et al.* 1983; Wetzel and Likens, 2001

2.3. Data analysis

The first analysis performed was the Student's paired t-test to determine which limnological variables are statistically different between *decoada* and post-*decoada* periods.

The second analysis aimed to visualize, in multivariate space, differences in standard limnological variables between sampling sites along a connectivity gradient and between sampling periods, using principal components analysis (PCA). This procedure intended to remove the influence of the different scales of each limnological variable used. The principal components analysis was performed using the rda command in the vegan package.

Complementary to the PCA, we generated a matrix of Euclidean distances among sampling points — the same used in a principal components analysis — which was used to perform a multivariate nonparametric permutational analysis of variance (permanova) to compare differences in limnological variables during and after the *decoada* phenomenon using 9999 permutations to test statistical significance. The permanova analysis was performed using the function adonis in vegan package (Oksanen *et al.,* 2015). All statistical analyzes were performed in the R platform (R Core Team, 2013).

3. RESULTS

Of the eighteen limnological variables considered, only eight exhibited differences between the two analyzed periods (Table 2). During the *decoada* period – D, there was a significant decrease in the mean values of water transparency, dissolved oxygen and nitrite compared to the post-*decoada* period - PD. The variables which tended to have higher values during the *decoada* event were: water temperature, water conductivity, orthophosphate, total nitrogen, total phosphorus and total iron (Table 2). The pH, water flux, sulphate, sodium, nitrate, total suspended solids (TSS), and chlorophyll-*a* did not differ significantly between the periods.

The results of the principal components analysis showed a clear differentiation of *decoada* and post-*decoada* periods based on the limnological characteristics at Castelo Bay, with Axis 1 explaining 58.4% of the variation in the data. Complementary, an effect of connectivity was detected by a gradient in the position of sample sites along Axis 2, which explained 20.3% of the variation in the data.

Higher values of dissolved oxygen, water transparency, nitrite, nitrate and sodium were observed in the post-*decoada* period, but mainly in sampling sites further, and more isolated, from the Paraguay River. Some limnological variables were observed to be not associated with

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any group, in particular chlorophyll-*a* and total suspended solids (Figure 2).

Table 2. Means and standard deviations of limnological variables of Castelo Bay during *decoada* and post-*decoada* periods in southern Pantanal. Paired student t-value and significance codes (ns=non-significant; *=significant to 5%; **=significant to 1% and ***=significant to 0.01%).

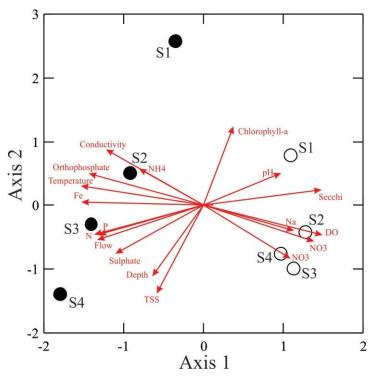| Variable	*Decoada*	Post-*Decoada*	t
Depth (m)	5.85±3.76	5.00±2.57	1.43ns
Water transparency (cm)	0.56±0.15	0.99±0.12	-5.73**
Water temperature	28.00±0.59	20.89±0.19	35.68***
Dissolved oxygen	0.40±19	7.79±0.13	-53.22***
pH	6.86±0.23	7.05±0.21	-1.39ns
Water conductivity	78.25±7.76	50.84±4.19	7.72**
Water Flux	0.05±0.04	0.01±0.01	2.21ns
Sulphate	6.41±1.78	4.90±0.79	1.58ns
Orthophosphate	8.18±0.67	1.87±0.51	13.66***
Na	1.70±0.05	1.82±0.10	-2.00ns
NH4	30.42±10.90	17.33±14.10	1.61ns
NO2	3.55±0.55	6.95±0.50	-7.67**
NO3	-1.19±1.39	3.61±3.20	-2.61ns
TSS	7.48±2.58	6.98±2.08	1.11ns
N total	674.10±56.14	569.30±42.30	4.13*
P total	36.70±6.37	29.30±2.50	1.93ns
Fe total	2.03±0.50	0.52±0.06	6.60**
Chlorophyll a	0.04±0.75	0.01±0.01	0.10ns

Figure 2. Scatterplot of the principal components analysis of four sampling sites during *decoada* (black circles) and post-*decoada* (white circles) in Castelo Bay in southern Pantanal, 2008.

Integrating all limnological variables, the permanova results also showed significant differences between *decoada* and post-*decoada* periods in Castelo Bay (F= 7.03; p= 0.03; r²= 0.54), reinforcing the results of the PCA analysis.

