SPECTRAL RESPONSE VARIATIONS AS INDICATORS OF SEASONAL FLOODS IN PANTANAL USING SPOT-VEGETATION TIME SERIES

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Abstract

Pantanal is Brazil's major wetland, and its main feature is the seasonal floods. The purpose of this study was to evaluate spectral response variability as an indicator of seasonal floods in Pantanal. We analyzed SPOT-Vegetation's NDVI (Normalized Difference Vegetation Index) in comparison to the historical standard (1998 to 2012) for each pixel and ten-day period, and compared it with the standardized rainfall estimates from TRMM (Tropical Rainfall Measuring Mission). The methodology used allows verifying how much the vegetation cover was above or below its normal behavior, enabling comparisons among different regions due to data standardization. We verified that the Standardized Vegetation Index (SVI) was an indicator of variability of seasonal floods for the Pantanal biome in the dry and rainy seasons of 2011/2012. We also verified a delay in the vegetation spectral response to water conditions. During the rainy season, the SVI was higher than normal due to the rainfall anomalies which led to a lower water layer thus causing an increase in NDVI. The analysis confirms that SVI and satellite-estimated rainfall anomalies were efficient indicators of flood variability in Pantanal.

Key words: Standardized Vegetation Index. SPOT-Vegetation. Rainfall. TRMM. Pantanal.

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Resumo

Variações da resposta espectral como indicador da dinâmica das inundações sazonais do Pantanal a partir da série histórica do SPOT-VEGETATION

O Pantanal é a principal área alagada do Brasil, e sua característica principal são as inundações sazonais. O objetivo deste estudo foi verificar a variabilidade da resposta espectral como indicador da dinâmica das inundações sazonais no Pantanal. Foi analisado o NDVI *(Normalized Difference Vegetation Index)* do SPOT-Vegetation em relação ao padrão histórico (1998 a 2012) para cada pixel e decêndio, e comparado com as estimativas de precipitação padronizada do TRMM *(Tropical Rainfall Measuring Mission).* A metodologia utilizada permite verificar o quanto a cobertura vegetal ficou acima ou abaixo do comportamento normal da vegetação, possibilitando realizar comparações entre diferentes regiões, devido à padronização dos dados. Verificou-se que o Índice de Vegetação Padronizado (IVP) foi um indicador da variabilidade das inundações sazonais no bioma Pantanal nos períodos seco e chuvoso, de 2011/2012. Verificou-se defasagem na resposta da vegetação às condições hídricas. No período chuvoso de 2011/2012, o IVP ficou acima do normal em decorrência da anomalia negativa de precipitação, que acarretou menor lâmina de água e, consequentemente, causou aumento do NDVI. As análises comprovam que o IVP, assim como anomalias de precipitação estimadas por satélite, foram eficazes como indicadores da variabilidade das cheias no Pantanal.

Palavras-chave: Índice de Vegetação Padronizado. SPOT-Vegetation. Precipitação. TRMM. Pantanal.

INTRODUCTION

The Pantanal biome is the largest tropical wetland area on the planet, and it is seasonally flooded by the Paraguai river and its tributaries (ABDON, 2004). This biome is characterized by the drought and flood cycles (flood pulse), and its annual flood cycle encompasses approximately 30% of its territory (ANDRADE et al., 2012). Overall, the flood regime influences the main biotic and abiotic processes, as well as the species composition in the landscape units (ADAMI et al., 2008). In the drought period, for example, several seasonally flooded areas are used for extensive beef cattle rearing (ABDON et al., 2007).

Interannual rainfall variability influences the flooding patterns. The historical climate instability, with a history of severe pluriannual flooding and extreme drought events, affects animal habitats as well as community structure, population size and behavior (ALHO e SILVA, 2012).

Variability indicators of the floods in Pantanal are of great social-economic importance for the region, for they enable planning not only livestock rearing, which is Pantanal's most important economic activity, but also fishery, tourism and navigation (GALDINO, 2000).

The characterization of current conditions and changes in land surface may be assessed using data from sensors aboard orbital platforms, which provide wide spatial and temporal coverage (ANDRADE et al., 2011). Thus, vegetation indices obtained using remote sensing techniques have been extremely useful in the monitoring of land use and land cover. Vegetation indices may be used in studies which characterize vegetation dynamics, thus aiding in the identification of land cover (VICTORIA et al., 2009), and in mapping and studying the expansion of agricultural areas (MORTON et al, 2006; VICTORIA et al., 2012).

The Normalized Difference Vegetation Index (NDVI), proposed by Rouse et al. (1973), is one of the mostly used to analyze land cover. It explores the contrast in reflectance values of the red and near-infrared channels, and is sensitive to the biophysical characteristics of vegetation (LIU et al., 2010).

