VEGETATION INDEX PERFORMANCE FOR THE PANTANAL REGION DURING BOTH DRY AND RAINY SEASONS

Denilson Ribeiro VIANA
Regina Célia dos Santos ALVALÁ

Abstract

This study aims to evaluate the performance of NDVI, EVI and LSWI in the Pantanal, considering the main types of land cover and seasonal rainfall. For this purpose, we used data from MODIS and TRMM monthly rainfall estimates. For the dry season, results varied between NDVI (0.4 and 0.8); LSWI (0.0 and 0.4); EVI (0.2 and 0.6). All indices also showed a poor correlation with rainfall, which was below 0.25. In the rainy season, NDVI presented the highest values, between 0.6 and 0.8. Only in some sections of the Evergreen Forest class, LSWI values were higher than the NDVI. The EVI showed values between 0.2 and 0.5 and the LSWI showed intermediate values between the NDVI and EVI from 0.2 to 0.7. Although alternating at times, the Savannah (*Cerrado*) and Deciduous Tropical Forest (*Chaco*) classes, LSWI and EVI were very similar. The NDVI and LSWI showed significant correlations with rainfall in all land cover classes. The LSWI showed the greatest amplitude, in all classes, and for both seasons, indicating to be most suitable for studies in the Pantanal, especially for the Savannah and Deciduous Tropical Forest classes during the rainy season, and Evergreen Forest class during the dry season.

Key words: NDVI. EVI. LSWI. Rainfall. TRMM.

Resumo

Desempenho de índices de vegetação na região do pantanal nas estações seca e chuvosa

Este trabalho avalia o desempenho dos índices de vegetação NDVI, EVI e LSWI no Pantanal, considerando os principais tipos de cobertura da terra e a sazonalidade da precipitação. Foram utilizados dados do sensor MODIS e estimativas de precipitação do satélite TRMM. Os resultados mostraram que, na estação seca, os valores de NDVI, LSWI e EVI variaram entre 0,4 e 0,8; 0,0 e 0,4; e 0,2 e 0,6, respectivamente. Todos os índices mostraram baixa correlação com a precipitação, inferiores a 0,25. Na estação chuvosa, o NDVI apresentou os maiores valores, entre 0,6 e 0,8. Apenas em alguns setores da classe Floresta Perene, os valores de LSWI superaram os de NDVI. O EVI apresentou os valores mais baixos, entre 0,2 e 0,5, enquanto o LSWI apresentou valores intermediários, entre 0,2 e 0,7. Nas classes Cerrado e Chaco, o LSWI e o EVI ficaram bastante próximos. O NDVI e o LSWI mostraram correlações significativas com a precipitação em todas as classes de cobertura. O LSWI apresentou a maior amplitude em ambas às estações, e em todas as classes, mostrando ser o índice mais adequado para estudos no Pantanal, especialmente para as classes Cerrado e Chaco na estação chuvosa, e Floresta Perene na estação seca.

Palavras-chave: NDVI. EVI. LSWI. Precipitação. TRMM.

[1] Geographer, MSc in Remote Sensing - Instituto Nacional de Pesquisas Espaciais (INPE) – São José dos Campos – SP, Brazil. E-mail: denilson.ribeiro@inpe.br

[2] Senior Researcher of the Centro de Ciências do Sistema Terrestre (CCST) - Instituto Nacional de Pesquisas Espaciais (INPE) – São José dos Campos – SP, Brazil. E-mail: regina.alvala@inpe.br

INTRODUCTION

Several studies were performed using spectral vegetation indices derived from orbital remote sensing data. Indices such as NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index) and LSWI (Land Surface Water Index) have been widely used to evaluate spatial and temporal characteristics of surface cover types. In general, these indices seek to characterize the different vegetation types and evaluate the seasonal response of vegetation, according to the climate conditions.

NDVI is the most intensely used vegetation index. It is used in monitoring studies of seasonal and inter-annual changes of vegetation. It is especially instrumental for the assessments of agricultural and forest landscapes and climate characterization. According to Jensen (2009), the NDVI shows some deficiencies. It can be influenced by noise, such as additive atmospheric effects like path radiance or by varying the substrate under the canopy. To minimize these factors, Justice et al. (1998) proposed the EVI, which included an adjustment coefficient for the soil, a gain factor and two adjustment coefficients compensating for the effects of atmospheric aerosols.

While the NDVI and EVI are based on the relationship between the red and near infrared wavelength reflectance, the LSWI uses the ratio between the near and mid-infrared. Hardisky et al. (1983) obtained better results with this index than NDVI, because of its strong correlation with the plant canopy water content, allowing to monitor changes in biomass and moisture in the vegetation. Moreover, the LSWI – an index that is still not widely employed – is more sensitive to water content, because the regions of absorption in the mid-infrared range are less influenced by atmospheric effects, possibly indicating the presence of moisture in vegetation and soil, allowing a stronger contrast between different land cover classes (WILSON; SADER, 2002).

For the Pantanal Biome, a series of studies was performed using spectral vegetation indices in order to evaluate the spatial-temporal characteristics of the vegetation (ANTUNES; ESQUERDO, 2006; COELHO et al., 2006; GOLTZ et al., 2006; LACRUZ; SOUSA JÚNIOR, 2006; APARICIO et al., 2009; CARDOZO et al., 2009; FERRARI et al., 2009; NICÁCIO et al., 2009; VICTORIA et al., 2009).

The Pantanal is composed of four intersecting phyto-ecological formations, regionally known as *Mata Decídua* (Evergreen Forest), *Mata Semidecídua* (Semi deciduous forest), *Chaco* (Deciduous tropical forest) and *Cerrado* (Savannah). Besides these formations, various parts of the Pantanal present contact zones between these phyto-ecological formations and pioneer vegetation. These areas are subject to seasonal river overflows, forming a complex of flooded fields and swamps (EMBRAPA, 2004).

Regarding the climatic conditions, the Pantanal is characterized by a climate type that varies from warm to sub-warm, with the dry period of 4 to 5 months, from April to September (NIMER, 1979). Based on the meteorological station of Corumbá (MS), the average rainfall is above 100 mm, occurring between October and March. According to Nimer (1979), the annual distribution of rainfall does not show great complexity. However, the Pantanal is located in an area of 'climatic tension', where low and high latitude systems interact (ALVES, 2009).

