Revista Brasileira de Geofísica
RBGf
Brazilian Journal of Geophysics

Revista Brasileira de Geofísica (2013) 31(4): 569-578
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ISSN 0102-261X
www.scielo.br/rbg

PHENOLOGICAL CHARACTERIZATION OF COFFEE CROP (*Coffea arabica* L.) FROM MODIS TIME SERIES

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ABSTRACT. Arabica Coffee (*Coffea arabica* L.) demonstrates a two-year phenological cycle, this knowledge is important for crop forecast in Brazil. This work aimed to describe the coffee crop phenology from MODIS vegetation index time series. The study area is located in the western Bahia State, Brazil, due to its remarkable agribusiness development. MODIS time series data comprehended 10-year Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). However, these times series are usually contaminated by noise caused by atmospheric variations that are harmful to the surface discrimination. Median filter and the Minimum Noise Fraction (MNF) were used together to smooth the original dataset. NDVI and EVI temporal profiles showed differences of amplitude and gradient. The results evidenced the Arabica Coffee phenological stages, as described in previous fieldworks. These results showed potential application for large-area land cover monitoring.

Keywords: vegetation index, remote sensing, digital image processing.

RESUMO. O Café Arábica (*Coffea arabica* L.) apresenta um ciclo fenológico de dois anos, sendo relevante o seu conhecimento para a previsão de safras no Brasil. O objetivo deste trabalho foi caracterizar a fenologia da cultura de café a partir de séries temporais de índices de vegetação do sensor MODIS. A área de estudo está localizada no oeste do estado da Bahia, Brasil, devido ao seu notável desenvolvimento do agronegócio. As séries temporais MODIS compreendem 10 anos do Normalized Difference Vegetation Index (NDVI) e Enhanced Vegetation Index (EVI). Contudo, essas séries temporais apresentam ruídos ocasionados por efeitos atmosféricos que prejudicam a discriminação dos alvos da superfície. O filtro de mediana e a transformação Fração Mínima de Ruído (FMR) foram usados em conjunto para suavizar os dados originais. Os perfis temporais NDVI e EVI apresentam diferenças de amplitude e gradiente. Os resultados evidenciaram os estágios fenológico do Café Arábica, como descritos em prévios trabalhos de campo. Esses resultados possuem potencial de aplicação para o monitoramento do uso da terra em extensas áreas.

Palavras-chave: índices de vegetação, sensoriamento remoto, processamento digital de imagem.

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INTRODUCTION

The monitoring of agricultural crops has implications for the economy, society, politics and environment (Ozdogan, 2010). The biophysical characteristics and phenological stages of crops are important for irrigation system, comprehension of seasonal exchange of carbon dioxide, productivity model, and in the prediction of net primary production (Bouman et al., 2001; Kimball et al., 2004; Sakamoto et al., 2010).

Spatial studies of crop phenology have been made from individual field evaluations, with high cost and without continuous spatial information (Ozdogan, 2010). In order to minimize these limitations, remote sensing has been used as a complementary tool for the detection of seasonal variations (Sakamoto et al., 2005; Xavier et al., 2006; Galford et al., 2008; Wardlow & Egbert, 2008). The vegetation indices are widely used in remote sensing images due to their correlation with biophysical changes in plants (Huete, 1985), being associated with the seasonal life cycles with specific duration, occurrence, synchrony and symmetry (Rathcke & Lacey, 1985). The Arabica Coffee (*Coffea arabica* L.) has a phenological cycle of two years, unlike the normally observed in other plants (Camargo & Camargo, 2001). This article aims to describe the phenology of Arabica Coffee plantation using NDVI-MODIS time-series.

Coffea arabica L. Phenology

Arabica Coffee is a plant native to Ethiopia and South Sudan, at altitudes between 1,600 m and 2,000 m, where the air temperature is between 18°C and 20°C and annual rainfall varies from 1,500 mm to 1,800 mm, being well-distributed, with a dry season periods (4-5 months) (Livramento, 2010; Meireles et al., 2009).