The ten-day NDVI product of the Vegetation (VGT) sensor aboard the SPOT satellite specifically performs vegetation imaging. Despite its low spatial resolution (1 km), the sensor's spectral bands were conceived specifically to monitor vegetation in large areas, and works within the following wavelength ranges: 0.43-0.47 μm (blue), 0.61-0.69 μm (red), 0.78-0.89 μm (near infrared) and 1.58-1.68 μm (mid infrared).

Aiming at quantifying anomalies in the form of standard deviation to the average, we obtained the Standardized Vegetation Index (SVI). This estimate proposed by Park et al. (2008) enables verifying how much the land cover is above or below the regular vegetation behavior, thus making comparisons among different regions possible due to the data standardization. The SVI monitoring for the Pantanal biome was obtained from SPOT-Vegetation time series by means of the standardization of the ten-day NDVI of the 1998 to 2012 time series.

In the absence of a dense network of pluviometers in Pantanal, the TRMM (Tropical Rainfall Measuring Mission) sensor is a good alternative for obtaining rainfall estimates. The TRMM sensor is a project jointly developed by the North-American National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), and was launched on November 27, 1997, with the specific aim of monitoring and studying rainfall at the tropics, as well as of verifying how it affects the global climate. The TRMM project generates several products (estimates) according to the instrument combination used in the calculation algorithm. Collischonn et al. (2007) showed that the TRMM sensor's rainfall estimate is quite precise when compared to soil data on the Alto Paraguai watershed.

Thus, the purpose of this study was to verify the variability of seasonal floods in Pantanal using a SPOT-Vegetation sensor's time series. In order to do so, we analyzed the vegetation index's relationship to the historical standard for each pixel and ten-day period of SPOT-Vegetation's NDVI product, and compared it to the standardized TRMM rainfall estimates for the dry and rainy periods.

MATERIAL AND METHODS

The study area was delimited by the Pantanal biome, and encompassed 150,355 km^2 (ABDON et al., 2007), occupying 1.76% of the Brazilian territory according to data from the Brazilian Institute of Geography and Statistics (IBGE) (Figure 1). According to Silva and Abdon (1998), Pantanal is a floodable area and occupies a total of 138,183 km^2. This biome lies on a continuous Brazilian plain, and has an average altitude of 100 m which varies from 60 m at its central region up to elevations above 500 m. The average altitude at the plain varies from 60 to 150 m. Besides, the average annual rainfall rate is of 1,400 mm, varying from 800 to 1,600 mm. The rainy period concentrates about 70-80% of the annual average rainfall, and the highest rainfall rates are observed at the plateau. The annual average temperature varies between 22 and 26ºC (ANDRADE et al., 2012).