Nicácio et al. (2009), evaluating the precipitation within the Coxim river watershed (MS), identified that the dry season occurs between April and September. The accumulated precipitation in the rainy season, from October to March, corresponds to 75% of the annual total. Considering the NDVI related to rainfall intensity, these authors also assessed the response of vegetation, indicating a lag of around four months. The correlations between NDVI and precipitation improve significantly when considering the monthly accumulated precipitation, suggesting that the index reflects the intensity of rainfall, observed 4-5 months before. Santos et al. (2009) analyzed the EVI for the Pantanal between 2000 and 2008 and found that the highest rates occurred between October and April, with a peak in January. The EVI begins to decrease in April, due to a reduction of precipitation. Nicácio et al. (2009) and Santos et al. (2009) showed that the vegetation indices in the region vary, depending on the rainfall variability. However, studies for the Pantanal Region, in general, do not evaluate vegetation indices for different types of land cover, focusing on single index assessments or homogeneous area. Thus, considering the intra-annual variability of rainfall, it is necessary to evaluate the index, or indices that best represent the state of each land cover type and season.

OBJECTIVES

This study aims to evaluate the performance of NDVI, EVI and LSWI with the main classes of land cover from the Pantanal Biome and the seasonality of rainfall in the region. Specifically, it is intended to investigate which of these indexes show greater separability between different types of vegetation in the region, and evaluate which of these indices are most sensitive to rainfall variability, under wet and dry conditions.

DATA AND METHODOLOGY

For this study, we used two different data sets: 1) monthly estimates of rainfall from TRMM satellite (Tropical Rainfall Measuring Mission), product 3B43, and 2) surface reflectance factor and vegetation indices, derived from MODIS (Moderate Resolution Imaging Spectroradiometer) product MOD13Q1, on board the Terra satellite.

The 3B43 algorithm combines the global rainfall estimates generated by the 3B42 with data from a global network of pluviometers from the Climate Assessment and Monitoring System (CAMS) and/or global pluviometric products generated by the Global Precipitation Climatology Centre (GPCC). The algorithm is executed once per month, generating a map of monthly rainfall, with a resolution of 0.25° x 0.25° (SIMPSON et al., 1996).

The validation of rainfall estimates TRMM/3B43 was done by several institutions around the globe. Dinku et al. (2007) found correlation coefficients of 0.92. Due to the complex topography of the region, these results were classified as 'exceptionally good' by the authors. Chiu et al. (2006) analyzed 3B43 estimates from New Mexico (USA) and found correlations above 0.86. Adeyewa and Nakamura (2003) evaluated the 3B43 in the major climatic regions of Africa, finding a high correlation with rainfall data. Feidas (2010) validated the 3B42 and 3B43 estimates in Greece at different spatial scales, and concluded that only the 3B43 estimates adequately assessed the climatic distribution and variability of rainfall. Viana (2009) evaluated the performance of 3B43 estimates for the Southern Region of Brazil and found correlation coefficients between 0.87 and 0.94.

The monthly estimates of rainfall 3B43/TRMM were used to select the period under study and evaluate the correlations with vegetation indices. Initially, the estimates between 1998 and 2010 were accumulated in annual rainy and dry periods. The rainy season for the Pantanal Region was defined as the period between October and March, when the average monthly rainfall exceeds 100 mm (NIMER, 1979, GOLTZ et al., 2007, SANTOS et al., 2009). Consequently, the dry period was defined as being between April and September. Based on 3B43/TRMM data, the climatology for dry and rainy seasons was then calculated. From this climatology, it was possible to assess the dry and rainy seasons when the observed rainfall was closer to the average. Finally, we selected two images from the MOD13Q1 product (tiles h12v10 and h12v11), referring to the end of the identified dry and wet seasons. Thus, it was possible to evaluate the performance of vegetation indices based on the average behavior of rainfall.

The MOD13Q1 product includes vegetation indices, reflectance factor data in the visible and infrared channels, orbit parameters and image quality, among others. This product has a 16-day temporal resolution and a 250 m spatial resolution (RUDORFF et al., 2007). The NDVI and EVI were obtained directly from the MOD13Q1 product, while LSWI was calculated using near and mid-infrared bands. The NDVI, EVI and LSWI are presented in Equations 1, 2 and 3, respectively:

$$NDVI = \frac{(\rho_{nir} - \rho_{red})}{(\rho_{nir} + \rho_{red})}$$

$$EVI = G\frac{(\rho_{nir} - \rho_{red})}{(\rho_{nir} + C_1\rho_{red} + C_2\rho_{blue} + L)}(1+L)$$

$$LSWI = \frac{(\rho_{nir} - \rho_{mir})}{(\rho_{nir} + \rho_{mir})}$$

where ρ is the reflectance factor for the near infrared (NIR), mid-infrared (MIR), red and blue bands. For the EVI, the L and G constants represent the adjustment factors for the soil and gain, respectively; while C1 and C2 are the adjustment factors for the aerosol effects (JENSEN, 2009). The values of these coefficients were empirically determined: L = 1, G = 2.5, C1 = 6 and C1 = 7.5.

Selected transects made it possible to assess the performance of the vegetation indices. The definition of the transects was designed to represent the main land cover classes, that describe the region. To represent these classes we used the SSiB (Simplified Simple Biosphere Model) Land Cover Map made compatible by Vieira et al. (2006), based on the PROBIO (EMBRAPA, 2004) cartography. We highlight that the SSiB defined classes represent the main types of land cover for the Pantanal Region, and that this model was coupled to atmospheric models for weather and climate forecasting. After defining the transects, the vegetation indices were extracted from the scenes and correlated to rainfall for the selected period.

The indices were represented as graphs, with transects being segmented according to land cover classes, and submitted to a moving average filter of size seven. In order to investigate the discrimination between different types of land cover, the indices were also assessed using box-plot graphs, which grouped class data from the transects. Furthermore, we evaluated the correlation between the rainfall and the vegetation index for each class of land cover. All the data was re-sampled to the spatial resolution of 1 km.

We used the following software: 1) Surfer 8.0, for the preparation of maps; 2) Statistica 6.0, for statistical analysis; 3) MRT - Modis Reprojection Toll, to convert MODIS image projection and format ; 4) ENVI 4.3, for processing MODIS images; and 5) Microsoft Excel 2003, for spreadsheets, charts and graphs.

RESULTS AND DISCUSSION

ANALYSIS OF DRY AND RAINY PERIODS

The aim of the analysis from dry and rainy seasons was to select of the periods when rainfall was similar to the average, in order to represent mean climate standards, from the choice of a specific year. This study analyzed the period between 1998 and 2010.

Regarding the dry season (April to September), the average accumulated rainfall in the Pantanal Region was 239 mm. The year in which rainfall was closer to average was 2008, with an absolute deviation of 4 mm. Table 1 shows the accumulated average rainfall in the dry season in the Pantanal, during the period under study and its respective deviations in module.