In Brazil, all the coffee production is located at latitudes greater than 4°, tropical/sub-tropical regions (Assad et al., 2001). The Cerrado biome corresponds to about 40% of the national production of coffee (Guerra et al., 2005a). The coffee phenology is subject the agrometeorological conditions, being affected by photoperiodic variations, rainfall distribution and air temperature, which affect productivity and product quality (Meireles et al., 2009). Recent studies have established the duration and magnitude of water stress for uniform flowering of the coffee in Central Brazil (Guerra et al., 2005b).

The complete phenological cycle of coffee is for two years, with the development of vegetative branches in the first year and flowering in the second year (Camargo & Camargo, 2001). Among the various models developed, we adopt the subdivision proposed by Camargo & Camargo (2001) with six phenological stages: two stages in the first year and four stages in the second year.

In the first phenological year, the first phase develops vegetative buds, usually occurring between September and March, when the days are longer (Camargo & Franco, 1985). The second stage marks the reproductive phase with induction, differentiation, growth and dormancy of flower buds, from April to August. Over the last two months, the dormant buds produce a pair of small leaves, marking the end of the first phonological year (Camargo & Camargo, 2001).

In the second year phenological, the third phase (September to December) starts at blossom after water stress, achieving the expansion of the fruits (Camargo & Franco, 1985). Fourth stage occurs between January and March with the grain formation, when a water stress can be detrimental to the development of these grains (Meireles et al., 2009). Fifth stage corresponds to the fruit maturation between April and June, with a moderate water deficit that benefits the product. In the last stage there is the self-prunning process represented physiologically by senescence (July-August), when the productive branches wither and die, limiting its vegetative growth (Camargo & Camargo, 2001).

Orbital Monitoring of Coffee Plantation

Few studies have been conducted with satellite images to distinguish coffee plantation until the 1990s (Tardin et al., 1992). Moreira et al. (2004) studied coffee crop (*Coffea arabica* L.) on two occasions of development, with less and more than five years old. These authors show that the spectral response in the TM-Landsat images of the coffee crops $<$ 5 years is similar to the pasture in the red and mid-infrared wavelengths. In contrast, the coffee plantation $>$ 5 years showed spectral differences.

Techniques for monitoring and estimates of coffee production are becoming more advanced, especially in the spatial-temporal analysis (Moreira et al., 2011a), spectral analysis (Vieira et al., 2006; Machado et al., 2010), and data integration from different sensors such as MODIS and high spatial resolution images available on Google Earth (Bernardes et al., 2011; Moreira et al., 2011b).

Study Area

The study area is located within the Ecoregion of the Chapadão do São Francisco (Arruda et al., 2006) in the Cerrado biome (Fig. 1A), between the municipalities of Luis Eduardo Magalhães (LEM) and Barreiras (Fig. 1B) (IBGE, 2008). The climate of the study area is divided in two well-defined seasons: a dry and cold season (from May to September) and a rainy and hot season (from October to April). The annual average precipitation is around 1.500 mm and annual average maximum and minimum temperature varies between 21.3°C and 27.2°C, respectively (Batistella et al., 2002; Meirelles, 2009). The soils are predominantly deep, intensely weathered, well-drained, nutrient-poor and acid, standing out Latosoil and Neosoil (Batistella et al., 2002). This region has growth potential for coffee crop, since the production systems are improved (Guerra et al., 2007). In the study area, the coffee plantations were started in 2000 (Fig. 1C).

MATERIALS AND METHODS

MODIS Data

Moderate resolution Imaging Spectroradiometer (MODIS) sensor is onboard the TERRA and AQUA platforms, acquiring images with high temporal-resolution (Justice et al., 2002). The images are corrected for atmospheric effects and georeferenced (Wolfe et al., 1998). MOD13 product is related to vegetation indices: Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), generated from the daily surface reflectance (MOD09) (Vermote et al., 2002). MOD13 product is a 16-days composite. In this work, both indices were used. The NDVI is the most widely used index, having the following formulation (Rouse et al., 1973):

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$

where, ρ_{NIR} is the near-infrared reflectance value (800-1100 nm) and ρ_{red} is the red reflectance value (600-700 nm). NDVI values range from -1 to 1.