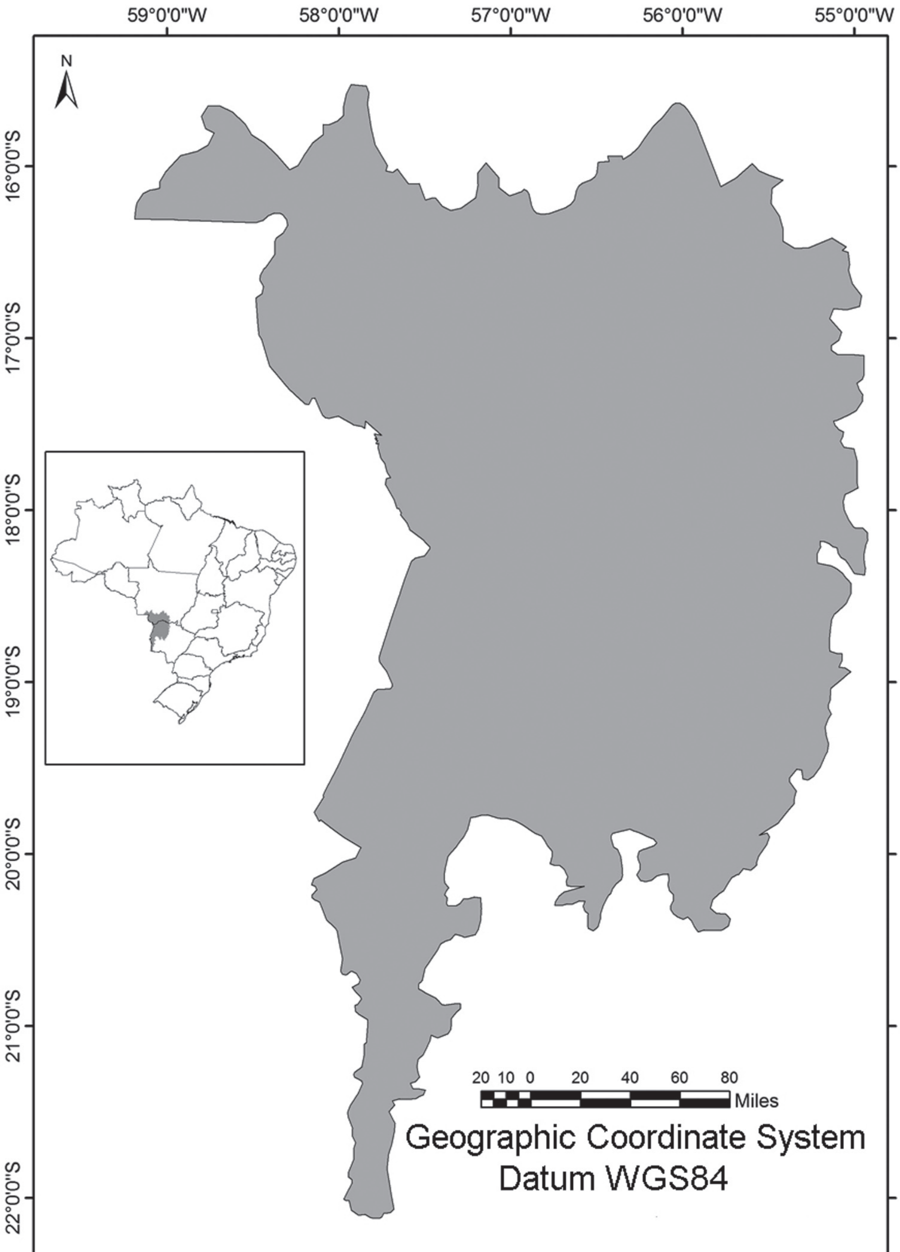

Figure 1 - Location of the study area

In the present work, we have studied the influence of flood seasonality on vegetation's spectral response in two periods in comparison to a SPOT-Vegetation's NDVI time series from 1998 to 2012. For the analysis, we considered as dry the period between April and September 2011, and as rainy the period from October 2011 to March 2012.

The SPOT-Vegetation (VGT) product used was V2KRNS10, which provides a ten-day synthesis of the NDVI and is obtained from the maximum value of the vegetation index observed during the temporal composite period (10 days) for each pixel in the image, method known Maximum Value Composite (MVC). Since the product is a ten-day synthesis, there is also less cloud contamination in the images, due to the qualitative selection of the NDVI values along the ten-day period. V2KRNS10's radiometric resolution is of 8 bits and its spatial resolution is of 1 km. The conversion of the image's digital values to NDVI values was performed using the following equation:

$$NDVI = (0.004 \times NC) - 0.1$$

Where NC is the gray level of each pixel.

To assess the quality of the NDVI data, we used the Status Map (SM) product, which acts as a filter, eliminating problems caused by clouds, shadows, among others. After we performed the corrections to the NDVI series, the data became distributed along the -0.1 and 0.92 ranges.

Then, we applied the method proposed by Park et al. (2008) and obtained the Standardized Vegetation Index (SVI) from the NDVI series of 1998 to 2012, which enabled quantifying the difference in the vegetation index value of a given ten-day period and the average long-term value for that same period.

To obtain the SVI, we had to generate the average NDVI images for each ten-day period, from April 1998 to March 2012. From there, we obtained the land cover anomalies in comparison to the time series of the analyzed period, i.e. how much the vegetation's vigor was above or below the average for the ten-day period studied. The SVI was obtained using:

$$SVI_{10-day} = \frac{NDVI_{10-day} - NDVI_{10-day\,avg}}{\sigma_{10-day}}$$

Where $SVI_{10\text{-}day}$ is the standardized vegetation index for the ten-day period studied; $NDVI_{10\text{-}day}$ is the vegetation index for the ten-day period studied; $NDVI_{10\text{-}day\ avg}$ is the average vegetation index for the ten-day period considering the whole data period; $\sigma_{10\text{-}day}$ is the vegetation index's standard deviation for the ten-day period considering the data of the whole period (1998 to 2012). The SVI values were categorized according to table 1, and show vegetation index values from far below normal (SVI $\leq$ -2) to far above normal (SVI $\geq$ 2).

We presented the results as standard deviation towards the average, i.e. vegetation anomaly towards the average, which enabled assessing the spatial distribution of the SVIs. The green scale corresponds to NDVI values slightly above normal, above normal and far above normal respectively, and means that the NDVI value is above expectation for the place and ten-day period analyzed. The areas shown in yellow are normal, i.e. the area's NDVI is similar to the average of the 1998/2012 period for the given pixel. Orange, red and dark red tones correspond to areas with NDVI slightly below normal, below normal and far below normal respectively. Gray tones show areas for which no data were obtained due to the presence of clouds or noisy pixels, eliminated during the preprocessing phase.

