ABES

Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Vegetation dynamics and precipitation sensitivity in three regions of northern Pantanal of Mato Grosso

A dinâmica da vegetação e a sensibilidade à chuva em três regiões do norte do Pantanal mato-grossense

Tonny Jader de Moraes[1], *Nadja Gomes Machado*[2], *Marcelo Sacardi Biudes*[1], *Nelson Mario Banga*[3], *Laís Braga Caneppele*[4]

ABSTRACT

The wet areas of the Pantanal provide important services such as water and carbon storage, improved water quality, and climate regulation. Analysis and monitoring of vegetated land and precipitation on a regional scale using remote sensing data can provide important information for the preservation of the landscape and biodiversity of the region. Thus, the purpose was to analyze characteristics of the green cycle of the vegetated surface and to what extent the vegetated surface responds to the variability of precipitation in the Pantanal. The areas include the regions of Cáceres (CAC), Poconé (POC), and Barão de Melgaço (BAM) in Mato Grosso. Time series of accumulated precipitation (PPT) and NDVI (Normalized Difference Vegetation Index) were used for the period from 2000 to 2016, obtained on NASA's Giovanni platform (National Aeronautics and Space Administration). The analysis of the wavelet transform was applied for NDVI data and there was cross-correlation analysis for PPT and NDVI data. The results showed that the highest correlation between PPT and NDVI was positive with a 1-month lag, but was significant with a lag of up to 3 months. The wavelet analyses showed that the largest wavelet powers occurred at the frequency between 0.5 and 1.3 years, i.e., the NDVI series presented the main variances on the approximately annual scale, indicating that these characteristics are important aspects of local phenology variability, such as cumulative green throughout the year and generalized senescence.

Keywords: NDVI; wavelet; cross-correlation; seasonality.

RESUMO

As áreas úmidas do Pantanal fornecem importantes serviços, como armazenamento de água e carbono, melhoria da qualidade da água e regulação do clima. A análise e o monitoramento da superfície vegetada e da precipitação em escala regional, com uso de dados de sensoriamento remoto, podem oferecer informações importantes para a preservação da paisagem e da biodiversidade da região. Assim, o objetivo deste estudo foi analisar características do ciclo do verde da superfície vegetada e em que medida a superfície vegetada responde pela variabilidade da precipitação no Pantanal. As áreas analisadas compreendem as regiões de Cáceres (CAC), Poconé (POC) e Barão de Melgaço (BAM), em Mato Grosso. Foram usadas séries temporais de precipitação acumulada (PPT) e índice de vegetação *Normalized Difference Vegetation Index* (NDVI) para o período de 2000 a 2016, obtidos na plataforma Giovanni da *National Aeronautics and Space Administration* (NASA). Foram aplicadas a análise da transformada *wavelet* para os dados de NDVI e a análise de correlação cruzada para os dados de PPT e NDVI. Os resultados mostraram que a maior correlação entre a PPT e o NDVI foi positiva com defasagem de um mês, mas foi significativa em até uma defasagem de três meses. As análises *wavelet* mostraram que as maiores potências ocorreram na periodicidade entre 0,5 e 1,3 anos, isto é, as séries de NDVI apresentaram as principais variâncias na escala aproximadamente anual, indicando que essas características são aspectos importantes da variabilidade da fenologia local, como o verde cumulativo ao longo do ano e a senescência generalizada.

Palavras-chave: NDVI; *wavelet*; correlação cruzada; sazonalidade.

[1]Universidade Federal de Mato Grosso – Cuiabá (MT), Brazil.
[2]Instituto Federal de Mato Grosso – Cuiabá (MT), Brazil.
[3]Zambeze University – Beira, Moçambique.
[4]Universidade do Estado de Mato Grosso – Cuiabá (MT), Brazil.
Correspondence address: Tonny Jader de Moraes – Rua 20, 16 – Santa Terezinha – CEP: 78089-758 – Cuiabá (MT), Brazil. E-mail: tonny@fisica.ufmt.br

Conflicts of interest: the authors declare no conflict of interest.
Funding: none.
Received on: 05/18/2021. Accepted on: 11/22/2021
https://doi.org/10.5327/Z217694781132

Introduction

The Pantanal, considered the largest tropical wet area in the world, has numerous rivers and is predominantly covered by different types of savannas and forests characterized by seasonal floods with varying intensities (Junk et al., 2006; Junk et al., 2014). The heterogeneity of the Pantanal is represented, according to Silva and Abdon (1998), by 11 sub-regions based on the flood, relief, soil, and vegetation aspects. The swamp plain has a periodic cycle of droughts and flooding (flood pulse), which plays an essential role in nutrient cycling and carbon sequestration, by preserving organic matter in flooded soils (Erwin, 2009; Hiraishi et al., 2014). These cycles govern all biodiversity and facilitate the development of animal and plant species in the Pantanal (Muniz et al., 2017).

The flood pulse of the Pantanal is controlled not only by local precipitation but also by precipitation in the headlands, where the Paraguay River has access to the Pantanal mainly from the North, in the subregions of Baron de Melgaço and Poconé (Lázaro et al., 2020). The disposition and diversity of species vary in and between different habitats, arranged along the flood gradient, from non-flooding to seasonal and permanently flooded (Junk et al., 2011). Thus, the interannual variability of precipitation also affects the vegetation of these regions differently near the flooded areas, with weaker and defaced responses to precipitation due to local water storage (de Deus et al., 2020).