Table 1 - Accumulated rainfall (mm) for the Pantanal Region, in dry season (April-September)

Years	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*Mean*
Mean Precip.	298	158	272	290	182	271	319	198	210	162	235	267	239
| Mean Dev. |	59	80	34	51	56	33	81	41	29	77	4	28	

Figure 1 shows the average accumulated rainfall during the dry season from 1998 to 2010, as well values observed in 2008. From the analysis of Figure 1, one observes that the spatial pattern of rainfall in 2008 (Figure 1b) is very similar to the cumulative average of the period under study (Figure 1a).

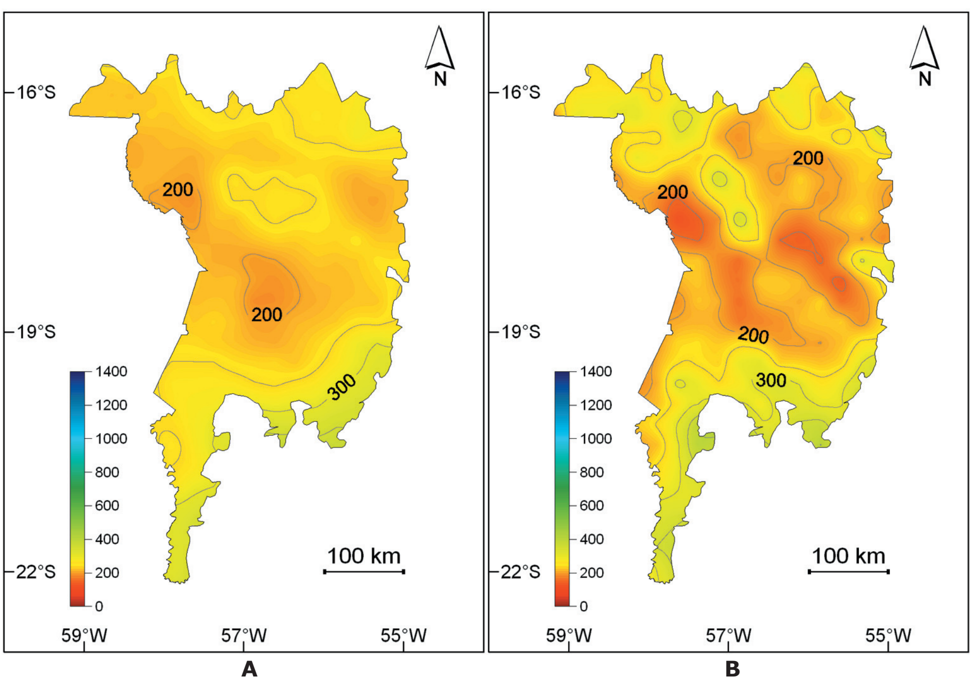


Figure 1 – Average accumulated rainfall (mm) in the dry season (a) and observed in 2008 (b)

For the rainy season (October to March), the average accumulated rainfall was 1,002 mm, and the year 2009 (October 2008 to March 2009), presented the shortest absolute deviation (19 mm). Table 2 shows the average accumulated rainfall for the rainy season period and the deviations from the module.

Table 2 - Accumulated rainfall (mm) for the Pantanal Region, in rainy season (October-March)

Years	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*Mean*
Mean Precip.	962	972	940	943	977	890	1161	979	1107	1048	983	1062	1002
| Mean Dev. |	40	30	62	60	25	112	159	23	105	46	19	60	

Figure 2 shows the average accumulated rainfall during the rainy season as well as the volumes observed in 2009. The rainfall observed for the 2009 rainy season (Figure 2b) shows a pattern that is very similar to the average accumulated rainfall, from 1999 to 2010 (Figure 2a). So the dry season of 2008 (April-September, 2008) and the rainy season of 2009 (October, 2008 - March, 2009) were selected as reference seasons for the analysis of vegetation indices from the Pantanal.

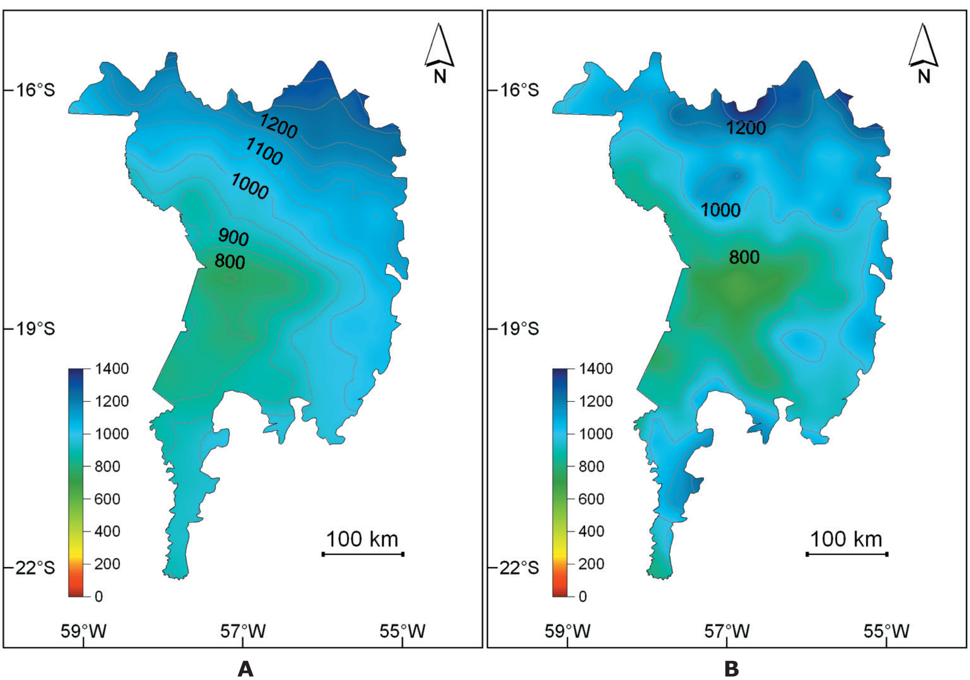


Figure 2 - Average accumulated rainfall (mm) in the rainy season (a) and observed in 2009 (b)

EVALUATION OF VEGETATION INDICES

After the selection of the reference seasons, two MODIS scenes were acquired: one scene representing the end of the dry season (Sept. 29th 2008) and another depicting the end of the wet season (Apr. 7th 2009) of the Pantanal. Following, transects were defined for the analysis of vegetation indices. Figure 3 offers the Land Cover Map made compatible by VIEIRA et al. (2006) for the SSiB model and plotted transects. The definition of transects took into account the main land cover classes in the Pantanal. From the eight defined land cover classes, four classes correspond to 97% of the total studied area: Savannah – SV (Cerrado), 48%; Evergreen Forest – EF, 25%; Deciduous Tropical Forest – DTF (Chaco), 13%; and Pasture – PT, 11%. Thus, two transects were established across the region: A-A' in NW-SE direction, and B-B' in the NE-SW direction (Figure 3).