EVI index reduced the saturation problem described by the NDVI in high biomass areas (Hobbs, 1995; Gilabert et al., 1996) and minimizes the atmosphere influences. The EVI is expressed by the following equation (Justice et al., 1998; Huete et al., 2002):

$$EVI = G\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C1\rho_{red} - C2\rho_{blue} + L}$$

where ρ_{blue} is the blue reflectance value (459-479 nm); G is a gain factor; $C1, C2$ are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band, and L functions as the soil-adjustment factor. The coefficients used in the MODIS EVI algorithm are, $G =$ 2.5, $C1 =$ 6, $C2 =$ 7.5, and $L =$ 1 (Justice et al., 1998; Huete et al., 1994; 1997).

Denoising Procedures for MODIS time series

This paper used time series of MODIS vegetation indices concerning to a period of 11 years (between 2000 and 2010), totaling 224 scenes with spatial resolution of 250 meters. The images were arranged in three dimensions, where X and Y axes represent the geographical coordinates and the Z axis the temporal profile (Fig. 2).

The following methods were used to noise reduction: median filter and Minimum Noise Fraction (MNF) transform (Carvalho Júnior et al., 2012). The median filter had a 7×7 window dimension and was applied over the time series. The median is determined by sorting all observation inside window from lowest pixel value to highest pixel value and takes the middle value, being a non-linear method. In addition, the MNF transformation was applied to the temporal images, which combines both the procedures for segregation of the noise component as well as to reduce data dimensionality (Green et al., 1988). This methodological sequence was successfully applied to MODIS time series to characterize the Cerrado vegetation (Carvalho Júnior et al., 2008, 2009, 2012). Some previous studies adopt only MNF transformation in noise reduction of time series, but have limitations with impulse noise (Carvalho Júnior et al., 2006; Couto Junior et al., 2011, 2012; Santana et al., 2010).

NDVI and EVI temporal profiles for phenological characterization of Arabica Coffee

Average time series of a coffee plantation (625,000 m^2) was calculated for each vegetation index (Fig. 1C). The phenological characterization of Arabica Coffee was performed from these temporal signatures, considering the six stages of Campbell & Campbell (2001).

The phenological transitions in the Arabica Coffee were found by calculating the first derivative. The cafe plantation behavior was compared with the Cerrado Sensu Stricto, in order to assess the ecological functioning of the irrigation system within that environment.

RESULTS AND DISCUSSION

Results of Noise Reduction

The median filter provided a significant reduction of impulse noise, consisting mainly by cloud cover and their respective shadows (Fig. 3). In addition, the MNF transformation eliminated the white-noise. The selection of first twenty MNF components containing less noise was performed by analyzing the eigenvalues plot. Thus, the MNF inverse transform using only the signal components reversed the data to the original values without noise (Fig. 3).

