# MONITORING THE TEMPORAL DYNAMICS OF FOUR VEGETATION COVER TYPES FROM THE PANTANAL USING THE WAVELET TRANSFORM APPLIED TO A TIME-SERIES OF EVI/MODIS DATA

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## Abstract

Although one of the most preserved ecosystems in Brazil, the Pantanal suffers under problems such as fire, deforestation and changes in the flood and drought cycles. Monitoring all the extension of the Pantanal is essential to detect problems related to land use changes and to infer on the level of floods in the wetlands. The objective of this study was to monitor four areas in the Pantanal with different vegetation cover using the Wavelet Transform applied to a time-series of EVI (Enhanced Vegetation Index) acquired from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, between 2005 and 2009, in order to analyze the vegetation phenology dynamics. The results showed that the Coiflet Wavelet Transform of 4$^{th}$ order with 90% power, was able to remove the high frequency noise and highlight the changes of the vegetation phenology with a higher precision, allowing a better analysis of trends in the inter-annual variability of EVI. Changes of the temporal EVI pattern may indicate changes in vegetation phenology, mainly due to rainfall seasonality. The technique is robust and can be extrapolated to other regions of the Pantanal in order to detect deforestation and fire occurrences.

**Key words:** Remote sensing. Image processing. Vegetation index. Temporal profile. Phenology detection.

## Resumo

### Monitoramento da dinâmica temporal de quatro coberturas vegetais do pantanal utilizando a transformada de *wavelet* em séries temporais de dados EVI/MODIS

Embora seja um dos ecossistemas mais conservados do Brasil, o Pantanal está sujeito a problemas como o fogo, desmatamentos e alterações dos ciclos de cheia e seca. O monitoramento de toda a extensão do Pantanal é fundamental para a detecção de problemas relacionados a alterações do uso do solo, assim como inferir sobre o nível das cheias que ocorrem na planície. O objetivo deste trabalho foi realizar o monitoramento de quatro áreas com diferentes coberturas vegetais no Pantanal, utilizando a Transformada de *Wavelet* aplicada à série temporal de EVI (*Enhanced Vegetation Index*) do sensor MODIS (*Moderate Resolution Imaging Spectroradiometer*), do ano de 2005 a 2009, para analisar a dinâmica da fenologia da vegetação. Os resultados mostraram que a Transformada de *Wavelet* Coiflet, de ordem 4 com potência de 90%, conseguiu remover os ruídos de alta frequência e destacar as mudanças de fenologia da vegetação com mais precisão, propiciando uma melhor análise das tendências interanuais de variabilidade do EVI. As alterações do padrão temporal do EVI podem indicar mudanças na fenologia da vegetação, principalmente devido a sazonalidade da precipitação. A técnica mostrou ser robusta e pode ser extrapolada para outras regiões do Pantanal para detectar ocorrências de desmatamentos e queimadas.

**Palavras-chave:** Sensoriamento remoto. Processamento de imagens. Índice de vegetação. Perfil temporal. Detecção da fenologia.

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## INTRODUCTION

The Pantanal is one of the largest floodplains worldwide and houses a large wildlife concentration. Although it is one of the most preserved ecosystems from Brazil, with 85% of its' original habitat, it is affected by problems such as fire and deforestation. Furthermore, human changes of vegetation in the Alto Paraguai Basin influence the flood and drought cycles. So it is very important that this region is constantly monitored for the detection of changes on land use and land cover.

Due to the large extension of the Pantanal, satellite images became important tools to study the dynamics of vegetation, because they provide a synoptic view of the entire biome, allowing the analysis of changes occurring on the surface.

The MODIS (Moderate Resolution Imaging Spectrometer) sensor, aboard orbital platforms from the international EOS (Earth Observing System) from NASA, obtained data which were processed for global vegetation studies. The TERRA satellite was launched in December 1999, crossing the Equator at 10:30 a.m. (local time), in descending orbit (SOARES et al., 2007).

MODIS data, with moderate spatial resolution, high repeatability, good radiometric quality, high geometric precision, with atmospheric correction and cost-free distribution, have a great potential application to monitor vegetation (ZHANG et al., 2003).

From MODIS data it is possible to extract products of vegetation indices which enhance the spectral response of plants, reducing the influence of soil, aiming to distinguish the vegetation phenology and changes in land use/land cover at the analysis of a temporal image series (WARDLOW et al., 2007).