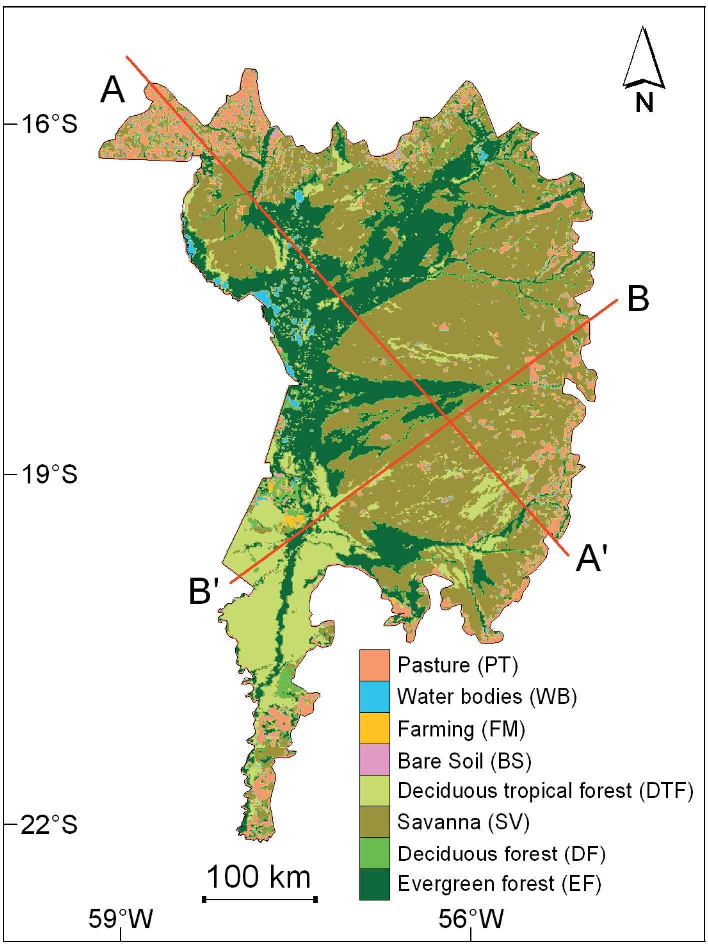
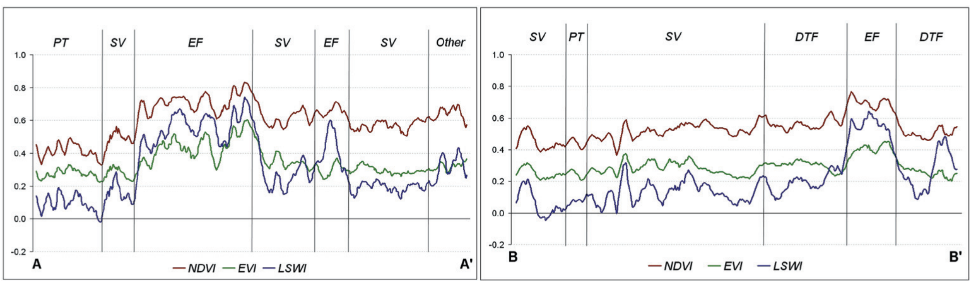


Figure 3 - SSiB model land cover classes and plotted transects

Font: Adapted from Vieira et al. (2006).

Dry season

The characterization of vegetation indices, along transects in the dry season of 2008 is presented in figure 4. The segmentation of indices, by type of coverage, indicates that, when compared to other indices, the NDVI showed the highest values in both transects, ranging on average between 0.4 and 0.8. The LSWI presented values between 0.0 and 0.4, except for the Evergreen Forest, where this index exceeded the EVI. For the Pasture, Savannah and Deciduous Tropical Forest classes, the LWSI ranged on average between 0.0 and 0.2. The EVI showed intermediate values between 0.2 and 0.4, except for the Evergreen Forest, as already discussed. In the class "Other" (Figure 4a), it was not possible to assess the index, because this area presents a mix of different types of land cover.



A B

Figure 4 - Vegetation indices derived from MODIS, at the end of the dry season of 2008 (SEP/29/2008 scene) of transects A-A '(a) and B-B' (b)

The results of this study confirm those found by Goltz et al. (2007), Freitas et. al (2007) and Moraes et al. (2009). Goltz et al. (2007) analyzed the EVI and NDVI, in the period between 2000 and 2005, in two southern Pantanal sub-regions (Paiaguás and Nhecolândia), in order to observe the vegetation dynamics over the years. These authors found that, in general, the results for EVI were lower than those for the NDVI, but presenting a similar variability. They concluded that EVI was more sensitive to changes occurring during flood and drought periods, although they did not evaluate the LSWI, which proved to be more sensitive than the EVI, to define the vegetation, during the dry season. Freitas et. al (2007) also analyzed the dynamics of spectral response of the vegetation in the sub-regions of Paiaguás and Nhecolândia, where vegetation is predominantly Savannah, in accordance with SSiB model classification. Using MODIS data for June 2000 to July 2006, these authors found that NDVI values ranged between 0.4 and 0.6 and EVI between 0.2 and 0.4. The ratio between MIR and NIR bands, which represent LSWI calculations, was around 0.15, in average. Moraes et al. (2009), using EVI data from 2000 to 2008, at the end of the dry season, observed that the most important changes in Pantanal occur in the southern (Deciduous Tropical Forest), central (Evergreen Forest and Savanna) and northern (Pasture) regions.

The analysis of vegetation indices by box-plots (Figure 5) showed that, for the evaluated land cover types, the LSWI had the highest amplitude in all classes. The NDVI showed an intermediate condition, while the EVI had a lower amplitude. These results indicate that, among the indexes examined, the LSWI presents a larger intra-class discrimination, in the dry season.