Table 1 – Ranges of Standard Vegetation Index (SVI) and TRMM´s standardized rainfall (SPI)

Values of SVI and SPI	Ranges	Legend
SVI or SPI ≤ - 2,0	Far below normal	Dark Red
-2,0 < SVI or SPI ≤ -1,5	Below normal	Red
-1,5 < SVI or SPI ≤ -1,0	Somewhat below normal	Orange
-1,0 < SVI or SPI ≤ 1,0	Normal	yellow
1,0 < SVI or SPI ≤ 1,5	Somewhat above normal	Light green
1,5 < SVI or SPI < 2,0	Above normal	Green
SVI or SPI ≥ 2,0	Far above normal	Dark green

For each ten-day period, we determined the average SVI variation along time by associating the SPOT-Vegetation's ten-day images to the reference map, which enabled determining the SVI for each place (pixel). We analyzed the SVI in comparison to the rainfall rate estimated by TRMM's product 3B43, which is obtained from microwave rainfall estimates by the TRMM Microwave Imager (TMI) and corrected using information on the vertical structure of the clouds, obtained from the Precipitation Radar (PR).

We estimated the rainfall temporal deviations using the Standardized Rainfall Index (SRI), which expresses the difference in rainfall for a given period in comparison to the average rainfall for that period, normalized by the standard deviation:

$$SRI = \left(\frac{P_{mi} - P_i}{\sigma_{P_i}} \right)$$

Where P_{mi} is the rainfall for a given year within period *i*, P_i is the long-term average rainfall for period *i*, and σ_{Pi} is the rainfall standard deviation for period *i*, which refers to the period from April 1998 to March 2012.

The rainfall data used to calculate the SRI were obtained from the monthly rainfall estimates produced by the TRMM sensor, product 3B43, which were obtained by ftp at http://daac.gsfc.nasa.gov/data/. Their spatial resolution is 0.25° x 0.25° (approximately 25 km) and they correspond to the accumulated monthly rainfall estimates adjusted from data of a world network of rainfall seasons.

Aiming at assessing Pantanal biome's humidity deficit, we analyzed Spot-Vegetation's ten-day period Normalized Difference Water Index (NDWI) (GAO, 1996), which is obtained by the ratio between the differences in near-infrared (ρIV) and mid-infrared (ρMIR) reflectances and their sum.

RESULTS AND DISCUSSION

We performed the monitoring of Pantanal's plant cover using the vegetation index's analysis in comparison to the standard time series for each pixel and SPOT-Vegetation's ten-day NDVI for the dry and rainy periods of 2011/2012. Pantanal's rainy season was defined as the period between October and March, when the monthly average rainfall is higher than 100 mm (GOLTZ et al., 2007, SANTOS et al., 2009). Consequently the dry season was defined as the period between April and September.

The analysis of the SVI's spatial distribution for the dry season (Figure 2) shows it varied from normal to above normal in the southern half of Pantanal between April and May 2011. From June to September 2011, the SVI remained around the values expected for the period, with areas above normal in the southwest of Pantanal, except in the 2nd ten-day period of June, when we observed SVI values predominantly below normal. This was due to the high standard deviation observed in comparison to the average vegetation indices, which generated a lower standardized vegetation index for the period. In the June-July-August quarter most areas showed normal rainfall incidence.

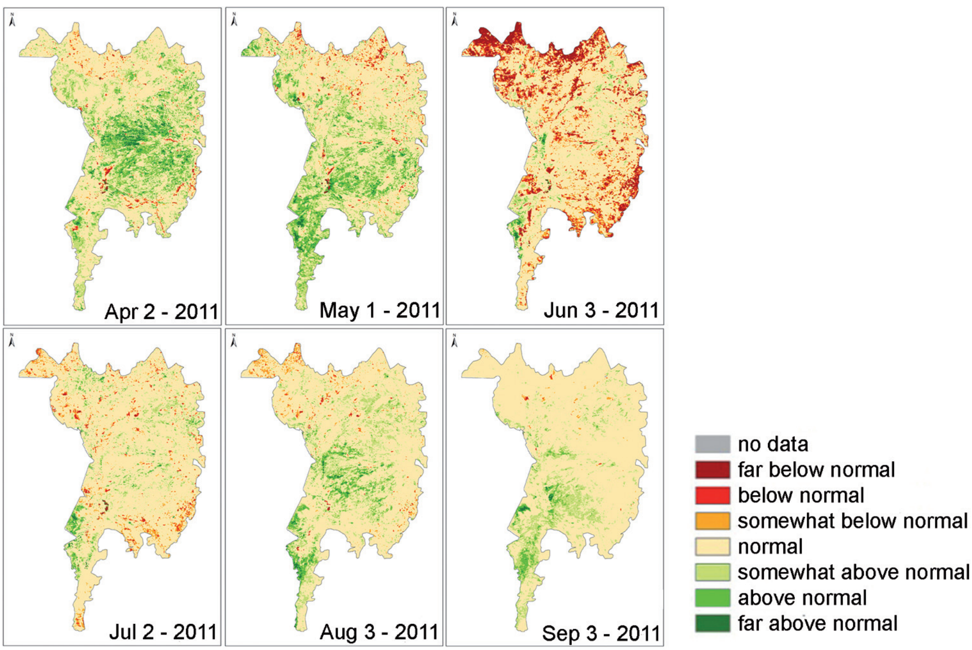

Figure 2 - Spatial distribution of the Standardized Vegetation Index in the dry season, from April to September 2011