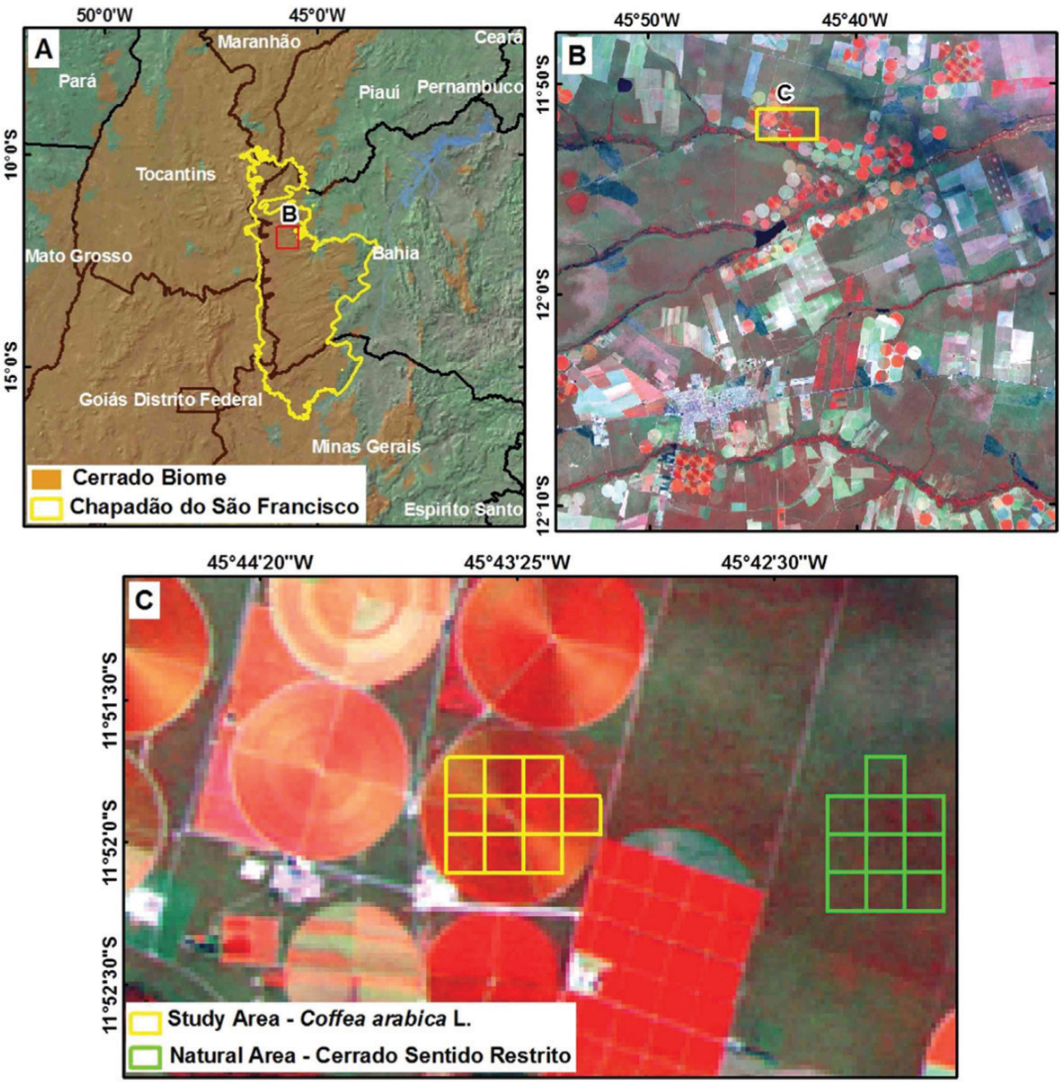

Figure 1 – Ecoregion of the Chapadão do São Francisco inside the Cerrado Biome (A); area with coffee plantations (B); study area with MODIS grid (250 meters spatial resolution) over the natural vegetation and coffee plantation in central pivot (C).

Results phenological analysis of Arabica coffee using time series

The NDVI index showed higher values than the EVI ($\sim$20%) (Fig. 3). On the other hand, the NDVI profile had lower seasonal amplitudes than the EVI. The NDVI values between 2000 and 2002 demonstrated a constant increase in the photosynthetic activity. In those first 24 months, the EVI values increased only during the phenological second-year. Since September 2002, seasonal averages were similar for each vegetation index. In mid-2007, the EVI seasonal amplitude reached a value of 0.25 and remained higher until the end of the study period (Fig. 3).

Figure 4 shows the first derivative curves for the temporal profiles, i.e. the rate of change (slope) of vegetation index over time. The peaks in the first derivative curves are indicative of an intense variation of NDVI or EVI values, which correspond to phenological changes. The highest values of first derivative occurred in the rainy season, due to an increase of photosynthetically active leaves. In contrast, the lowest vegetation indices values occurred in the dry season, during the self-pruning stages at the end of each phenological year.

In 2008, NDVI first derivative values showed a strong decreased, followed by increase in 2009, due to the planting renewal. This increment represented the carbohydrate generation, attending to branches, roots and fruits growth and new blossom out leaves. The EVI first derivative profile showed higher peaks (positive and negative) over the period 2007 to 2009.