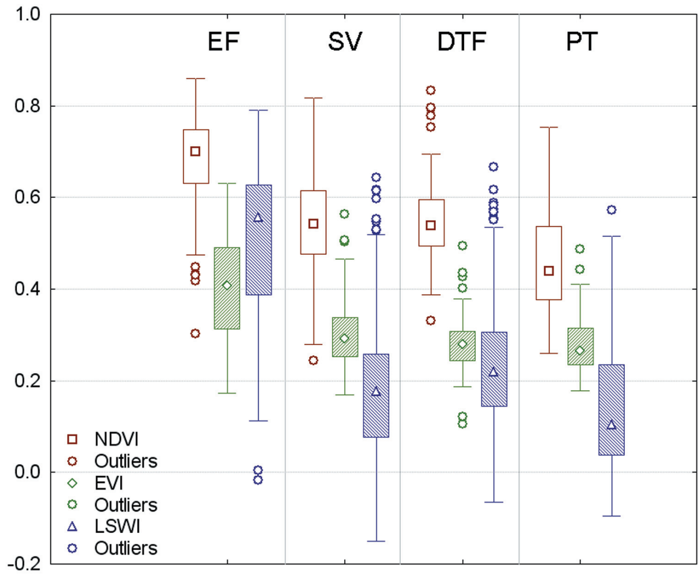


Figure 5 - Box-plots of vegetation indices, grouped by land cover type, in the dry season of 2008

The correlation between vegetation index and rainfall in the dry season was less than 0.25 in all classes (Figure 6). Only the class Savannah showed significant correlation of 5%, at the three indices (NDVI: 0.12, EVI: 0.22; LSWI: 0.23). For the class Deciduous Tropical Forest, only NDVI presented a correlation with rainfall (0.25), while the Pasture class, only EVI showed a correlation (0.23). The Evergreen Forest class did not correlate with any one of the three indexes.

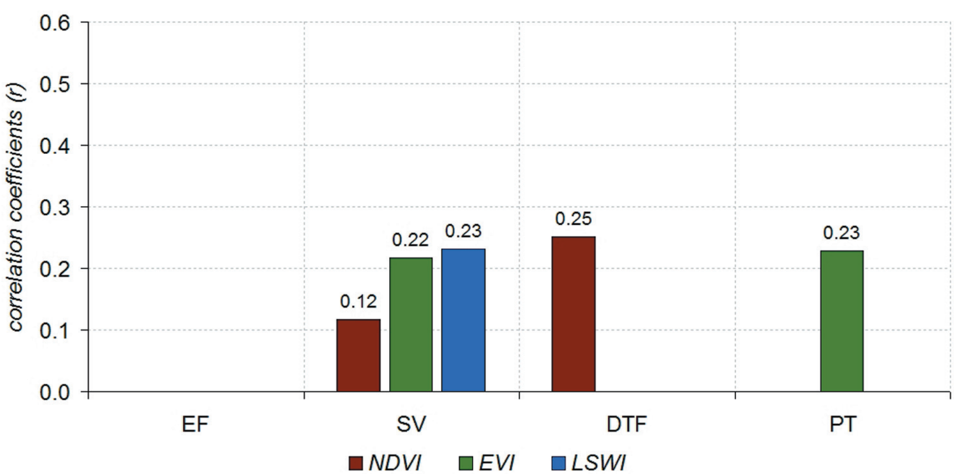
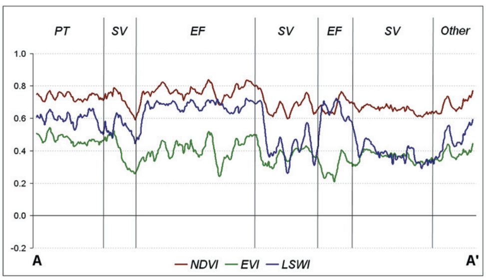
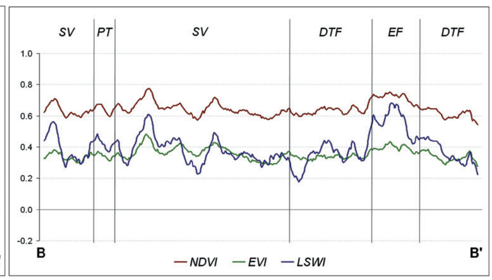


Figure 6 - Correlation coefficients between rainfall and vegetation indices for land cover types, in the dry season of 2008

Rainy season

Figure 7 shows the behavior of vegetation indices along transects A-A’ and B-B’ at the end of the 2009 rainy season. The analysis by type of vegetation indicates that NDVI had the highest values in almost the full length of both transects, ranging between 0.6 and 0.8. Only at transect A-A’ (Figure 7a), at Evergreen Forest class, the LSWI values were above those of NDVI, in some sectors. The LSWI presented intermediate rates between NDVI and EVI, from 0.2 to 0.7. In general, EVI showed the lowest values of the indices, ranging from 0.2 to 0.5. In classes Savannah and Deciduous Tropical Forest, LSWI and EVI indexes were very close, alternating at times.





A **B**

Figure 7 - Vegetation indices derived from MODIS at the end of the rainy season of 2009 (APR/07/2009 scene), in transects A-A ‘(a) and B-B’ (b)

The results for the rainy season also corroborate with those obtained in the study by Freitas et al. (2007) who found NDVI values between 0.7 and 0.8, EVI between 0.4 and 0.5, and the ratio between NIR and MIR (LSWI) around 0.5. Noteworthy is the fact that, EVI and LSWI showed opposite variability for the Evergreen Forest class (Figures 7a and 7b).As for classes Savannah and Deciduous Tropical Forest, despite the similar variability, we found that, with respect to maximum and minimum values, the LSWI has a wider range than EVI.

Goltz et al. (2007), observing the values of the indices NDVI and EVI, concluded that the first index showed the greatest contrast between flooded and non-flooded areas, indicating greater sensitivity to changes in vegetation. However, as for the dry season, these authors did not evaluate LSWI content. Moraes et al. (2009) observed that flooded areas (Deciduous Tropical Forest) present a larger variability of vegetation. According to these authors, this was expected because the land cover elevation is altered by the water level, which varies during the period under study. The results obtained by Moraes et al. (2009), as well as those found in this study, indicate that LSWI is the most adequate index for assessing vegetation moisture content, especially for the Savannah and Deciduous Tropical Forest classes, presenting details which are not observed by other indexes.

The box-plots of vegetation indices for land cover classes (Figure 8) demonstrate that the variability of the rainy season with LSWI is similar to that of the dry season, showing higher amplitude than the other. NDVI generally had the lowest distribution and the highest values, with maxima around 0.9. EVI showed an intermediate distribution, especially in Evergreen Forest and Pasture classes.