In the rainy period, from October 2011 to March 2012, areas with negative rainfall anomalies estimated by the TRMM sensor were predominant in Pantanal.

The SVI responded to rainfall below normal between October and January. From February on, it remained above normal, especially during the last ten-day period of March, i.e. Pantanal's vegetation showed greater greenness than expected for the period. SVI's variability in the rainy period (Figure 3) may be explained by the negative rainfall anomaly indicated in the TRMM sensor's data (Figure 4b), for, because the rainfall remained below/far below normal in Pantanal, the flooded area was smaller and consequently the vegetation area was more exposed, which is indicated by the NDVI increase.

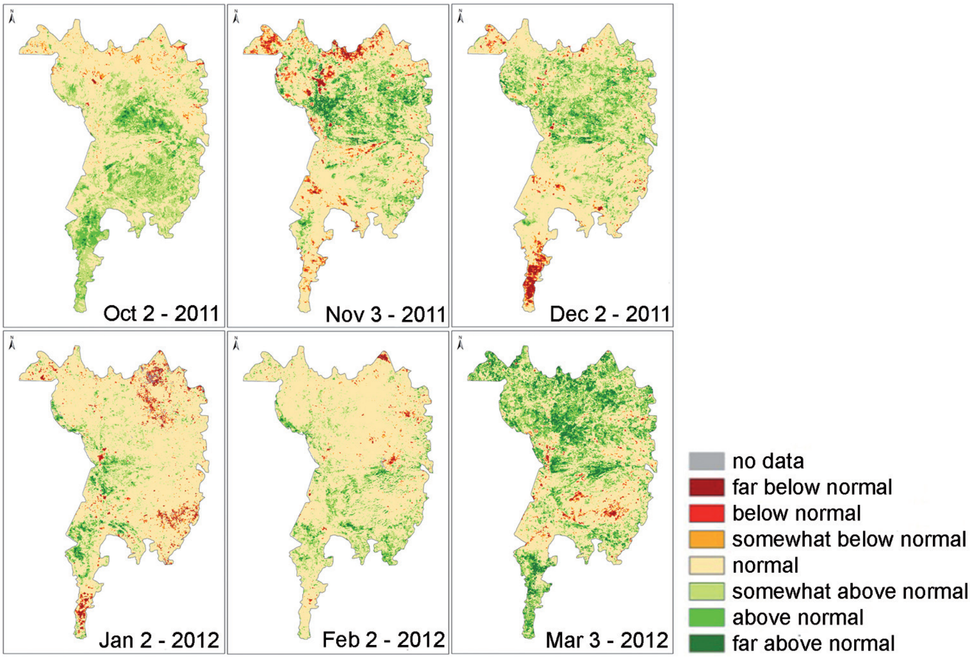

Figure 3 - Spatial distribution of the Standardized Vegetation Index in the rainy season, from October 2011 to March 2012

The decrease in flooded area may be detected using NDWI data, which show hydric deficit in a large part of Pantanal's area (Figure 5). During this period, the 6th Naval District of the Brazilian Marines detected a decrease in the Paraguai river level in 2012. It is important to highlight that negative rainfall anomalies had persisted since the dry season, thus hindering the decrease in flooded areas in Pantanal.

The rainfall estimates obtained from the TRMM sensor show seasonal variability (Figure 4). Satellite data have a tendency towards overestimating total rainfall values. The difference we detected is in agreement with that found in previous studies (COLLISCHONN et al., 2007; COLLISCHONN et al., 2008), and the results we obtained may be considered satisfactory. Collischonn et al. (2007) verified that the TRMM estimates rainfall over the Alto Paraguai watershed quite well. The satellite overestimated rainfall at some peaks and underestimated it at others. Another important characteristic of the TRMM sensor is that it correctly estimates the absence of rainfall. Thus, the alternation between dry and wet seasons, which is characteristic of Pantanal, is well represented (COLLISCHONN et al. , 2007).