However, several changes have impacted the biodiversity of the Pantanal, such as the expansion of agricultural activities and hydroelectric development (Bergier, 2013; Ioris et al., 2014), and recent studies based on predictive models also indicate a gradual growth in the frequency of intense precipitation and long periods of stress (Hirabayashi et al., 2013; Marengo et al., 2015, 2021). In addition to these disturbances, the vegetation is highly sensitive to the ocean-atmosphere climatic phenomena El Niño and La Niña, which cause changes in the hydrological cycle (Vicente-Serrano et al., 2013; Hilker et al., 2014; Penatti et al., 2015; Li et al., 2016). Thus, extreme events show that climate change poses a high risk of environmental degradation for the Pantanal and many other wet areas around the world (Thielen et al., 2020).

Knowledge of the current behavior and the possible changes of the cycle of increase and decrease of the green of the vegetation, in response to climatic changes, is fundamental to the understanding of the ecosystem dynamics of the Pantanal. For example, precipitation availability and periodicity are key factors controlling biogeochemical cycles, primary productivity, and vegetation growth and reproduction phenology, while regulating agricultural production (Feng et al., 2013; Baptista et al., 2018). However, more studies are needed, with greater scope, over several long time scales (> 10 years) to understand the complex relationship between precipitation regimens and vegetation, as well as the system's responses to different magnitudes of human and climate pressures (Schulz et al., 2019).

Monitoring of regional environmental data in the Pantanal at a reasonable cost is a challenge due to difficulties in representing the spatial heterogeneity of precipitation and some parameters of vegetation (Penatti et al., 2015). However, orbital remote sensing is an efficient source of data to observe potential impacts that climate change can cause on the Pantanal (Miranda et al., 2018a).

Due to the spectral response characteristic of the vegetation, it is possible to use geoprocessing techniques for its identification and evaluation, which allows obtaining information, such as those of complexity and heterogeneity of the vegetation (Miranda et al., 2018a), changes in the use and coverage of the land (Paranhos Filho et al., 2014; Corrêa et al., 2017), classification of vegetation types (Bispo et al., 2013), the relationship between vegetation indices and soil water content (Danelichen et al., 2016), hydrological dynamics (Penatti et al., 2015) and spatial-temporal variability of vegetation (de Almeida et al., 2015).

Among the vegetation indices we can highlight the Normalized Difference Vegetation Index (NDVI), which is widely used in the evaluation of various biophysical parameters (Tartari et al., 2015; de Morais Danelichen and Biudes, 2020), proving suitable for monitoring phenological changes in plant formations (Miranda et al., 2018a). In addition, NDVI time series are generally non-stationary, i.e. they have different frequency components, such as seasonal variations, long-term and short-term fluctuations, whose analysis of these components cannot be limited to just the average of the series, as these components affect their general structure of variance (Qiu et al., 2013).

In addition to the trend analysis for a time series of vegetation index, the interannual changes may also contain significant information on the response of vegetation to forced weather (Zoffoli et al., 2008; Martínez and Gilabert, 2009). Therefore, different mathematical techniques and statistics can be used to monitor vegetation dynamics from multi-temporal data, among which the analysis of main components (de Almeida et al., 2015) and curve adjustment (Zhang et al., 2006), self-correlating function (Zoffoli et al., 2008) and spectral frequency techniques, such as Fourier analysis (Quiroz et al., 2011; Vourlitis and Rocha, 2011), and, recently, the wavelet decomposition (Soto-Mardones and Maldonado-Ibarra, 2015), which was also used to identify the phenological dynamics of vegetation (Martínez and Gilabert, 2009; Kuplich et al., 2013; Qiu et al., 2013). However, the wave analysis is an efficient resource to expose many characteristics of a time series, such as trends, periodicity, discontinuities, and points of change (Nikhil Raj and Azeez, 2012; Joshi et al., 2016).

The analyses carried out in this study may show whether the green increase of the vegetated surface will respond positively to precipitation on a monthly scale, whether these vegetation responses differ based on local characteristics of the areas, and lastly whether the wavelet analysis can provide relevant information on the vegetation dynamics of northern Pantanal, such as the essential aspects of the temporal variability of surface phenology, that is, the characteristics of the phenological cycle of the vegetated surface.

To understand the different key characteristics related to the phenology of the vegetated surface and to what extent the vegetated surface responds to the variability of precipitation in the northern region of the Pantanal, the objective was: analyzing the periodicity and intensity of the phenology of the vegetated surface at various time scales using the transformed wavelet applied to the NDVI (Normalized Difference Vegetation Index) time series and analyzing the green response of the vegetation of the surface in reaction to the variability of the precipitation through the analysis of cross-correlation, i.e., measuring the degree of association between the monthly average of NDVI and the monthly accumulated precipitation in the region of CAC, BAM, and BAM in the Pantanal.

Materials and methods

Description of the study area

The study areas are in the north of the Pantanal, comprising the southern region of the state of Mato Grosso, located in the central west of Brazil (Figure 1), in the municipalities of Cáceres, Poconé, and Barão de Melgaço. Three quadrants were selected, one quadrant in each of the municipalities of Cáceres, Poconé, and Baron de Melgaço for seasonal monthly NDVI analysis and monthly accumulated precipitation (Figure 1).