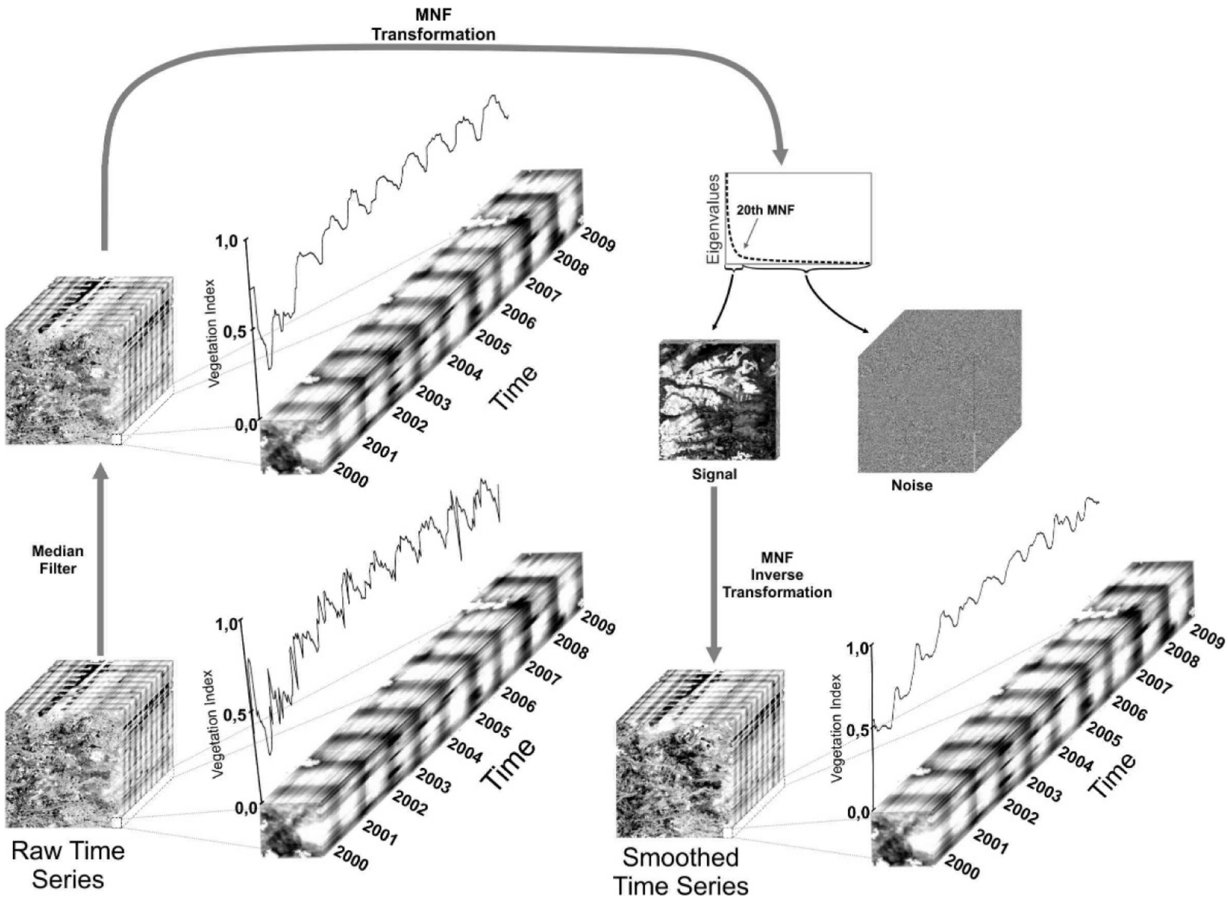

Figure 2 – Noise reduction scheme.