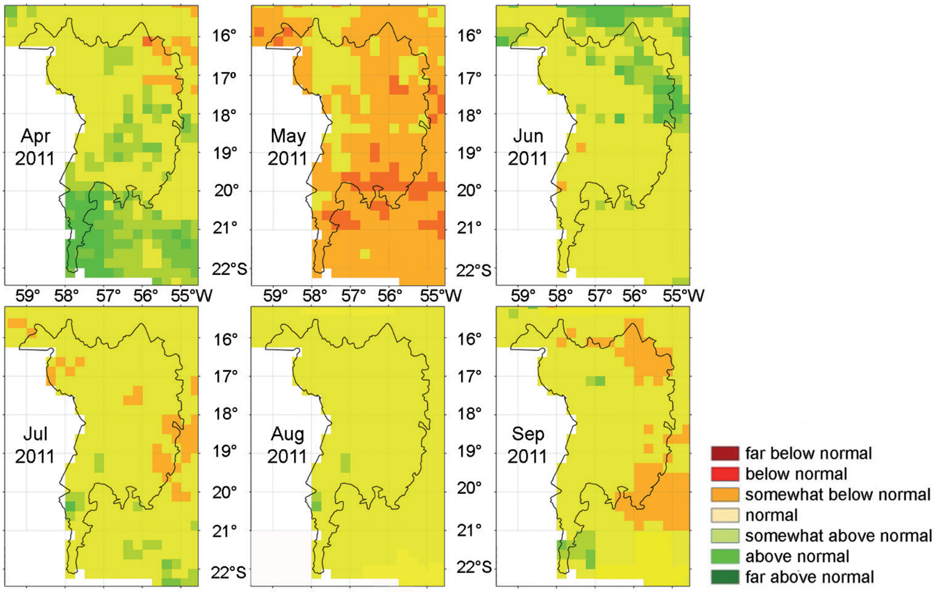

Figure 4a - Spatial distribution of the Standardized Rainfall Index (SRI) obtained from the TRMM sensor, from April 2011 to March 2012 (dry season)

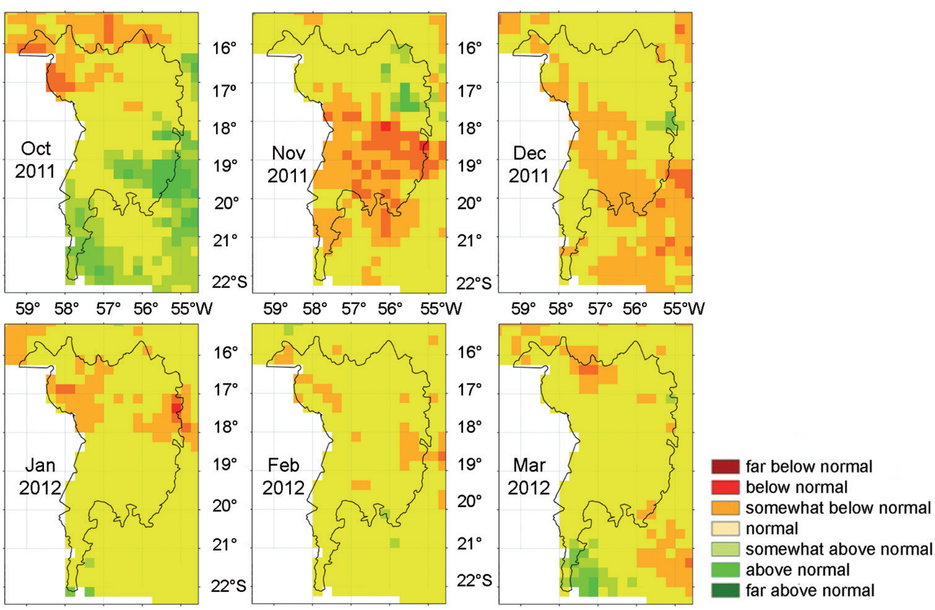

Figure 4b - Spatial distribution of the Standardized Rainfall Index (SRI) obtained from the TRMM sensor, from April 2011 to March 2012 (rainy season)

There is a shortfall between the SVI and TRMM's standardized rainfall (Figure 4a e 4b). NDVI' behavior is strongly influenced by rainfall, as well as by the shortfall time between rainfall and NDVI, as already detected in previous studies such as those by Campos et al. (2009) and Wang et al. (2003). Ávila et al. (2009) observed a two-month shortfall between the NDVI response and the rainfall, and also detected that other variables must also be involved in this process for NDVI behavior determination. Viana and Alvalá (2011) found correlation between the EVI, NDVI and LSWI vegetation indices and rainfall in the dry and rainy seasons in Pantanal. Pavri and Aber (2004) observed that seasonal and interannual environmental variations, such as rainfall and high temperature, may cause variability in flooded zones. Nicácio et al. (2009) showed that NDVI reflects the rainfall intensity registered during the previous 4 to 5 months. Nicácio et al. (2009) and Santos et al. (2009) showed that the response of the vegetation indices in that region varies according to land cover characteristics, as well as to rainfall variability.