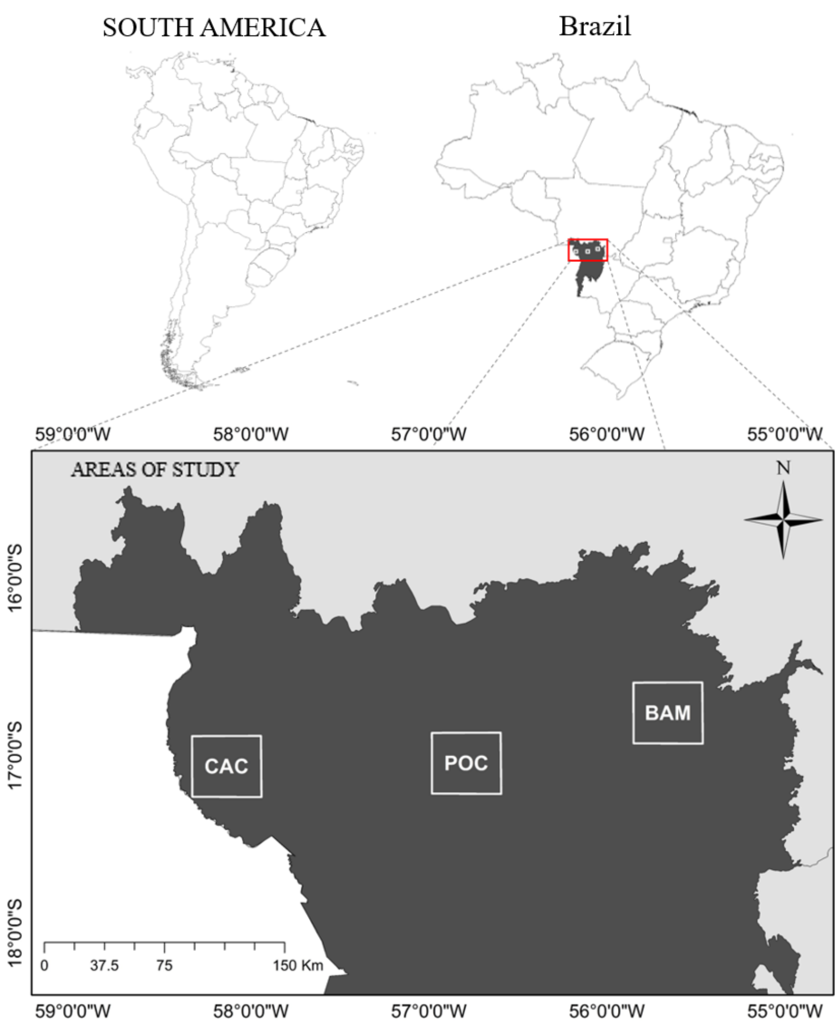

Figure 1 – Location of the Pantanal in Brazil and the areas of study (line in white color) selected respectively in the municipalities of Cáceres (CAC), Poconé (POC) and Barão de Melgaço (BAM).

According to the Köppen classification, the climate of the study area, in the north of the Pantanal, is the Aw, characterized by being warm and humid with precipitation in summer and dry in winter. The annual precipitation is approximately 1,400 mm and there is a marked dry season between May and September. The average air temperature ranges from 29 to 32°C, and the minimum from 17 to 20°C (Machado et al., 2015).

The characteristics of the predominant types of vegetation, soil, location, and sizes of the selected areas in each of the municipalities of Cáceres, Poconé, and Baron de Melgaço (respectively, CAC, POC, and BAM) are described in Table 1.

Products derived from orbital remote sensors used

The analysis of the dynamics of vegetative vigor was based in a monthly NDVI time series from 2000 to 2016, derived from the product MODIS-TERRA MOD13C2, obtained on the platform Giovanni National Aeronautics and Space Administration (NASA), through the link http://giovanni.gsfc.nasa.gov/. NDVI data have a spatial resolution of 0.05° X 0.05° (5600 m) and monthly temporal resolution (Didan, 2015).

Vegetation indices are generally calculated from remote detection data based on the fundamental optical characteristics of vegetation that are strongly absorbent in the red, but highly reflective in the near-infrared (NIR) regions of the solar spectrum (Rouse Jr. et al., 1974; Tucker, 1979). This is possible because vegetation has low reflectance in the visible band (as a function of the absorption of electromagnetic radiation by photosynthetically active leaf pigments) and high in the near infrared (due to the spread of electromagnetic radiation in the internal leaf structure) (Rosemback et al., 2013).

The product (TRMM 3B42 7) of the TRMM (Tropical Rainfall Measuring Mission) mission from NASA's Giovanni platform (site: https://giovanni.gsfc.nasa.gov/giovanni/) was used for the study. The precipitation data have a spatial resolution of 0.25° X 0.25° and monthly temporal resolution (from 2000 to 2016).

Subsequently, cross-correlation analysis was performed on a monthly scale for the monthly average precipitation and NDVI series for the same precipitation data period 2000-2016. Cross-correlations reveal the degree of interconnection between two variables in certain time series (Derrick and Thomas, 2004). The coefficient was used to measure the degree of association between the monthly mean of NDVI and the monthly accumulated precipitation in the region of CAC, POC, and BAM in the Pantanal.

The transformed wavelet

The temporal variations of the NDVI were evaluated using wave analysis, which allows the decomposition of the series as a function of time and frequency, that is, it allows the identification of the main modes of variability and the way they vary over time, as well as analyzes the periodicity at different time scales (Santos et al., 2013). The wavelet transform implements the decomposition of a signal at different spatial or temporal scales into a set of basic functions. It has been widely applied in remote sensing data analysis (Galford et al., 2008; Martínez and Gilabert, 2009; Quiroz et al., 2011; Kuplich et al., 2013; Shihua et al., 2014; Fontana et al., 2015).