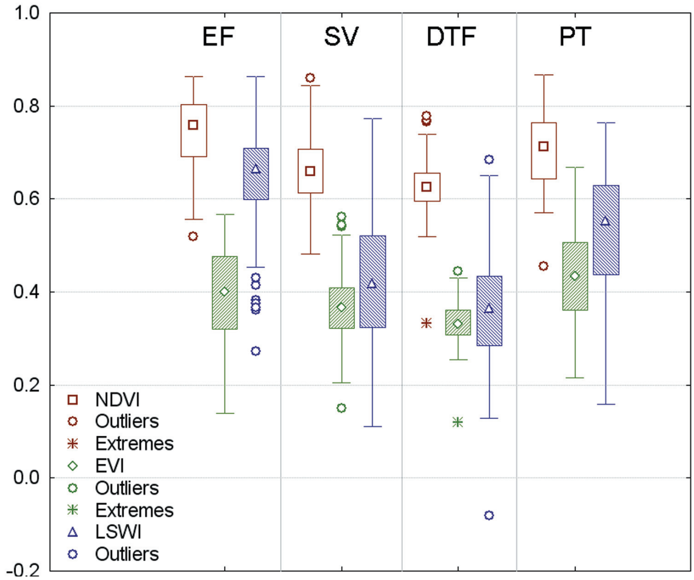


Figure 8 - Box-plots of vegetation indices grouped by land cover type at the end of the rainy season of 2009

The analysis among rainfall and vegetation indices, in the rainy season, indicates that NDVI and LSWI show significant correlations up to 5% in all categories (Figure 9). EVI is correlated with rainfall only in the classes Evergreen Forest and Pasture. The highest correlation of NDVI and EVI were in Evergreen Forest (0.5 and 0.41, respectively), followed by LSWI and EVI for the Pasture class (0.39 and 0.34, respectively).

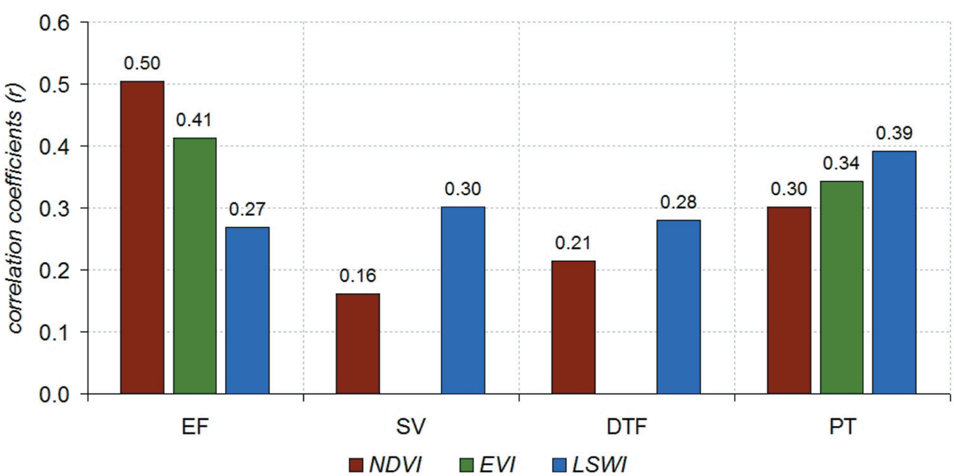


Figure 9 - Correlation coefficients between precipitation and vegetation indices for land cover classes at the end of the rainy season of 2009

One should note that there are some inherent limitations to the characteristics of intra and inter-annual rainfall in the Pantanal. According to Rodela and Queiroz-Neto (2006), the beginning of the rainy season is variable, which may start with the average amount of rainfall, usually in September, but also in August or in November/December. In some years, rainfall can vary from month to month, alternating between dry and wet or intermediate precipitation. According Rodela (2006), the greatest rainfall variability was recorded in May, September and October. In wet years, the rainy season occurs between October and May; and in drier years, between December and March. In years near the average, the wet season occurs between November and April. There are also inter-annual fluctuations of rainfall, related to the amount and seasonal distribution. However, the usual distribution of rainfall during the year is as follows: the rainy season (November to March), intermediate period (April/May, with soil moisture remaining till June and September/October, and soil can be very dry until October) and dry season (June to August/September).

Goltz et al. (2006), evaluating the NDVI and EVI in the dry and rainy seasons found that in general the results for EVI values were lower than those for NDVI. However, EVI was more sensitive to changes that occurred along the dry and rainy seasons. Observing the results of the indices, EVI showed a higher contrast between flooded and non-flooded areas than the NDVI, indicating greater sensitivity to variations that occur between the flood and drought periods. Such results corroborate to those found by this study. Becerra et al. (2009) assessed the seasonal dynamics of vegetation using NDVI and EVI for the Savannah Biome, in the State of Tocantins. The authors noted that EVI showed a higher correlation with rainfall for the detection of the period with less leaf biomass production, for land use/ land cover classes. Considering a seasonal vegetation analysis, the NDVI showed an improved separability of classes and identification of land use/land cover, along the annual cycle. Since we observed significant correlations between precipitation and vegetation for the Savannahin the dry season, the results obtained by Becerra et al. (2009) for EVI corroborate with those obtained in our study.

Adami et al. (2008) emphasized that, in the Pantanal, different kinds of vegetation receive different amounts of rainfall, in different locations and, consequently, have different spectral responses. The analysis of the temporal behavior of rainfall and EVI indicates that there is a time pattern consistent with the rainfall. Permanently flooded areas (wetlands) had low EVI values and great variability, non-flooded areas with vegetation presented EVI values that followed the vegetation seasonality, flooded areas with vegetation close to or aside stream systems suffer little influence of seasonal rainfall. Results similar to those found by Adami et al. (2008), on flooded areas and wetlands, were obtained by Padovani et al. (2005), Antunes and Esquerdo (2007), Goltz et al. (2007) and Lacruz and Sousa Júnior (2007), using different methods. These results demonstrate the complexity of vegetation types in the region and its relationship with rainfall.

Besides the seasonal and inter-annual variations of precipitation in the region, it is important to observe that there is a limitation for the use of vegetation indices, based on band ratio, especially with related to the NDVI, to the LAI estimation, and also to monitor the canopy development. According to Jensen (2009), since this is an index based on ratio, meaning it is non-linear, the NDVI can be influenced by the additive effects of noise, such as additive atmospheric effects like path radiance. Besides that, the NDVI is very sensitive to the substrate under the canopy, where the higher values occur with darker substrates.

Nevertheless, the main limitation of the NDVI is saturation, when the LAI is high, (WANG et al., 2005). The index efficiency decreases when the target has a high biomass. With the development of the vegetation cover, there is an increasing value of NDVI. However, the saturation point of the IAF is 2-3, in the red, and 6-8 in the infra-red band. Since these bands are those ones used to obtain the NDVI, the result is a reversal of this trend and a fall in the NDVI value, due to saturation points and the shadow effect from tree canopies.

The radiance response in the red band has an inverse non-linear relation with the green biomass. Such a response is due to the dominant process of absorption (proportional to the amount of chlorophyll) by a canopy, caused by photosynthetic pigments. This explains the photosynthetic sensitivity of this index. On the other hand, the near-infrared region presenting radiance measurements that are captured by the sensor, are directly linked to the process of intra and interlayer scattering, which depend on the amount of existing leaves as well as on their distribution and spatial arrangement on a canopy (PONZONI, 2001).