In this research line there are several studies related to the scope of this work and several standing out scientific articles which use temporal series of the Enhanced Vegetation Index (EVI), to monitor the degree of fragmentation from the Amazon landscape and evaluate its impact on the ecological processes and habitat quality (FERREIRA et al., 2010), to observe the course of the flood dynamics in the Pantanal of Southern Mato Grosso, determining both those areas susceptible for flooding and dry areas (ADAMI et al., 2008), and also to detect changes of land cover to measure the increase of agricultural production in the Amazon region (BROWN et al., 2007).

The harmonic analysis has been used for the study of long temporal series of vegetation indices, based on changes occurring on the Earth surface, facilitating to understand the temporal dynamics.

One of the techniques used in temporal series, which normally have no periodicity due to the inherent vegetation vigor, is the Wavelet Transform, based on the fitting of a curve, aiming to remove the high frequencies associated to noise, remaining sensitive to changes in the plant phenology. This mathematical transformation is applied to process non-stationary signs to decompose and reset data in different temporal scales, to obtain hidden information in the frequency domain, where each scale is represented by a specific frequency (SAKAMOTO et al., 2005).

In this context, the objective of this work was to execute the temporal monitoring of four different vegetation cover types from the Pantanal, using the Wavelet Transform applied to the temporal series of EVI/MODIS data, from the timeframe 2005-2009, aiming to analyze the dynamics of vegetation phenology.

## MATERIAL AND METHODS

The biome of the Brazilian Pantanal has a size of approximately 160,000 km$^2$ of which 138,183 km$^2$ are located within the States Mato Grosso and Mato Grosso do Sul, inserted at the Alto Paraguai Basin (SILVA; ABDON, 1998), as illustrated by Figure 1. The Pantanal floodplain is the largest wetland area of the Planet, and it is temporarily flooded every year, during the rainy season, by the Paraguai and its' tributaries, due to the low slope of the relief, where cattle raising is the main activity. The average yearly temperature is 25.5º C and the annual rainfall varies between 1,000 and 1,400 mm. The rainy season occurs between December and May and the drought from June to November (JUNK et al., 2006).

In order to perform the temporal monitoring, four areas were selected which represent the main vegetation cover types of the Pantanal floodplain. Area 1 is composed by Semi-deciduous Seasonal Forest with trees 15 to 20 m high, which lose 20 to 50% of the leaves during the dry season, located at the margins of Taquari River. Area 2 is made up of Savanna Park Steppe with sparse trees and grass cover located at the Nabileque River, prone to inundation. Area 3 is covered by Planted Pasture with grass of brachiaria type, located at the subregion of Nhecolândia. Area 4 consists of irrigated rice plantation, using controlled inundation, located at the subregion of Miranda.

In each area spectral data were collected in a window of 2 x 2 pixels, encompassing a sample area of 250,000 m$^2$ (25 ha), in order to choose quite homogeneous sections since, due to the moderate spatial resolution of MODIS images, there is a certain level of spectral mixture of the phytophysiognomies found in the pixel set of each place. Due to this procedure, the sample areas reflect the spatial average of the spectral response of a set of similar phytophysiognomies which tend to represent an unique landscape pattern.

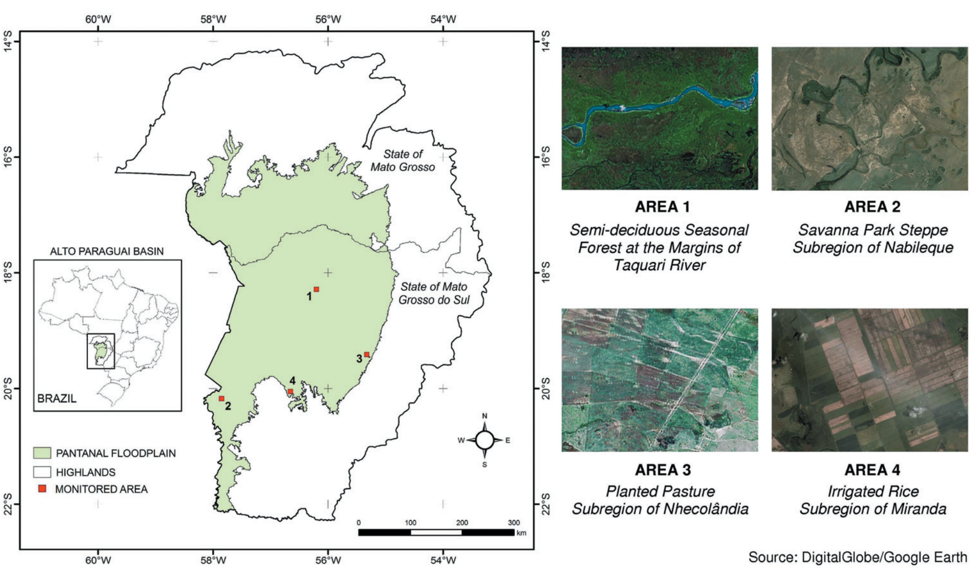



**Figure 1 - Alto Paraguai Basin and the four areas monitored in the Pantanal**

For this study the Vegetation Index MOD13Q1 of MODIS/TERRA with spatial resolution of 250 m was used, obtained free-of-charge of LP-DAAC (Land Processes Distributed Active

Archive Center), from EOS/NASA in form of tiles of 1,200 x 1,200 km, at HDF (Hierarchical Data Format) and on sinusoidal cartographic projection (LP-DAAC, 2009).