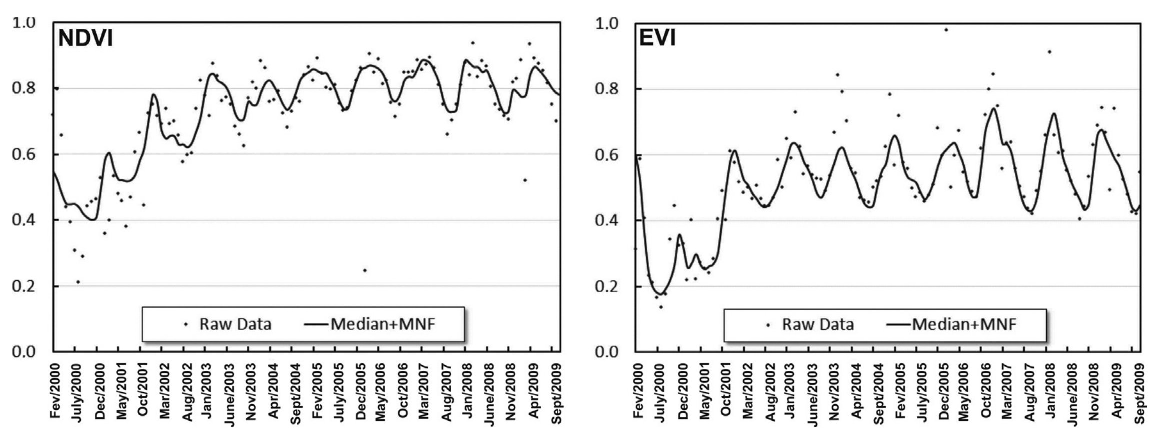

Figure 3 – Original data distribution (black dots) and the smoothed time series (black lines) for the two vegetation indices.

The coffee plantation presented vegetation indices greater than natural vegetation (Cerrado Sensu Strictu), approximately 20% higher for NDVI and 25% higher for EVI (Fig. 5). Those higher values indicated the influence of irrigation system on crops.

Figure 6 shows the temporal profiles of NDVI and EVI with the six phenological stages proposed by Camargo & Camargo (2001). The temporal profiles of the two indices had different shapes. The EVI curves presented a slight asymmetry, while the NDVI curves tended to have a more symmetrical behavior. At

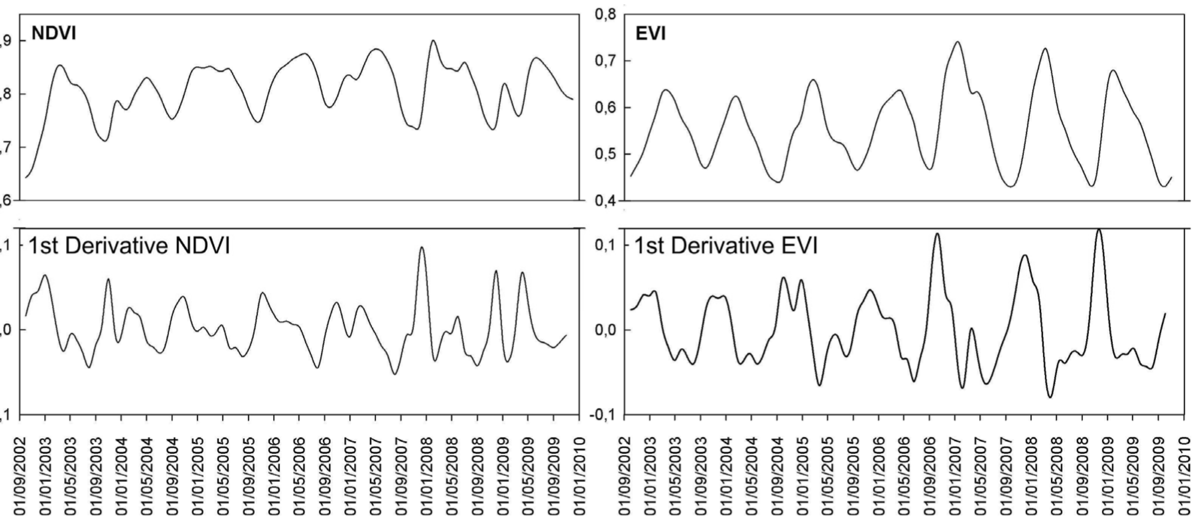

Figure 4 – Comparisons of the NDVI and EVI profiles (top), first derivative of the respective profiles (bottom).