4. DISCUSSION

The results indicate that there are significant differences between the two study periods with respect to some of the limnological variables, analyzed as a result of the *decoada* phenomenon. The rise in water level changes the limnological characteristics of water bodies as a result of interactions between the aquatic and terrestrial environments (Junk *et al.*, 1989; Hamilton *et al.*, 1997; Calheiros and Hamilton, 1998; Oliveira and Calheiros, 2000), due to leakage of water from the riverbeds and drainage channels that reach the floodplain. The *decoada* phenomenon at Castelo Bay can last more than one month and cause significant fish mortality (Calheiros and Hamilton, 1998; Oliveira and Calheiros, 2000; Oliveira *et al.,* 2013), thereby influencing fish density, diversity and species composition, as has been observed in another floodplain region (Bunch *et al.,* 2015)

The land-water interaction due to the annual flood pulse variation is responsible for the levels of dissolved oxygen, such that during flooding of the Pantanal, and especially in the months of February, March and April, the dissolved oxygen could be lower than 3.0 mg.L^{-1}. During *decoada* events, the concentrations of dissolved oxygen can fall from 8 mg.L^{-1} to complete anoxia or 0.0 mg.L^{-1}. In the present study, we observed minimum dissolved oxygen levels between 0.15 and 0.55 mg.L^{-1} during this period, compared to values considered "normal" (7.7 mg.L^{-1}). The decomposition of organic matter resulting from the death of submerged terrestrial vegetation, which had grown in the preceding dry season, and dead aquatic vegetation from the same period, directly affects the dissolved oxygen concentration because of the oxidation processes promoted by the decomposition of vegetation consuming the oxygen in the water column (Hamilton *et al.,* 1997; Calheiros and Hamilton, 1998). The low oxygen concentrations indicate high bacterial activity, originating from the drift of organic matter into the body of water (Motta and Uieda, 1995).

Temperature is another important factor in the process of *decoada*. Normally, at the time of flooding (December to April) high summer temperatures in the Pantanal help accelerate the decomposition, and are therefore indirectly responsible for the lower concentrations of dissolved oxygen during this period, as well as the natural decreasing of gases' dissolution into the aquatic environment. With the entry of cold fronts, the temperature can fall for a few days, slowing down decomposition processes and, consequently, improving the water quality (Oliveira and Calheiros, 2005).

In our study, during the *decoada* a lower dissolved oxygen content (DO = 0.15 mg.L^{-1}) was recorded than in 1994 when a major fish kill was observed (Calheiros and Hamilton, 1998). The observation of many fish breaking the surface to obtain swallow air, together with low levels of dissolved oxygen in the water and an increase in free carbon dioxide, strongly suggests that suffocation is the leading cause of fish death during a *decoada* on the flood plain (Calheiros and Hamilton, 1998).

Any environmental changes can be considered stressful when they are unpredictable and uncontrollable (Schulte, 2014). However, if *decoada* occurred every year at the Pantanal, yet the intensity remained variable, the life cycle of aquatic animals could adapt, and minimize its impact on their populations. For fish, *decoada* are known to cause respiratory distress culminating in mass mortality. Nevertheless, the intensity of hypoxia/anoxia can be explained by the exposed area (subject to grasses covering) and duration of the previous dry period and the velocity of next flooding (Bulhões *et al.,* 2020). Differences in hypoxia have been documented during the *decoada* phenomenon, with lower dissolved oxygen concentration in stagnant, vegetated waters (Calheiros and Hamilton, 1998; Hamilton, 2002). Nonetheless,

smaller fish species (eg. *Odontostilbe* spp., *Pyrhulina australis*, *Aphyocharax* spp., among others) can be encountered in these habitats, suggesting a higher tolerance to hypoxia. On the other hand, the exotic mollusc *Limnoperma fortunei*, which were broadly distributed in Castelo Bay in 2005, disappeared completely after the 2006 *decoada* (Oliveira *et al.,* 2011). Clearly a detailed evaluation of the effects of hypoxia on the distribution of the aquatic animals of the Pantanal is needed (Andrade *et al.,* 2015).

Seasonal hydrologic flood pulses play an important role in the functioning of the ecology and hydrology of floodplain wetlands by supplying sources of nutrients, including carbon and salts. These, in turn, are essential for the maintenance of the structure, composition and biomass dynamics of communities of aquatic organisms and, ultimately, the entire aquatic food chain (Junk *et al.,* 1989), resulting in the provision of ecosystem services such as fisheries (Calheiros and Oliveira, 2011; Calheiros *et al.,* 2012). Considering the many possible scenarios of global warming and possible hydrological alteration in the Pantanal, the dynamics of this ecosystem, like any other, can be altered, and the magnitude and duration of *decoadas* could be modified as well. On the other hand, the construction of hydroelectric power dams (HPD) in the rivers that form the Pantanal Wetland can alter water sediment and nutrient flows as well as the flooding area downstream (Oliveira *et al.,* 2020; Fantin-Cruz *et al.,* 2020). Many rivers are already blocked with 47 dams and 133 HPD are still predicted.

Therefore, a better understanding of this unique phenomenon is of fundamental importance for the development of conservation policies and the management of fisheries resources.

5. CONCLUSIONS

The results corroborate that the *decoada* is a unique limnological phenomenon, a synthesis of hydrological, geomorphological, biogeochemical and ecological interrelationships of the extensive seasonal and spatially flood-pulsed wetland of Pantanal. The extensive flooded area contributes as a self-source of nutrients and ions, and changes the respiratory gases' equilibrium, altering water quality and promoting the regulation of the structure and composition of aquatic organisms.

6. ACKNOWLEDGEMENTS

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