The data manipulation for the selection of product, mosaic, section of interest area and definition of the cartographic projection was done automatically by routines implemented on IDL (Interactive Data Language) of software from ENVI (ITTVIS, 2010), with the execution of programs from the free software package MRTools (MODIS Reprojection Tools) (LP-DAAC, 2010).

The product MOD13Q1 consists of pixel compositions of high radiometric quality, improved observation geometry, minimum presence of clouds and aerosols, selected from daily images during a period of 16 days. The present version is collection 5 which presents significant changes to increase the quality of the products (LATORRE et al., 2007).

The band of product MOD13Q1 selected for this work was from EVI (Enhanced Vegetation Index), aiming to better represent the vegetation dynamics along a temporal series. According to Huete et al. (2002) EVI was developed to optimize the spectral response of vegetation, improving the sensitivity in regions with higher biomass densities, besides propitiating to monitor the vegetation by the reduction of the effects of the canopy substratum and of atmospheric influences, calculated by Equation (1):

$$\mathrm{EVI} = \mathrm{G} \times \left[ \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{C}_1 \times \mathrm{RED} - \mathrm{C}_2 \times \mathrm{BLU} + \mathrm{L})} \right] \tag{1}$$

where:

BLU = Reflectance on band 3 of blue (459-479 nm);
RED = Reflectance on band 1 of red (620-670 nm);
NIR = Reflectance on band 2 of near infrared (841-876 nm);
G = 2.5 gain factor;
L = 1: canopy adjustment factor, adopted by LP-DAAC for the index generation;
$C_1$ = 6.0 and $C_2$ = 7.5: aerosol resistance coefficients using the blue band to reduce the influence of aerosols in the red band.

The values of coefficients $C_1$ and $C_2$ and of factors G and L, specified earlier, are based on Huete et al., (1994) and Huete et al. (1997) in order guarantee the sensitivity of EVI to most different landscapes, from deserts to dense forests. LP-DAAC adopts these same values for the generation of EVI, available on product MOD13Q1 of MODIS/TERRA. Although the MODIS products present information on the reliability of spectral values (pixel reliability), they are not considered in this study purposely, in order to evaluate the performance and to verify the robustness of the decomposition and filtering technique in temporal series, containing data with higher oscillation.

The rainfall distribution in the Pantanal can affect the standard of phenology peaks from vegetation. To help the analysis of temporal dynamics the accumulated rainfall data, calculation was done by interpolation of 72 rainfall gauges from Agritempo (Agrometeorological Monitoring System) (EMBRAPA INFORMÁTICA AGROPECUÁRIA; CEPAGRI/UNICAMP, 2009) in the States of Mato Grosso and Mato Grosso do Sul, for the entire temporal series.

For the decomposition and filtering of the temporal series of EVI/MODIS, the discrete Wavelet Transform was used, defined by Daubechies (1992) where $\phi(t)$ is a function of oscillation with finite energy and null average, according to Equation (2):

$$\int_{-\infty}^{+\infty} \phi(t)\,\mathrm{d}t = 0 \tag{2}$$

The Wavelet Transform W(a,b) is defined by Equation (3):

$$W(a,b)_i = \frac{1}{\sqrt{|a|}} \int \phi^* \left( \frac{t-b}{a} \right) s(t) \mathrm{d}t \quad (3)$$

where, s(t) is the entry signal analyzed and $\phi^*$ is the mother wavelet or base. In this equation, the width of the wavelet is determined by the scale parameter "a" and its' center is determined by parameter "b" with a, b $\in$ R e a $\neq 0$. To work with discrete signals normally special values are used for "a" and "b", being $a = 2^j$ e $b = k2^j$, com j, k Î Z. Changing the value of parameter "a" there is a dilatation (a > 1) or contraction (a < 1) effect, while changes on parameter "b" have a translation effect to analyze the function $\phi(t)$ around this point. The variable "t" represents the time interval in the temporal series where the integration is performed. The advantage of the Wavelet Transform is the maintenance of information related to width (scale) and localization (time) of the characteristics present in s(t). According to Gendrin et al. (2006), Equation (4) can be used to reconstruct the signal.

$$W = \sum_{i=1}^{x} W(a,b)_i \quad (4)$$

The temporal wavelet W is the sum of wavelets with decreasing widths of "i" to "x", where "x" is the number of transformations needed to reach a defined number of coefficients retained from input data. The wavelet filtering starts with the application of the smoothing function at the temporal series to remove high frequency noise. The smoothing temporal series of EVI is then reconstructed with the discrete Wavelet Transform.