Several authors, as aforementioned, have already shown that vegetation responds to hydric regime with a shortfall. In our study, it is worth emphasizing that the reflectance response of Pantanal's cover is associated with rainfall up to the moment the soil's field capacity is reached, and the response is directly related to rainfall volume and biomass increase. When the rainfall volume is too high, the surface response will be based on the water characteristics, thus decreasing the NDVI. When the rainfall anomaly is negative, as observed in the rainy season, the surface spectral response will be related to plant cover, with exposed biomass, thus showing an increase in vegetation vigor in comparison to what would be expected for the period based on SPOT-Vegetation 1998 to 2012 time series.

Since from the 3rd ten-day period of September 2011 on there was also an NDWI (Normalized Difference Water Index) product available, provided by Vito (Vision on Technology - Flemish Institute for Technological Research), Belgium, we chose to analyze it to subsidize our results, even though it did not encompass the whole period of the dry season. We observed that, from December on, in a large portion of Pantanal, the NDWI index was below zero, i.e. there was hydric deficit (red). In September 2011 (Figure 5), the NDWI index became greater than zero (blue tone) in the area encompassing Paraguai, Paiaguás and Nabileque, in the western and southern regions of Pantanal. From December 2011 on, there was a predominance of areas with NDWI below zero, i.e. with a low humidity index (red) which was predominant in the eastern region of Pantanal, which encompasses Nhecolândia and Paiaguás. These regions with low NDWI coincide with the results obtained by Cardozo et al (2009) depicted in annual maps of flooded areas based on the 2000 to 2010 hydrologic years.

The use of satellite images for the monitoring of flooded areas proved efficient, with rainfall estimates by TRMM below normal in the dry season persisting in the rainy season and aggravating the hydric deficit situation, as verified by the NDWI index (Figure 5).

The results obtained in this study corroborate those obtained by Santos et al. (2009), which identified flooded areas in the Pantanal biome using spatial-temporal variations of MODIS satellite's EVI (Enhanced Vegetation Index) index in the 2000 to 2008 period and TRMM data identifying the region's dynamics during the dry and rainy seasons. Moraes et al. (2012) detected a reduction of flooded areas in the Pantanal Plains in 2012 by analyzing MODIS' time series and comparing them to TRMM rainfall.

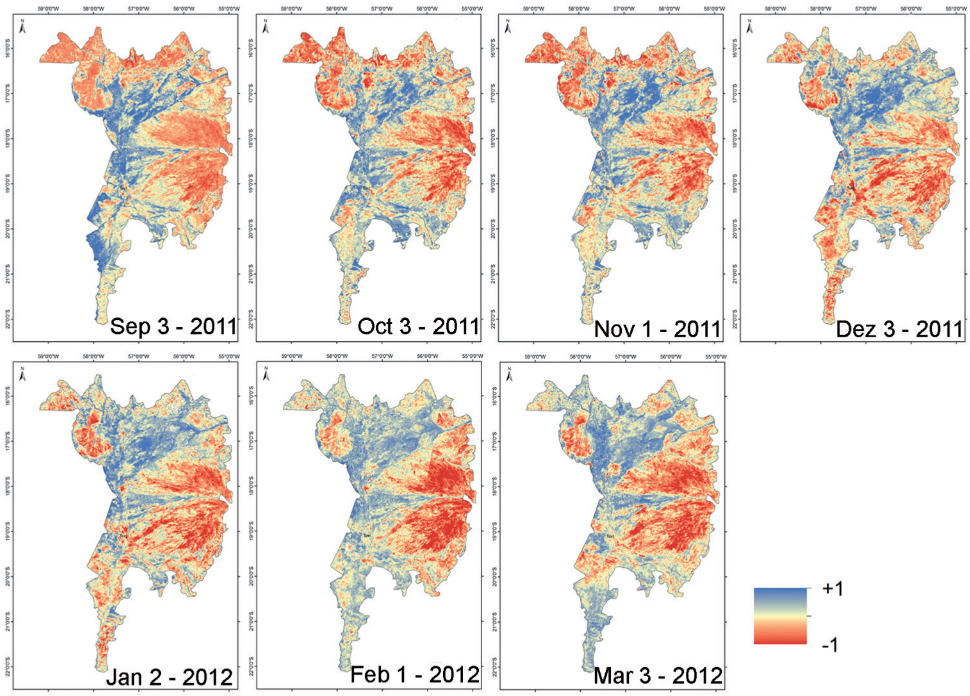

Figure 5 - Spatial distribution of the NDWI index from September 2011 to March 2012