CONCLUSIONS

The analysis of the variability among NDVI, EVI and LSWI, in different seasons, unveiled some important features of the Pantanal Region. In general, the NDVI showed the highest values in both seasons. This index tends to saturate the images, thus exposing one of its weaknesses. The NDVI also showed a low amplitude in the wet season, indicating low discriminatory power for the identification of vegetation classes, for this season.

The EVI was more sensitive than LSWI for the dry season, except in the Evergreen Forest class. In the rainy season, the LSWI showed higher values and greater amplitude compared to the EVI, presenting better discrimination of intra-class variations of the vegetation.

Regarding the precipitation correlation, the indices showed low values for the dry season. As for the rainy season, only the EVI did not correlate significantly with precipitation in the Deciduous Tropical Forest and Savannah classes

Especially for the dry season, the results corroborate with other studies on the LSWI, demonstrating that this index is a good indicator of the moisture content from the vegetation. The LSWI, presenting higher values than the EVI, is particularly significant, if one considers the assessment of Evergreen Forest formations that are more resistant to the seasonality of the precipitation.

Therefore, among the analyzed indices, LSWI proved to be most suited for the Pantanal Region, because it captures better the changes of vegetation, which are especially useful to monitor the Savannah and Deciduous Tropical Forest biomes, during the rainy season, and Evergreen Forest during the dry season. This index showed the largest amplitude for all land cover classes analyzed in both seasons, indicating a stronger discrimination capacity for vegetation types. We stress that an evaluation of these indices related to the inter-annual variability of rainfall is needed, as well as more detailed analysis of the phenologic characteristics from vegetation cover classes.

REFERENCES

ADAMI, M.; FREITAS, R. M.; PADOVANI, C. R.; SHIMABUKURO, Y. E.; MOREIRA, M. A. Estudo da dinâmica espaço-temporal do bioma Pantanal por meio de imagens MODIS. **Pesquisa Agropecuária Brasileira**, v. 43, n. 10, p. 1371-1378, 2008.

ADEYEWA, Z. D.; NAKAMURA, K. Validation of TRMM radar rainfall data over the major climatic regions in Africa, **J. Appl. Meteorol. Climatol.**, 42, p. 331 – 347, 2003.

ALVES, L. M. Climatologia da Região Centro-Oeste. In: CAVALCANTI, I. A. F; FERREIRA, N. J.; SILVA DIAS, M. A. F.; SILVA, M. G. A. J. (Org.). **Tempo e Clima no Brasil.** São Paulo: Oficina de Textos, 2009.

ANTUNES, J. F. G.; ESQUERDO, J. C. D. M. Geração automática de produtos derivados de imagens AVHRR-NOAA para monitoramento de áreas inundáveis do Pantanal. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 1. (GEOPANTANAL), 2006. Campo Grande. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2006. CD-ROM.

ANTUNES, J. F. G.; ESQUERDO, J. C. D. M. Geração automática de produtos derivados de imagens AVHRR-NOAA para monitoramento de áreas inundáveis do Pantanal. **Revista Brasileira de Cartografia**, v.59, p.115-122, 2007.

APARÍCIO, C.; ALVALÁ, R. C. S.; BECERRA, J. A. B. Metodologia de avaliação espaço-temporal da transição Pantanal-Cerrado-Amazônia. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 2. (GEOPANTANAL), 2009. Corumbá. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2009.

BECERRA, J. A. B.; SHIMABUKURO, Y. E.; ALVALÁ, R. C. S. Relação do padrão sazonal da vegetação com a precipitação na região de Cerrado da Amazônia Legal, usando índices espectrais de vegetação. **Revista Brasileira de Meteorologia**, v. 24, n. 2, p. 125-134, 2009.

CARDOZO, F. S.; PEREIRA, G.; SILVA, G. B. S.; SILVA, F. B.; SHIMABUKURO, Y. E.; MORAES, E. C. Discriminação de áreas alagadas no Pantanal sul-matogrossense a partir de imagens orbitais. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 2. (GEOPANTANAL), 2009. Corumbá. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2009. CD-ROM.

CHIU, L.S., LIU, Z., VONGSAARD, J., MORAIN, S., BUDGE, A., NEVILLE, P., BALES, C. Comparison of TRMM and water district rain rates over New Mexico. **Advances in Atmospheric Sciences**, v. 23, n. 1, p. 1-13, 2006.

COELHO. F. A.; PARANHOS FILHO, A. C.; ALBUQUERQUE, L. M. M. Comportamento sazonal da cobertura do vegetal no estado de Mato Grosso do Sul. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 1. (GEOPANTANAL), 2006. Campo Grande. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2006.

DINKU, T., CECCATO, P., GROVER-KOPEC, E., LEMMA, M., CONNOR, S.J., ROPELEWSKI, C.F. Validation of satellite rainfall products over East Africa's complex topography. **International Journal of Remote Sensing**, v. 28, n. 7, p. 1503-1526, 2007.

EMBRAPA. **Levantamento e mapeamento dos remanescentes da cobertura vegetal do bioma Pantanal, período de 2002 na escala de 1:250.000.** Campinas: Embrapa Informática Agropecuária. 2004. 43 p.

FEIDAS, H. Validation of satellite rainfall products over Greece. **Theoretical and Applied Climatology**, v. 99, n. 1-2, p. 193-216, 2010.

FERRARI, D. L.; SILVA, J. S. V.; ABDON, M. M. Avaliação do uso de NDVI em imagens CBERS-2B/CCD na caracterização de pastagens degradadas no município de Camapuã, MS. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 2. (GEOPANTANAL), 2009. Corumbá. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2009. CD-ROM.

FREITAS, R. M.; ADAMI, M.; SUGAWARA, L. M.; SHIMABUKURO, Y. E.; MOREIRA, M. A. Dinâmica da resposta espectral de duas sub-regiões do Pantanal Sul–Matogrossense. In: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 13. (SBSR), 2007, Florianópolis. **Anais...** São José dos Campos: INPE, 2007. p. 3921-3928. CD-ROM; On-line. ISBN 978-85-17-00031-7. (INPE-16368-PRE/10946). Available at: <http://urlib.net/dpi.inpe.br/sbsr@80/2006/11.15.21.42>. Access in: 23 nov. 2010.

GOLTZ, E.; BRANDÃO, D.; TOMÁS, L. R.; MANTELLI, L. R.; ADAMI, M.; SHIMABUKURO, Y. E.; FORMAGGIO, A. R. Utilização de índices espectrais de vegetação (MODIS) na determinação de áreas suscetíveis a alagamento no Pantanal Sul-matogrossense. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 1. (GEOPANTANAL), 2006. Campo Grande. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2006. CD-ROM.