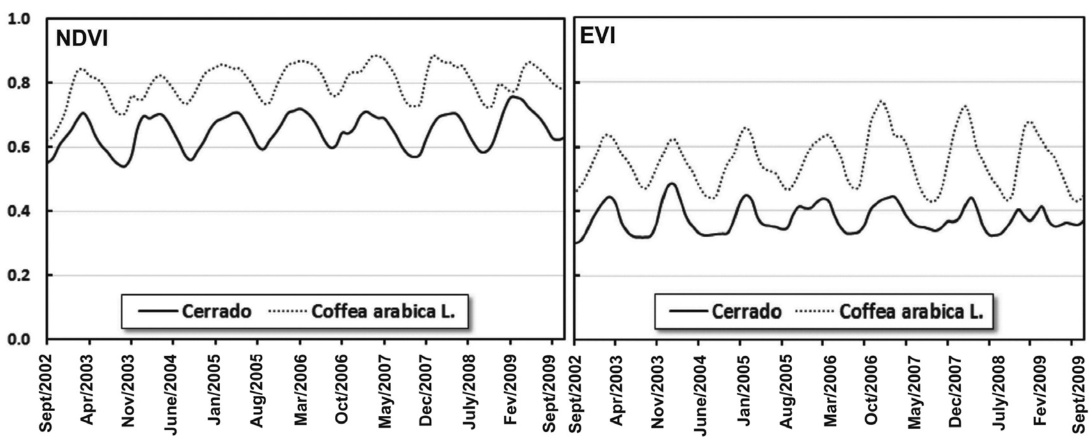

Figure 5 – Comparison between temporal signatures of Arabica Coffee and Cerrado *Sensu Strictu*.

the beginning of each year, the NDVI showed an increase of their values, which remained at higher levels than EVI. Thus the decay of NDVI values was delayed compared to the EVI. Therefore, NDVI negative gradients were constrained to periods of fallow and self-prunning (end of year), associated with a drop of tertiary and quaternary branches. Those different shapes were apparently due to saturation of the NDVI.

The first stage showed higher coefficients of variation (CV%), standard deviation, and range for both indices (Table 1). These values reflect the vegetative growth and formation of leaf buds. The highest average NDVI value (0.8451) was observed in the fifth phenological stage, while for the EVI (0.6364) in the fourth stage, evidencing a distinct symmetry between the curves (Table 1).

Table 1 – NDVI and EVI measures of central tendency and variability in reference to the coffee phenological stages. Mean; Standard Deviation (SD); Coefficient of Variation (CV %), Minimum value (Min), Maximum value (Max), and Range (R).

	Stage	M	SD	CV(%)	Min	Max	Ran
NDVI	1	0.8027	0.0653	8.14	0.6431	0.8750	0.2319
	2	0.8184	0.0420	5.13	0.7323	0.8843	0.1520
	3	0.7651	0.0389	5.09	0.7148	0.8349	0.1201
	4	0.8416	0.0399	4.74	0.7719	0.9003	0.1284
	5	0.8451	0.0259	3.06	0.7975	0.8757	0.0782
	6	0.7869	0.0294	3.73	0.7527	0.8351	0.0824
EVI	1	0.5874	0.0881	15.00	0.4463	0.7416	0.2953
	2	0.5408	0.0534	9.87	0.4484	0.6340	0.1856
	3	0.5001	0.0491	9.81	0.4310	0.5754	0.1445
	4	0.6364	0.0452	7.10	0.5862	0.7266	0.1403
	5	0.5756	0.0571	9.91	0.4826	0.6694	0.1868
	6	0.4734	0.0262	5.53	0.4414	0.5158	0.0744