The set of basic functions {ψ a, b (t)}, can be generated by translating and staggering the so-called parent wave (t), according to the Equation 1:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi(\frac{t-b}{a}) \quad (1)$$

where a is the "dilation" parameter used to change the scale, and b is the translation parameter used to slide in time. The spectral frequency technique of the wavelet transform (or wavelet) is a relatively recent tool in trend detection studies and there are few studies based on the wavelet technique (Pandey et al., 2017). The main idea of the wave transformation is to analyze a signal or time series according to different scales or resolutions (Martínez and Gilabert, 2009), so the main advantage in using this technique concerning time methods is to investigate the variability of variables in a range of time and frequency scales (Rhif et al., 2019).

In this study, the wavelet transform was applied through the DOG (Derivative of Gaussian) parent function with parameter 2 and a significance level of 0.05. The DOG function was chosen for greater precision in the time domain as compared to frequency (Farge, 1992;

Table 1 – Areas of study and types of vegetation and soil.

Área	Sub-Region	Coordinates of studied polygons	Study Area (Km²)	Vegetation	Soil
Cac	Cáceres	17°13' S; 58°22' W 16°52' S; 57°56' W	1580	Savana, with pioneering formations of river influence near the Paraguay River, grassy savannah, shrubby savannah and forest formations	sandy
Poc	Poconé	17°13' S; 56°59' W 16°51' S; 56°35' W	1580	Cerrado, vegetation under river influence and forest formations	clay
BAM	Barão de Melgaço	16°56' S; 56°51' W 16°34' S; 55°27' W	1580	Shrubby cerrado, wooded savanna and vegetation under river influence	sandy

Source: adapted from Silva and Abdon (1998) and Paranhos Filho et al. (2014).

Torrence and Compo, 1997; Santos et al., 2013), and also made it possible to represent a time series through a time-frequency diagram called a scalogram (Mallat, 2008). The coefficients are defined by the color scale, the blue color representing less intensity of the wave coefficient, energy, or power, and the red color representing greater power. Thus, the wave analysis was applied using the algorithm available in http://paos.colorado.edu/research/Wavelets, for the code, and the Matlab Software was used.

Results and Discussion

Seasonal dynamics of precipitation and NDVI

Seasonal trends were observed in the monthly accumulated precipitation time series and the monthly average of NDVI, with approximately coincident maximum and minimum values for the analyzed regions (Figure 2). The monthly precipitation accumulated during the wet season represented approximately 63% of the annual total sum in