GOLTZ, E.; BRANDÃO, D.; TOMÁS, L.; MANTELLI, L. R.; ADAMI, M.; SHIMABUKURO, Y. E.; FORMAGGIO, A. R. Utilização de índices espectrais de vegetação do sensor MODIS na determinação de áreas suscetíveis a alagamento no pantanal sulmatogrossense. **Revista Brasileira de Cartografia**, v. 59, n. 1, p. 35-44, 2007.

HARDISKY, M.A., KLEMAS, V., SMART, R.M. The influence of soil salinity, growth form, and leaf moisture on the spectral radiance of Spartina alterniflora canopies. **Photogrammetric Engineering & Remote Sensing**, v. 49, n. 1, p. 77-83, 1983.

JENSEN, J. R. **Sensoriamento Remoto do Ambiente:** Uma perspectiva em Recursos Terrestre. 2ª ed. São José dos Campos: Parêntese, 2009.

JUSTICE, C.O.; VERMOTE, E.; TOWNSHEND. J. R. G.; DEFRIES, R.; ROY, P. D; HALL, D. K, SALOMONSON, V.;PRIVETTE, J. L.; RIGGS, G.; STRAHLER, A.; LUCHT, W.; MYNENI, B; KNYAZIKHIN, Y.; RUNNING, W. S.; NEMANI, R. R.; WAN, Z.; HUETE, A. R.; LEEUWEN, W. V.; WOLFE, R. E.; GIGLIO, L.; MULLER, J. P; LEWIS, P.; BARNSLEY, M. The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research. **IEEE Transactions on Geoscience and Remote Sensing**, v. 36, n. 4, p. 1228-1247, 1998.

LACRUZ, M. S. P.; SOUSA JÚNIOR, M. A. Uso de séries temporais EVI/MODIS e análise harmônica para o estudo da bacia do rio Taquari. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 1. (GEOPANTANAL), 2006. Campo Grande. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2006. CD-ROM.

LACRUZ, M.S.P.; SOUSA JÚNIOR, M. de A. Uso de séries temporais EVI/MODIS e análise harmônica para o estudo da bacia do rio Taquari. **Revista Brasileira de Cartografia**, v.59, n. 1, p.9-15, 2007.

MORAES, E. C.; PEREIRA, G.; ARAI, E. Uso dos produtos EVI do sensor MODIS para a estimativa de áreas de alta variabilidade intra e interanual no bioma Pantanal. **Geografia.** Rio Claro. v. 34, número especial, p. 757-767, Dez. 2009.

NICÁCIO, R. M.; ARAUJO, L. L.; GONZAGA, E. P.; LIBOS, M.; OLIVEIRA, L. M. T. Relação NDVI e precipitação na bacia do rio Coxim – MS. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 2. (GEOPANTANAL), 2009. Corumbá. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2009.

NIMER, E. **Climatologia do Brasil.** Rio de Janeiro: IBGE. 1979. 422 p.

PADOVANI, C.R.; ASSINE, M.L.; VIERA, L.M. Inundação no leque aluvial do rio Taquari. In: GALDINO, S.; VIEIRA, L.M.; PELLEGRIN, L.A. (Ed.). **Impactos ambientais e socioeconômicos na bacia do rio Taquari**: Pantanal. Corumbá: Embrapa Pantanal, 2005. p.183-198.

PONZONI, F. J. Comportamento Espectral da vegetação. In: Meneses, P. R [org].; Madeira Netto, J. S. [org.]. **Sensoriamento remoto:** reflectância dos alvos naturais. Brasília: UnB/ Embrapa Cerrados, 2001. 262 p.

RODELA, L. G.; QUEIROZ NETO, J. P. Estacionalidade do clima no Pantanal da Nhecolândia, Mato Grosso do Sul. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 1. (GEOPANTANAL), 2006, Campo Grande. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2006. p. 126-135. CD-ROM. ISBN 85-17-00029-3.

RODELA, L.G. **Unidades de vegetação e pastagens nativas do Pantanal da Nhecolândia, Mato Grosso do Sul**. Tese (Doutorado). São Paulo: Fac. Filosofia, Letras e C. Humanas, Universidade de São Paulo, 2006, 222p.

RUDORFF, B. F. T.; SHIMABUKURO, Y. E.; CEBALLOS, J. C. (Coord.). **Sensor MODIS e suas Aplicações Ambientais no Brasil.** 1.ed. São José dos Campos: Editora Parêntese, 2007. 425 p.

SANTOS, J. S.; PEREIRA, G.; SHIMABUKURO, Y. E.; RUDORFF, B. F. T. Identificação de áreas alagadas no bioma Pantanal – Brasil – utilizando dados multitemporais Terra/ MODIS. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 2. (GEOPANTANAL), 2009. Corumbá. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2009. CD-ROM.

SIMPSON, J., KUMMEROW, C., TAO, W.-K., ADLER, R.F. On the tropical rainfall measuring mission (TRMM). **Meteorology and Atmospheric Physics**, v. 60, n. 1-3, p. 19-36, 1996.

VIANA, D. R. **Comportamento espaço-temporal da precipitação na Região Sul do Brasil utilizando dados TRMM e SRTM**. 2009. 162 p. (INPE-15738-TDI/1484). Dissertação (Mestrado em Sensoriamento Remoto) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos. 2009.

VICTORIA, D. C.; ANDRADE, R. G.; PAZ, A. R. Série temporal de imagens EVI/MODIS para discriminação de formações vegetais do Pantanal. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 2. (GEOPANTANAL), 2009. Corumbá. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2009.

VIEIRA, R. M. S. P.; ALVALÁ, R. C. S.; FERRAZ NETO, S.; MELLO, E. M. K. Metodologia para mapeamento da vegetação e uso da terra da região do Mato Grosso do Sul para utilização em modelagem meteorológica. In: SIMPÓSIO DE GEOTECNOLOGIAS NO PANTANAL, 1. (GEOPANTANAL), 2006. Campo Grande. **Anais...** Campinas: Embrapa Informática Agropecuária; São José dos Campos: INPE, 2006. CD-ROM.

WANG, Q., ADIKU, S., TENHUNEN, J., GRANIER, A. On the relationship of NDVI with leaf area index in a deciduous forest site. **Remote Sensing of Environment**, n. 94, n. 2, p. 244-255, 2005.

WILSON, E. H.; SADER, S. A. Detection of forest harvest type using multiple dates of Landsat TM imagery. **Remote Sensing of Environment**, v. 80, p. 385-396, 2002.