In a similar study using a 1985-2009 time series from the Landsat sensor, Kayastha et al. (2012) mapped changes in floodable ecosystems in northern Virginia and detected loss of flooded zones, as well as other changes caused by development, harvests and agricultural practices. Dahl (2006) and Ramsey et al. (2001) verified that human activities, such as lumber industry and agriculture were the principal source of errors both in the mapping of wetlands and in the analyses of changes. The moment of image acquisition with human activities may increase the error in variation analysis even more. Although these changes in land use do not result in loss of flooded areas, they may significantly change reflectance characteristics, thus leading to ambiguities in the detection of changes. With this in mind, we have assessed the behavior of the plant cover during the dry and rainy periods while taking into consideration the historical pattern of the region for each ten-day period, with the aim of increasing the capacity of characterizing the temporal variability and of detecting changes in flooded areas.

The results obtained in our study corroborate those of Viana and Alvalá (2011), which assessed the performance of the NDVI, EVI (Enhanced Vegetation Index) and LSWI (Land Surface Water Index) indices in Pantanal in the dry and rainy seasons using MODIS' data and TRMM's rainfall estimates. Nicácio et al. (2009) observed the vegetation response by means of an NDVI analysis in comparison to rainfall intensity. These authors observed a shortfall of approximately four months in the vegetation response. NDVI and rainfall variations significantly improved when the accumulated monthly rainfall was considered, which suggests that the index reflects rainfall intensity with a shortfall of 4 to 5 months.

Goltz et al. (2007) analyzed EVI and NDVI in the period from 2000 and 2005 in two Pantanal subregions (Paiaguás and Nhecolândia), in order to observe the vegetation dynamics over the years. The authors discovered that, in general, the results obtained for EVI were lower than those obtained for NDVI, but showed similar variability. Moraes et al. (2009), using EVI data from 2000 to 2008, observed that the most important changes in Pantanal occur in the southern (deciduous tropical forest), central (ombrophilous forest and savanna) and northern (pasture) regions.

Adami et al. (2008) emphasized that, in Pantanal, different types of vegetation receive different amounts of rainfall at different places, and therefore show different spectral responses. Hence the importance of analyzing standardized data to verify pixel-to-pixel variability in comparison to the local historical standard. Studies by Padovani et al. (2005), Antunes and Esquerdo (2007), Goltz et al. (2007) and Lacruz and Sousa Júnior (2007) have demonstrated the complexity of the region vegetation and its relationship to rain.

Several studies have used different methods to classify changes in flooded areas using time series. Goltz et al (2007) determined areas susceptible to floods in the Paiaguás and Nhecolândia (Pantanal Sulmatogrossense) regions using multitemporal images of vegetation indices (NDVI and EVI) from the MODIS/TERRA sensor for the period between the years 2000 to 2005 using images of minimum and maximum (EVI and NDVI) for each year, and generated difference images. The authors observed that some areas showed negative values in the difference images, i.e. in these regions the values of the vegetation indices were higher in the dry season than those in the flood season, and thus concluded that these areas (with negative values) were flooded during the flood season (their vegetation indices values were lower). Vogelmann et al. (2012) used the linear regression model to verify changes in the ecosystem.

Verifying floodable areas is a hard task, because of the wetlands dynamics and because they show a high degree of temporal variability, which is due to seasonal variations in water level caused by changes in rainfall, temperature and other environmental conditions, as well as by human influence. Over the last years, several studies have used interannual time series to characterize several landscape disturbances. Misinterpretation of wetlands gains or losses may also be a result of factors such as agriculture practices in the flooded regions during the drought, drought conditions, and surface water excess or floods (DAHL, 2006).

Although SPOT-Vegetation temporal frequency is high, its spatial resolution is low. We therefore suggest that future studies use images with higher spatial resolution. Another important tool to aid in the monitoring of flooded areas is aerial photographs used along with field investigations, topographic and soil maps.

CONCLUSIONS

From the results obtained, we conclude that the integrated analysis of rainfall anomaly images and vegetation indices enabled verifying the shortfall of the Standardized Vegetation Index's (SVI) response in comparison to the negative rainfall anomaly of the TRMM sensor.

The SVI variability along the rainy period may be explained by the negative rainfall anomaly: with the decrease of the water layer in comparison to its normal amount for the period there was an increase in NDVI values in comparison to what was expected.

Despite the natural temporal variability and the low spatial resolution of SPOT-Vegetation NDVI images, the results obtained were satisfactory for a ten-day monitoring of the flooded and non-floodable areas in the Brazilian Pantanal.

Due to SPOT-Vegetation images high temporal resolution, the products offered by this sensor show considerable potential in the monitoring of the seasonable variability of floods in Pantanal. We find it important to highlight the need for validations in the field, as well as for quota analysis and for the use of images from a sensor with higher spatial resolution.

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