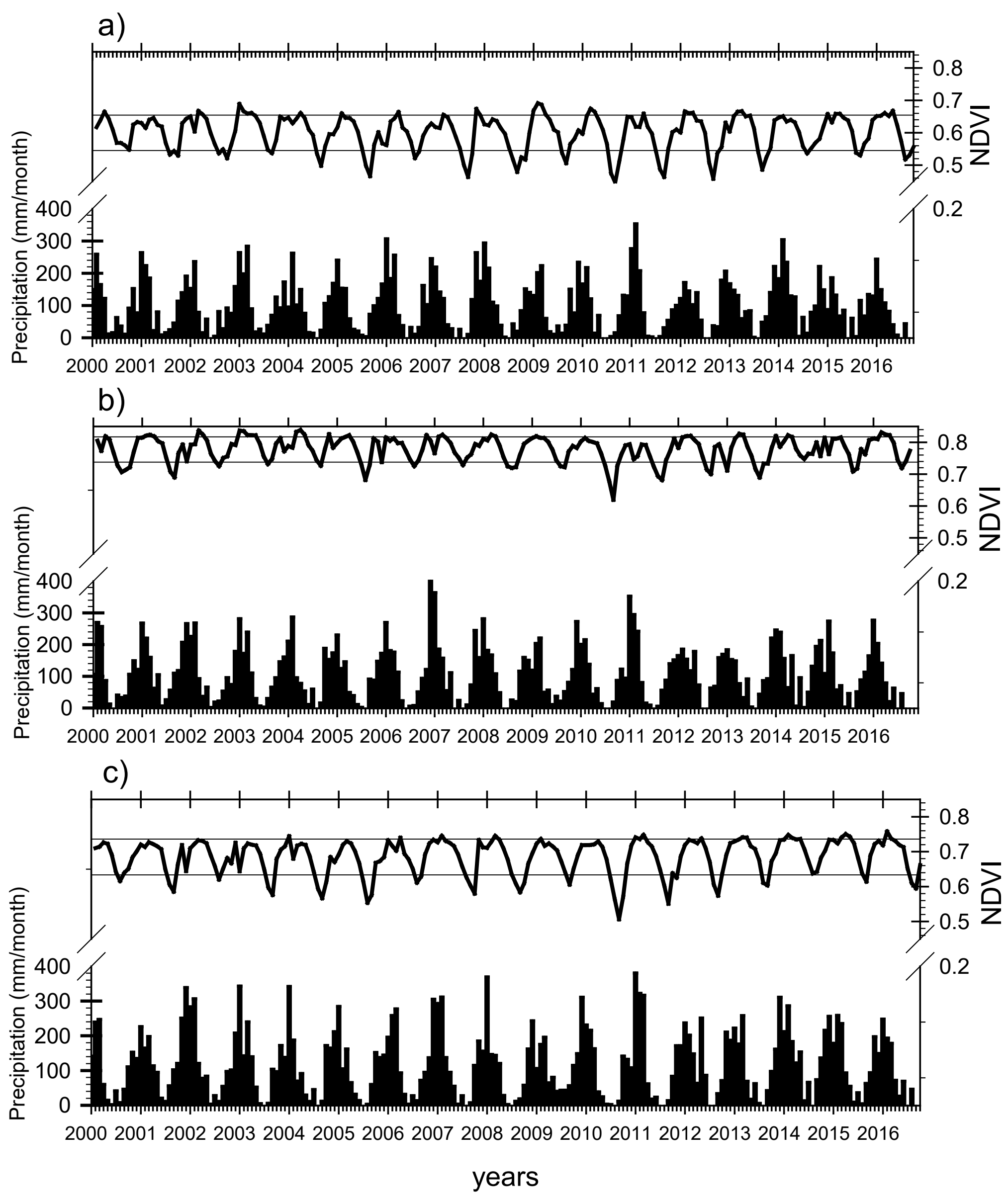

Figure 2 – Monthly seasonal change of NDVI and Precipitation of the period 2000-2016, the line (in black) represents the lower and higher limits of the standard deviation of the period average. (A) Cáceres – CAC, (B) Poconé – POC, and (C) Barão de Melgaço – BAM, in the northern region of the Pantanal in the State of Mato Grosso.

RBCIAMB | v.57 | n.1 | Mar 2022 | 125-136 - ISSN 2176-9478

the BAM, 73% in the CAC, and POC (Figure 2). These seasonal patterns occurred synchronously for the regions analyzed and were consistent with the climatology of the region (Biudes et al., 2012; Machado et al., 2015; Novais et al., 2015; Penatti et al., 2015).

The synchronicity of the seasonal pattern of precipitation is associated with a unimodal pattern with precipitation occurring throughout the Upper Paraguay basin (Ivory et al., 2019). During the wet period, the South Atlantic Convergence Zone (ZCAS) is associated with a convergent moisture output from the Amazon to the Brazilian Southeast, which is responsible for extreme precipitation events (Rao et al., 1996).

Moreover, as observed in Figure 2, the seasonal cycle of vegetation follows the pattern of annual variability of precipitation in the Pantanal, with the river line and greenness coinciding with the beginning of the rains (de Almeida et al., 2015). These patterns indicates that vegetation phenology tends to follow relatively well-defined temporal patterns (Fontana et al., 2015; Schwieder et al., 2018). Also, according to de Almeida et al. (2015), the cycle of vegetation observed by the NDVI of the Pantanal regions can be explained by two factors together, the seasonal pattern of precipitation and the seasonal pattern of floods.

Observing the variability of the average monthly precipitation between the regions, the CAC values corresponded to the maximum value of 212.19 mm in February and a minimum of 15.4 mm in June (Figure 2A), while the mean value is 99.9 ± 11.4 (mean ± standard deviation). In the POC area, the average monthly precipitation was 229.7 mm/month in January (Figure 2B), a minimum of 16.5 in August, and an average of 107.6 ± 12.3 (average ± confidence interval). Finally, in the BAM area the average monthly precipitation was the maximum of 252.4 mm/month in January (Figure 2C), a minimum of 11.9 in August, and the mean value was 116.2 ± 13.5. These differences observed in the monthly precipitation values between the regions analyzed CAC and POC, POC and BAM may be related to the difference in the amount of precipitation over the Upper Paraguay watershed, where the largest precipitated amounts occurred in the northern and eastern regions of the basin (Penatti et al., 2015; Macedo et al., 2019), strongly influenced by regional differences (Bergier et al., 2018).

There was greater standard deviation and greater predominance of below-average values (observing the bottom line of the standard deviation of Figure 2A) in the minimum NDVI phase (average September 0.51 ± 0.02) in CAC (2005, 2007, 2008, 2010, 2011, 2012 and 2013) as compared to BAM areas (0.59 ± 0.02) (2004, 2005, 2010 and 2011) and POC (0.71 ± 0.02) (2005, 2010, 2011 and 2013) (Figure 2). Higher variability (standard deviation) and higher predominance of lower-than-average NDVI values (0.51 ± 0.02) of CAC can be explained by the greater sensitivity of planted, natural and arable pasture areas to rainfall, although precipitation and NDVI are approximately synchronous in the region, vegetation responses differ based on the geographic location of the flooded areas (Ivory et al., 2019). However, the lowest standard deviation of the NDVI and the lowest prevalence of extreme values (Figure 2B) in POC may be related to local characteristics, such as being close to river flows and bodies of water (Miranda et al., 2018a; Ivory et al., 2019). The lower mean NDVI in the CAC may also be related to high ligneous mortality rates, which favors the development of grass species (Lehmann et al., 2011; Miranda et al., 2018b), and human interference (Wessels et al., 2004; Jacquin et al., 2010). On the other hand, the highest NDVI value in POC may be related to the influence of precipitation, as the highest precipitated values occurred in the northern and eastern regions of the Upper Paraguay basin (Penatti et al., 2015; Macedo et al., 2019).

The temporal patterns of NDVI were approximately sinusoidal with the maximum value in March and April, an intense decline from the end of April until the phase of minor NDVI in August, and resuming the increase in October completing the formation of the cycle (Figure 3). According to Zhang et al. (2006), these points of change in the curvature of the monthly NDVI averages of Figure 3 correspond to the transition dates of a phenological cycle of the vegetated surface, which does not change abruptly, but gradually, such as senescence, Greenup, dormancy, and maturity. This vegetative development is determined by the continuous increase of green biomass until reaching a maximum quantity (Fontana et al., 2015). For example, in deciduous vegetation in many crops, the emergence of leaves tends to be followed by a period of rapid growth, followed by a relatively stable period of maximum foliar area (Dalmolin et al., 2015; Schwieder et al., 2018).