The wavelet functions are obtained by a dilatation and a translation, forming a base which is not necessarily orthogonal. One of the advantages to work with orthogonal bases, such as the Wavelet called Coiflet is the possibility of the perfect reconstruction of the original signal from the wavelet coefficients (MORETTIN, 1999).

The application of the Wavelet Transform in a temporal series of EVI requires the definition of order and power of the mother wavelet which define the behavior of the curve. Order is a smoothness measure, where the highest values produce stronger smoothness. Power corresponds to the amount of retained coefficients from the temporal series EVI. A stronger power generates a narrower wavelet, which includes details of a finer scale, but it can also retain more noise. A lower power removes more noise due to the larger form of the wavelet and it could capture tendencies in all the temporal series, but it could loose phenologic details (GALFORD et al., 2008).

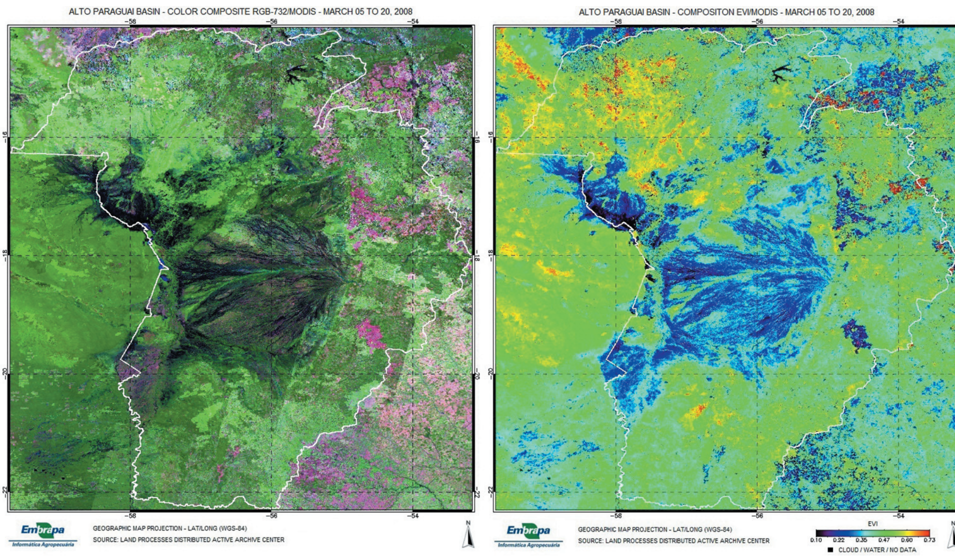
In this study we used discrete wavelet mother Coiflet, orthogonal and almost symmetric of 4th order, because its shape is more similar to phonologic peaks. The power used was of 90% to detect the peaks at the smoothed temporal series of EVI with higher precision and so, to allow an improved analysis of phenology patterns from vegetation (SAKAMOTO et al., 2005).To investigate only the tendencies of the temporal series of EVI, we used 70% and 50% power.

The processing was made using package IDL Wavelet Toolkit from ENVI, which is an implementation of a set from graphic interfaces and routines for the Wavelet Transform, based on Torrence & Compo (1998).

## RESULTS AND DISCUSSION

The MOD13Q1 image processing consisted on a mosaic of tiles H12V10, H12V11, H13V10, H13V11 which cover the area under study, the transformation for the geographic cartographic projection, the section with the borders of the Alto Paraguai Basin, the EVI product extraction and recording on format GeoTIFF. From this set we obtained compositions of 16 days for EVI from the timeframe January to December 2005 to 2009, 23 images for each year, totaling 115 images for the entire temporal series.

Figure 2 presents a color composite RGB-732 (mid-infrared, near infrared, red) and the EVI composition, representing the image processed in the timeframe March 5$^{th}$ to 20$^{th}$ 2008.