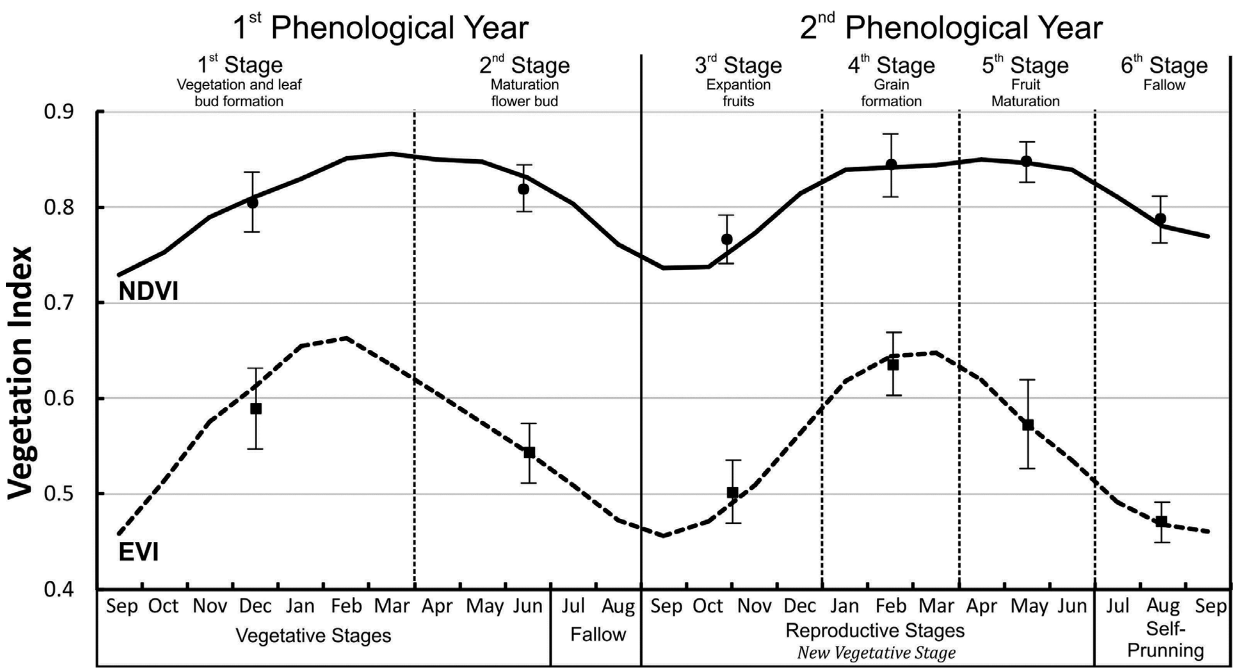

Figure 6 – NDVI and EVI temporal profiles in relation to the Arabica coffee phenological cycle (24 months). The markers correspond to averages with their confidence intervals of 95%, NDVI is represented by the black circle, and EVI by the square.

CONCLUSION

Remotely sensed time-series data offers considerable promise as a tool for monitoring crop phenology. The combination of median filter with the MNF transformation reduces the noise of MODIS time series. First derivative curves are excellent qualitative indicators of phenological changes.

NDVI and EVI temporal signatures showed evident variations of amplitude and frequency, both on the natural vegetation and coffee plantation. The saturation of the NDVI on the coffee crop is also evident, in which the EVI profile compared to the NDVI shows larger amplitudes and different slopes during the transitions between the rainy and dry periods. The higher values of coffee crop regarding to the Cerrado *Sensu Strictu* (natural vegetation) was due to irrigation system and consequently the canopy structure and closure.

Results showed similarities between the MODIS temporal profiles and the Arabica Coffee phenological stages described in the fieldwork. Thus, this approach should be used to coffee crop monitoring, with the development of temporal libraries for different managements and regions. Therefore, MODIS time-series data are suitable to integrate with field experiments and biophysical variables, especially for long-term data.

ACKNOWLEDGEMENTS

The authors would like to thank Coordenação de Aperfeiçoamento de Pessoal de nível Superior (CAPES) for conceding the doctorate scholarship to the researcher Antonio Felipe Couto Junior; and Conselho Nacional de Desenvlvimento Científico e Tecnológico (CNPq) for financial support from fellowship to the researchers: Osmar Abílio de Carvalho Júnior and Éder de Souza Martins. Special thanks to Mr. Gabriel Bartholo for their important considerations.

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Recebido em 10 fevereiro, 2012 / Aceito em 27 dezembro, 2012
Received on February 10, 2012 / Accepted on December 27, 2012

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