Based on the standard deviation to the second of the year (period of 2000-2016) in Figure 3, the greatest variabilities occurred in the phase of decrease and increase of the NDVI (dry period and beginning of wet period). However, the smallest deviations occurred in the phase of maximum NDVI (March, April, and May). The greater variability of NDVI in the dry period may be related to the change in the availability

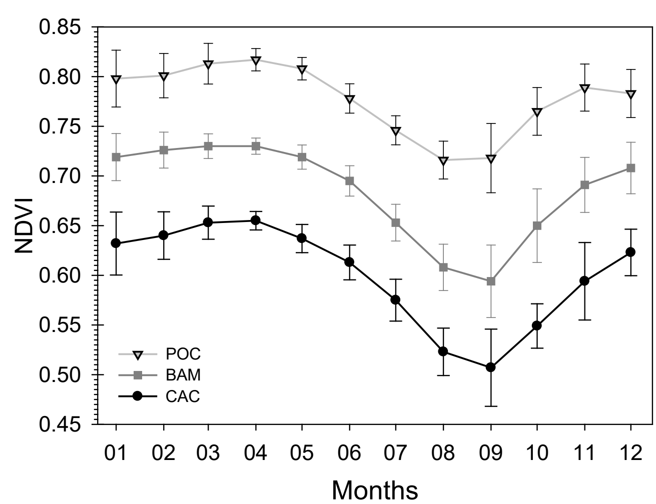

Figure 3 – Monthly average and standard deviation of the NDVI from the period 2000-2016, in three areas of study, Cáceres (CAC), Poconé (POC) and Barão de Melgaço (BAM), in the northern region of the Pantanal in the State of Mato Grosso.

of soil water due to the difference in the amount of precipitation between years (Miranda et al., 2018b). Due to the lower water availability during dry season, early senescence may occur causing more severe and longer dormancy period, as an artifice to maximize the carbon gain, increasing the rates of carbon assimilation of vegetation when the first rains begin (Franco et al., 2005; Rossatto et al., 2009).

So, the biggest difference in the intensity and the variability of the NDVI in the regions of CAC, POC, and BAM can be associated with strategies of use of the water, in other words, gramineous like those in the CAC region are considered intensive explorers, while in the trees and shrubs of forests of POC and BAM, explorers are spread out (Burgess, 1995). Therefore, grasses with dense and shallow root systems make use of provisional water available in the upper layer of the soil, while trees, which have root systems that enter the shallow and deep layers of the soil, have a more constant supply of water in the soil (Scanlon et al., 2002).

The data from the analysis of the cross-correlation between monthly accumulated precipitation and monthly mean NDVI are provided in Table 2 for CCS, POC, and BAM regions for the period from 2000 to 2016. The correlation coefficients of the sites were positive and significant in up to a 3-month lag, however, the maximum correlations occurred with a one-month lag between precipitation and NDVI (Table 2). The greatest correction between precipitation and NDVI was for the BAM region ($\beta = 0.71$, $p < 0.001$), followed by CAC and CDVI (respectively, $\alpha = 0.69$ and $\beta = 0.64$ $p < 0.001$). Thus, the results of Table 2 indicate the strong synchronicity of precipitation between CCS, POC, and BAM regions. In addition, vegetation productivity is out of phase with a delay of at least one month regarding precipitation (Ivory et al., 2019). The higher coefficient of CAC and BAM, as mentioned above, may be related to the greater dependence of vegetation on precipitation, since in the Pantanal, differences in vegetation type and soil cover can result in a strong dependence on climate or local conditions (Viana and Alvalá, 2011; Ivory et al., 2019).

Other studies (de Almeida et al., 2015; Penatti et al., 2015; Ivory et al., 2019) indicate that the seasonal pattern of vegetation productivity in the Pantanal is heterogeneous and complex in its relation to the regional climate, such as Penatti et al. (2015), as compared to the time series of EVI, precipitation and water storage in the Pantanal in the Upper Paraguay basin, and observed a strong relationship between precipitation and vegetation variability, and, in addition, water storage time in different regions of the basin varies based on geomorphology, soil type and plain drainage (Ivory et al., 2019).

NDVI analysis by wavelet transformation

Figures 4A, 5A and 6A show that the highest concentrations of wave powers (ranging from -1 to 1, from light blue to dark red) of NDVI in the Wave Power Spectrum (WPS) were significant, as they occurred within the line-delimited region (blue) representing the level of significance. These major wavelet powers occurred periodically between 0.5 and 1.3 years, indicating that the CAC NDVI series, POC, and BAM have a strong annual variation throughout 2000 – 2016. It is also observed (Figures 4B, 5B, and 6B) that the time series of the average scale (selected for the period range of 0.3 to 1.3 years) has a Gaussian distribution, centered on the peak of the drought, coincident with the generalized senescence.

The annual periodicity observed in Figure 4A, also observed in Figures 2A and 3A, may be associated with the essential aspects of the spatial-temporal variability phenology of the vegetated surface of these sites, that is, the cumulative green throughout the year (Fontana et al., 2015; Schwieder et al., 2018). The higher power intensity (Figure 6A) and the higher variance (Figure 4B) in CAC, as compared to POC and BAM, may be associated with greater variability of vegetation productivity due to a greater influence of the climax of the drought season (de Almeida et al., 2015).