**Composite RGB-732** **EVI Composition**

**Figure 2 - MODIS products of the Alto Paraguai Basin**

Taking into account the details of the Earth surface allowed by the 250 m spatial resolution of a MODIS image, the derived products can be analyzed for applications in regional scale. The color composite RGB-732 offers a good contrast of targets from the Earth surface. Areas in darker green tone correspond to the natural vegetation, those in clear green tone to pastures and agriculture areas, those in magenta to bare soil and the dark ones to water bodies. The highest of the EVI composition appear in red and represent those areas of higher biomass with more vegetation. The lowest values appear in green or blue and constitute areas of low biomass, such as bare soil and swampy areas.

Figure 3 shows the graph of accumulated rainfall from 16 days of the four areas monitored in the timeframe 2005-2009.

Based on the understanding of the graph, one can perceive that the annual accumulated rainfall distribution on 16 days in the four areas monitored has similar oscillations, with drought periods occurring from June to November, recording maximum 50 mm rainfall and with precipitation periods extending from December to May, when volumes of up to 250 mm are recorded.

The rainfall regime in the Pantanal determines an alternation of the land cover conditions, which could affect the phenology pattern from the vegetation. There are higher located regions which are never flooded, low sections which are almost always underwater, as well as regions of intermediate altitude which are dry during the largest part of the year and flooded during some months.

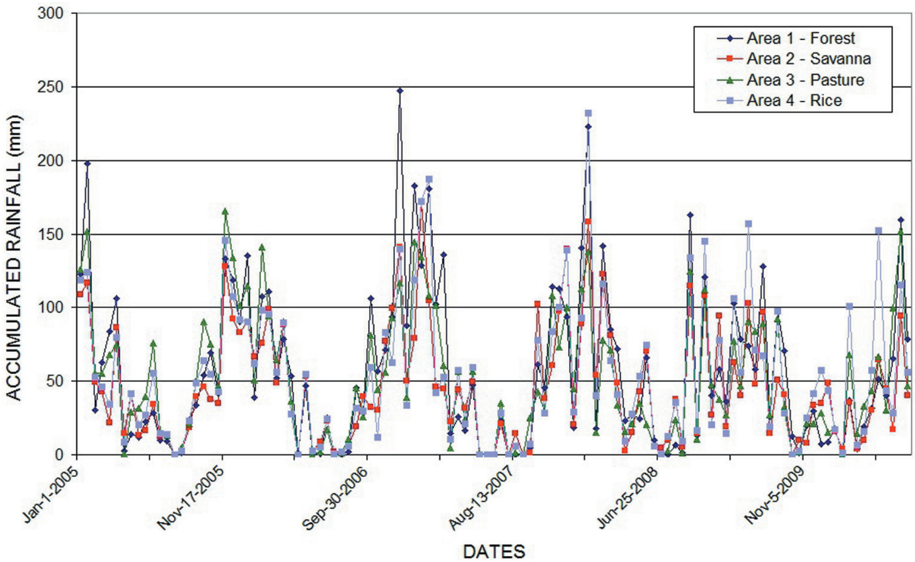


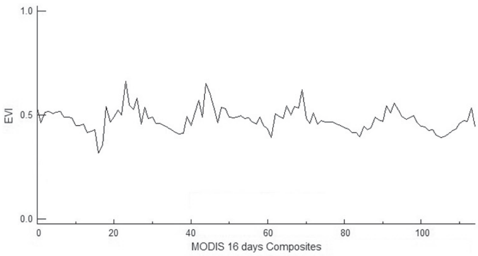

**Figure 3 - Accumulated rainfall from 16 days of the monitored areas between 2005 and 2009**

Source: Agritempo (2009).

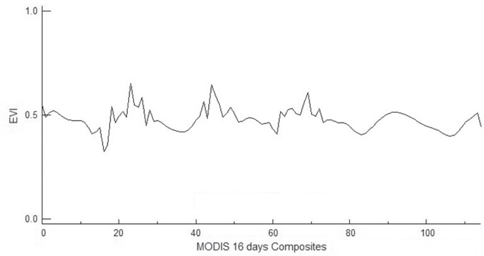
Based on that, monitoring was done of four areas with different vegetation cover in the Pantanal, using the Wavelet Transform applied to the temporal MODIS series of the timeframe 2005-2009. The dynamics of vegetation phenology was analyzed, according to what is presented in the sequence of figures 4, 5, 6 and 7.

In order to help understanding the graphs, the MODIS composition of 16 days with Nr. 1 starts on Jan. 1$^{st}$ 2005, Nr. 20 on Nov. 1$^{st}$ 2005, Nr. 40 on Sept. 14$^{th}$ 2006, Nr. 60 on July 28$^{th}$ 2007, Nr. 80 on June 9$^{th}$ 2008, Nr. 100 on April 23$^{rd}$ 2009 and Nr. 115 on Dec. 29$^{th}$ 2009.