It was observed in Figures 4B and 6B that there was greater variance and greater predominance of higher power intensities for CAC and BAM (in the years 2005, 2007, 2008, 2010, 2011, 2012, and 2013) as compared with the area of POC (Figure 5B). The higher mean-variance and higher predominance of higher power intensities of CAC and BAM, as mentioned above, may be related to the greater dependence of vegetation on precipitation, but other authors also attribute the higher sensitivity of these areas to extreme weather events such as El Niño, for example. Gris et al. (2020) analyzed the influence of precipitation on an arboreal species (*Erythrina fuscano*) in the Cáceres region and

Table 2 – Cross-correlation between Precipitation and NDVI.

lag (month)	Places		
	CAC	POC	BAM
All correlations are significant for p < 0.001			
0	0.66*	0.59*	0.68*
1	0.69*	0.64*	0.71*
2	0.57*	0.50*	0.55*
3	0.29*	0.22*	0.27*

*$p \leq 0.001$

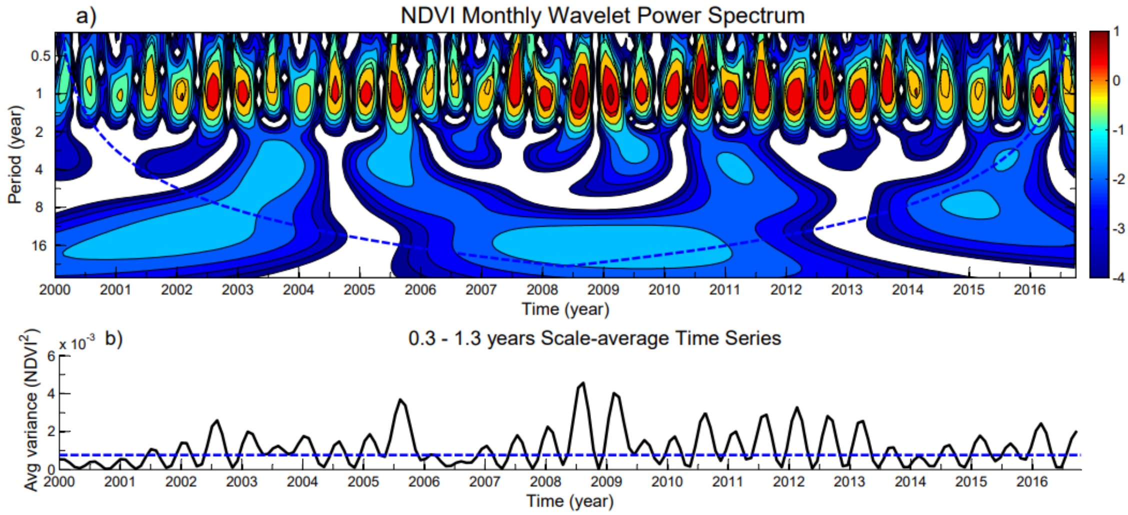

Figure 4 – (A) The wave power spectrum of NDVI for the Cáceres region (C) from 2000-2016. The region bounded by the U-shaped curved line represents the cone of influence (level of 5% significance). (B) Time series of the average band scale 0.3-1.3 years. The line dashed in blue is the 95% confidence level.

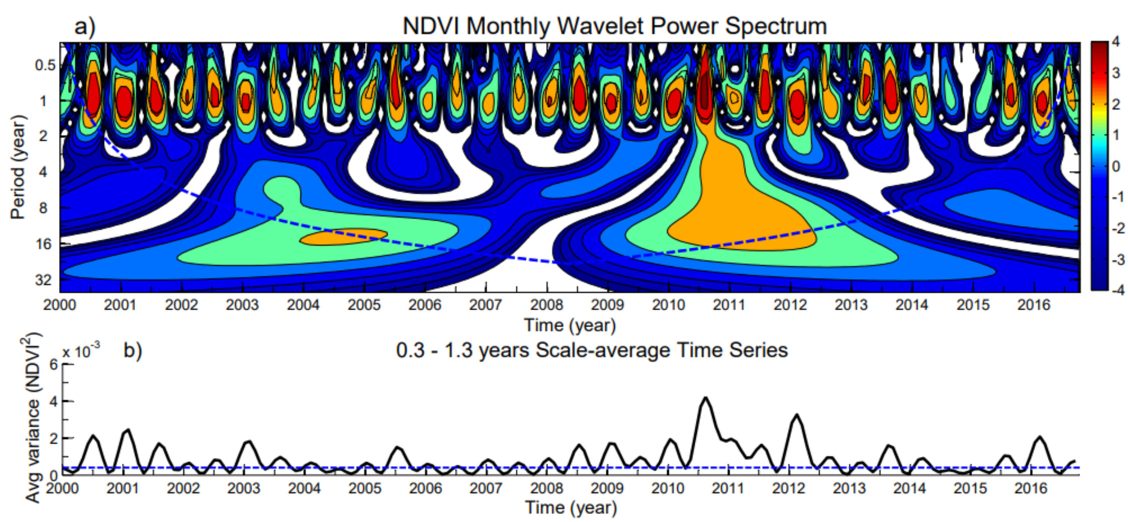

Figure 5 – (A) The wave power spectrum of NDVI for the Poconé region of 2000-2016. The region bounded by the U-shaped curved line represents the cone of influence (level of 5% significance). (B) Time series of the average band scale 0.3-1.3 years. The line dashed in blue is the 95% confidence level.

observed that El Niño events reduce precipitation in the Pantanal, and in turn result in a decrease in the growth of individuals.