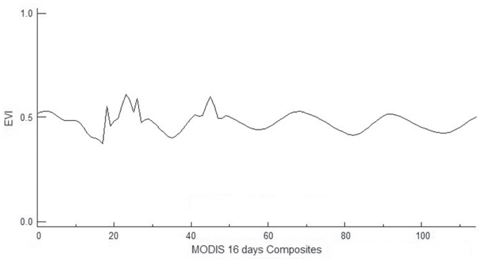
Figure 4 shows the graphs of the original EVI profile and smoothed by the Wavelet Coiflet, of 4th order, with 90%, 70% and 50% power, of Area 1 - Forest.



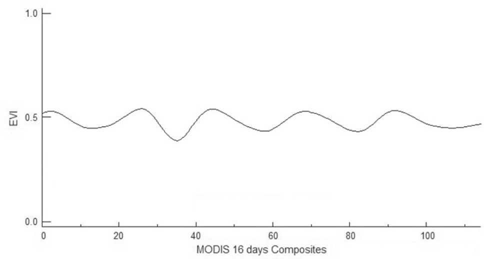

**Area 1 - Forest - Original Series**




**Area 1 - Forest - Smoothed Series - Power 90%**



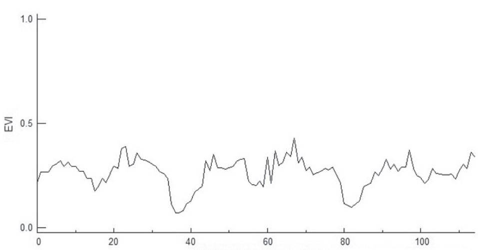

**Area 1 - Forest - Smoothed Series - Power 70%**



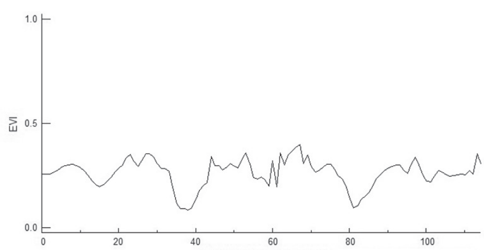

**Area 1 - Forest - Smoothed Series - Power 50%**

**Figure 4 - EVI temporal profile of Area 1 - Forest monitored between 2005 and 2009**

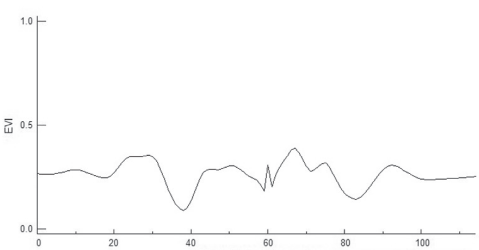
Figure 5 shows the graphs of original EVI profile and smoothed by Wavelet Coiflet, of 4th order with 90%, 70% and 50% power, of Area 2 - Savanna.



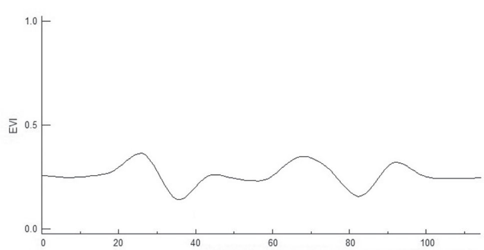

**Area 2 - Savanna - Original Series**




**Area 2 - Savanna - Smoothed Series - Power 90%**



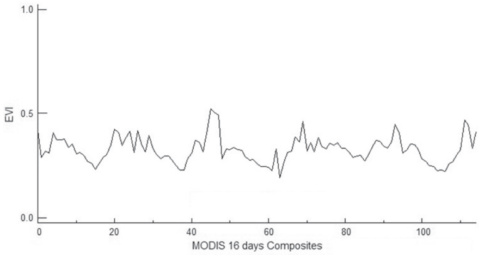

**Area 2 - Savanna - Smoothed Series - Power 70%**



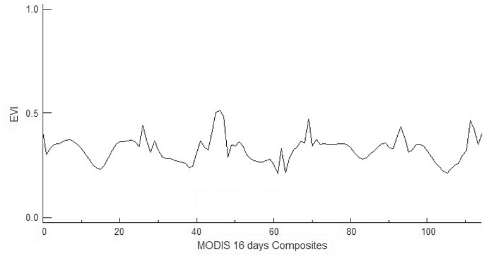

**Area 2 - Savanna - Smoothed Series - Power 50%**

**Figure 5 - EVI temporal profile of Area 2 - Savanna monitored between 2005 and 2009**

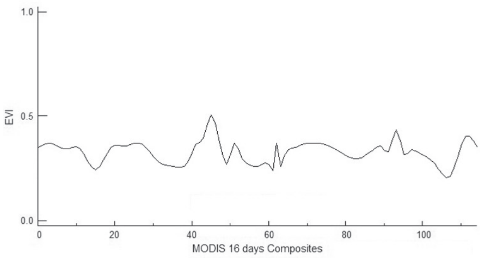
Figure 6 shows the graphs of original EVI profile and smoothed by Wavelet Coiflet, of 4th order with 90%, 70% and 50% power, of Area 3 - Pasture.



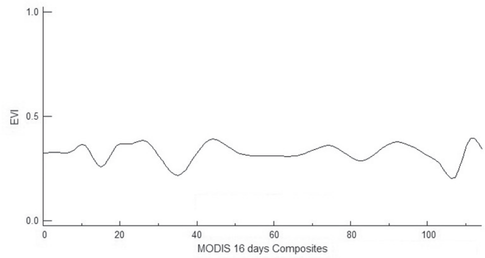

**Area 3 - Pasture - Original Series**




**Area 3 - Pasture - Smoothed Series - Power 90%**



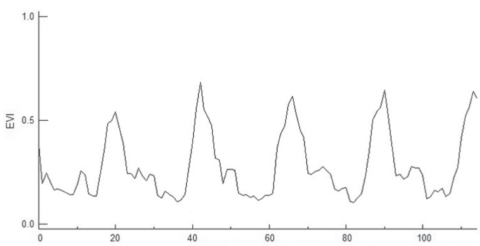

**Area 3 - Pasture - Smoothed Series - Power 70%**



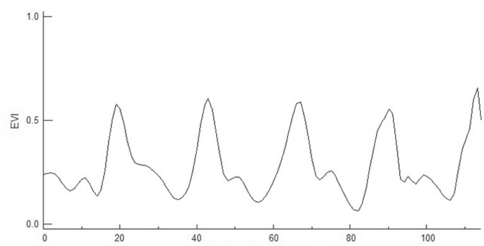

**Area 3 - Pasture - Smoothed Series - Power 50%**

**Figure 6 - EVI temporal profile of Area 3 - Pasture monitored between 2005 and 2009**

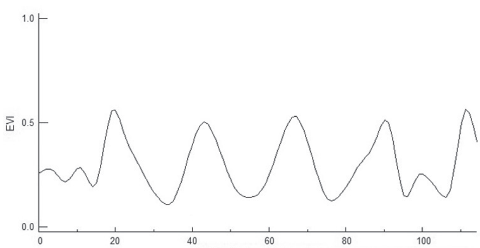
Figure 7 shows the graphs of original EVI profile and smoothed by Wavelet Coiflet, of 4th order with 90%, 70% and 50% power, of Area 4 - Rice.



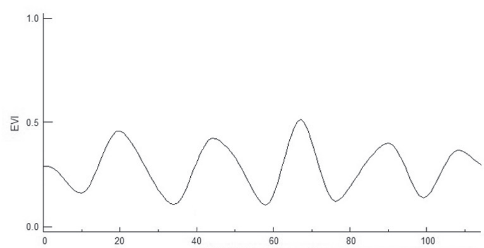

**Area 4 - Rice - Original Series**




**Area 4 - Rice - Smoothed Series - Power 90%**




**Area 4 - Rice - Smoothed Series - Power 70%**




**Area 4 - Rice - Smoothed Series - Power 50%**

**Figure 7 - EVI temporal profile of Area 4 - Rice monitored between 2005 and 2009**

The phenology of Area 1 - Forest (Figure 4) presents small variations of EVI between the dry and wet seasons, with values above 0.31, but not exceeding 0.67, keeping an average value of 0.48. This is a characteristic behavior of this vegetation type, formed by trees of medium size which loose part of its leaves during the dry season. The lowest values occur in June, during the dry period, and this is justified since the year 2005 had a long drought period.

The smoothed temporal series with power of 70% and 50% shows a cyclic tendency which is practically constant of EVI along the years, but the curves have a lower variation of values, with a reduction of important annual peaks of phenology from the forest.

The phenology of Area 2 - Savanna (Figure 5) has an average drop of EVI around 0.26, with some seasonal variations between 0.06 and 0.43. Since it is localized in a region of possible inundations, due to flooding in the Pantanal, this area can have a more marked variation of EVI, and it could decrease strongly, such as in July 2006 and 2008, years of large flooding. The dates for the occurrence of these EVI decreases change from year to year, due to changes of the flooding periods in the Pantanal and to the variation of the vegetation vigor.