Also, Fortes et al. (2018) identified that El Niño events significantly reduced precipitation in the Pantanal and resulted in a drop in trunk diameter increment for arboreal species *V. divergens*. Thus, the occurrence of El Niño may result in a decrease in precipitation compared to the neutral period (Moura et al., 2019) and, consequently, with the reduction of precipitation, the ecosystems respond in a highly plastic way to the availability of water (Hilker et al., 2014).

Average variance values on the 0.3 to 1.3 positive years scale have a Gaussian distribution (Figures 4B, 5B, and 6B) starting approximately in May, peaking in September, and ending in October. This temporal variation of the series, centered on the peak of the drought, coincides with the generalized senescence, the rift, and the greening of the vegetation of the regions, as seen in Figures 2 and 3. Thus, the series also exhibits an annual cycle and may be associated with a phenological variation of the vegetated surface (Penatti and Almeida, 2012).

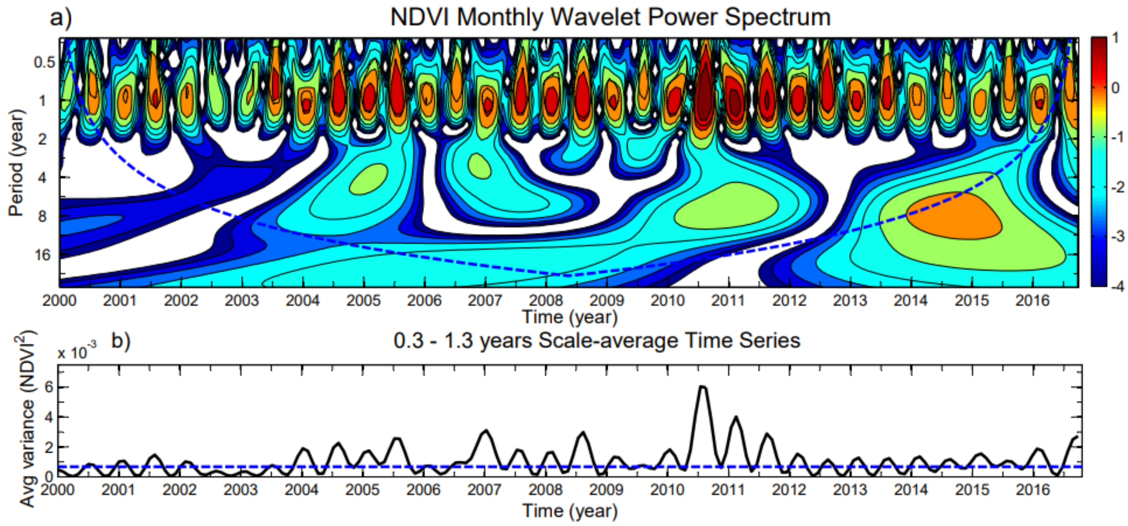

Figure 6 – (A) The wave power spectrum of NDVI for the Barão de Melgaço (BAM) sub-region 2000-2016. The region bounded by the U-shaped curved line represents the cone of influence (level of 5% significance). (B) Time series of the average band scale 0.3-1.3 years. The line dashed in blue is the 95% confidence level.

Conclusion

The cycle of increase and decrease of the green of the vegetation follows the pattern of annual variability of precipitation in the Pantanal and the rift and greenness (greenness) coincident with the beginning of the rains. In addition, it was observed that the seasonality of precipitation is synchronized and is related to a strongly unimodal pattern with precipitation occurring throughout the Upper Paraguay basin.

In the NDVI time-series Profiles, of CAC, POC and BAM, an intense decline occurred from April until the phase of lower NDVI in August., These points of change in the curvature of the monthly averages of NDVI may correspond to the transition dates of a phenological cycle of the vegetated surface, which changes gradually, such as senescence, Greenup, numbness, and maturity.

The correlation between precipitation and NDVI for CAC, POC, and BAM was positive and significant in up to 3 months of lag. However, maximum correlations occurred with a 1-month lag. The greatest correction between precipitation and NDVI was for the BAM region, followed by CAC and POC, respectively. Thus, the results indicate the strong synchronicity of precipitation between CAC, POC, and BAM regions. In addition, vegetation productivity is out of phase with a delay of at least one month regarding precipitation. These results may be indicative that the seasonal relationships between precipitation and vegetation productivity differ based on the position relative to flooded areas.

The largest wavelet powers occurred periodically between 0.5 and 1.3 years, indicating that the NDVI time-series for CAC, POC, and BAM has a strong annual variation throughout the 2000-2016 period. The annual periodicity observed in CAC, such as those of POC and BAM, may be associated with the essential aspects of spatial-temporal phenology variability of the vegetated surface of these sites, i.e., cumulative green throughout the year. And the higher power intensity and the higher variance in CAC as compared to POC and BAM may be associated with greater variability in vegetation productivity due to a greater influence of the climax of the drought season.

Acknowledgements

We thank CAPES for its financial support to the research group of the Postgraduate Program in Environmental Physics at *Universidade Federal de Mato Grosso*. NASA EOSDIS Land Processes Distributed Active Archive Center (DAAC), USGS/Earth Resource Observation and Science Center (EROS), for NDVI (MOD13C2 v006) and Tropical Rainfall Measuring Mission (TRMM) products (2011).

Contribution of authors:

Moraes, T.J.: Formal Analysis, Methodology, Resources, Software, Writing – Original Original Draft, Writing – Review and Editing. Machado, N.G.: Funding Acquisition, Project Administration. Biudes, M.S: Supervision, Validation, Visualization, Writing – Review and Editing. Banga, N.M.: Conceptualization; Data Curation; Investigation. Caneppele, L.B.: Conceptualization; Data Curation; Investigation.

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