The smoothed temporal series with power of 70% and 50% represents the tendency of slow EVI variation along the years, but the curves present an increase of the lowest values and loose the yearly important peaks for the characterization of the savanna phenology, mainly the occurrence details of the large flooding.

The phenology of Area 3 - Pasture (Figure 6) is not susceptible to the flooding regime. EVI has an average around 0.32, larger than Area 2 - Savanna, and smaller than Area 1 - Forest, with small seasonal variations between 0.18 and 0.52, decreasing in dryer times of the year due to the decrease of vegetation vigor and increasing during the rainy season, such as in December 2006.

The smoothed temporal series with 70% and 50% power presents a tendency of small season EVI variations along the years, however the curves have a decrease of the highest values and loose important details for the characterization of pasture phenology, such as the peaks with higher or lower vigor of vegetation.

The phenology of Area 4 - Rice (Figure 7) shows large EVI variations with bimodal temporal pattern, related to different development cycles during the year, where cycle is characterized by a maximum in the temporal series. EVI values increase strongly after September, with the highest peak in November and another lower peak in March. In this temporal series, EVI can grow 0.10 at the beginning of the agricultural cycle up to 0.70 at the vegetative peak, with an average value of 0.28. This abrupt variation is related to the high spectral dynamics of the rice culture which presents bare soil at the beginning of the cycle and a high biomass quantity during the period of highest vegetative vigor.

The smoothed temporal series with power of 70% and 50% presents a tendency of large EVI variations along the years, the curves however have a reduction of the highest values and loose very important annual peaks of phenology characterization from rice culture so as to not detecting the temporal bimodal pattern of cultivation which occurs all years.

When comparing the results obtained from the analysis of graphs of figures 4, 5 6 and 7 with data from accumulated rainfall shown on figure 3, we verified that in not changed by men, 1 - Forest, 2 - Savanna and 3 - Pasture, the biomass peaks coincide with periods of higher rainfall, in spite of a time interval between the beginning of the rain season and the response of vegetation. In Area 4 - Rice, the biomass peaks occur some weeks before the precipitation peaks, due to specific phenology characteristics of the irrigated rice culture.

The fitting of the curve generated by the Coiflet Wavelet Transform, of 4$^{th}$ order and 90% power was evaluated by the RMS error among the difference of the temporal original and smoothed EVI for the four monitored areas, as shown on table 1.

**Table 1 - Retained coefficients and RMS error of the smoothed curves for the four areas**

| Area | Retained Coefficients (%) | RMS Error | RMS Error (%) |
|---|---|---|---|
| 1 - Forest | 27.3 | 0.0164 | 30.0 |
| 2 - Savanna | 25.0 | 0.0212 | 30.1 |
| 3 - Pasture | 25.8 | 0.0191 | 30.0 |
| 4 - Rice | 15.6 | 0.0464 | 30.0 |

The smoothed curve fittings for the four areas obtained a quite similar performance with the RMS error magnitude around 30.0%. The fitting of Area 4 - Rice can be considered the most precise because it retained only 15.6% of the coefficients from the original time series for the reconstruction of the smoothed curve, with the same error level from the other curve fittings.

One must observe that the analysis done from the MODIS data are applied ion regional scale and therefore they could have limitations inherent to the details of the surface with 250 m of spatial resolution. In spite of that, it must be emphasized that the results obtained with the understanding of the temporal EVI dynamics in the four areas monitored, could be extrapolated to other regions within the Pantanal, where samples of homogeneous vegetation types could be extracted, and so increasing the representativeness of the method used in the study, in terms of extension.

## CONCLUSIONS AND SUGGESTIONS

The results of this work showed the potential of temporal monitoring at the detection of phenology patterns on four predominant vegetation cover types from the Pantanal, whose understanding is important to verify its inter-annual variations.

The Coiflet Wavelet Transform of 4$^{th}$ order and 90% power applied to the EVI/MODIS temporal series is a quiet robust technique because it succeeded in the removal of high frequency noise and detached changes on vegetation phenology with higher precision, propitiating an improvement on the analysis of variability tendencies of EVI. Changes at the temporal pattern of EVI may indicate changes of vegetation phenology, especially due to the seasonality of rainfall.

Variations of the temporal pattern from EVI however can also denote changes of vegetation caused by other natural or human actions. For the continuation of this study we suggest to aggregate geo-referenced historical information from the areas in the Pantanal which suffered deforestation and burning, where vegetation cover was eliminated in order to verify changes in the EVI pattern. After monitoring the temporal dynamics of vegetation it would be possible to detect abrupt variations of the spectral patterns related to the occurrence of these events.

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