Fraction images for monitoring intra-annual phenology of different vegetation physiognomies in Amazonia

Liana O. Anderson a, Luiz E. O. C. Aragão b, Yosio E. Shimabukuro c, Samuel Almeida d & Alfredo Huete e

a School of Geography and the Environment, University of Oxford, Dyson Perrins Building, South Parks Road, Oxford, OX1 3QY, UK
b School of Geography, University of Exeter, Rennes Drive, Devon, EX4 4RJ, UK
c National Institute for Space Research (INPE), Divisão de Sensoriamento Remoto, Av. dos Astronautas, 1758, São José dos Campos, Brazil
d Museu Paraense Emílio Göeldi, Belém, Pará, Brazil
e University of Arizona, Department of Soil, Water and Environmental Sciences, 1200 E. South Campus Drive, Room 429, Shantz Building 38, Tucson, AZ, USA


To cite this article: Liana O. Anderson , Luiz E. O. C. Aragão , Yosio E. Shimabukuro , Samuel Almeida & Alfredo Huete (2011): Fraction images for monitoring intra-annual phenology of different vegetation physiognomies in Amazonia, International Journal of Remote Sensing, 32:2, 387-408

To link to this article: http://dx.doi.org/10.1080/01431160903474921

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any
instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.
Fraction images for monitoring intra-annual phenology of different vegetation physiognomies in Amazonia

LIANA O. ANDERSON*,† LUIZ E. O. C. ARAGÃO‡, YOSIO E. SHIMABUKURO§, SAMUEL ALMEIDA¶ and ALFREDO HUETE

†School of Geography and the Environment, University of Oxford, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY, UK
‡School of Geography, University of Exeter, Rennes Drive, Devon, EX4 4RJ, UK
§National Institute for Space Research (INPE), Divisão de Sensoriamento Remoto, Av. dos Astronautas, 1758, São José dos Campos, Brazil
¶Museu Paraense Emílio Goeldi, Belém, Pará, Brazil

*Corresponding author. Email: liana.anderson@ouce.ox.ac.uk

In this study we investigate the potential of fraction images derived from a linear spectral mixture model to detect vegetation phenology in Amazonia, and evaluate their relationships with the Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation indices. Time series of MODIS 250-m data over three contrasting land cover types in the Amazon were used in conjunction with rainfall data, a land cover map and a forest inventory survey to support the interpretation of our findings. Each vegetation physiognomy was characterized by a particular intra-annual variability detected by a combination of the fraction images. Both vegetation and shade fractions were important to evaluate the seasonality of the open tropical forest (OTF). The association of these results with forest inventory data and the literature suggests that Enhanced Vegetation Index (EVI) and vegetation fraction images are sensitive to structural changes in the canopy of OTF. In cerrado grassland (CG) the phenology was better characterized by combined soil and vegetation fractions. Soybean (SB) areas were characterized by the highest ranges in the vegetation and soil fraction images. Vegetation fraction and vegetation indices for the OTF showed a significant positive relationship with EVI but not with Normalized Difference Vegetation Index (NDVI). Significant relationships for vegetation fraction and vegetation indices were also found for the CG and soybean areas. In contrast to vegetation index approaches to monitoring phenology, fraction images provide additional information that allows a more comprehensive exploration of the spectral and structural changes in vegetation formations.

1. Introduction

Vegetation distribution and phenology are largely associated with climate, landscape characteristics and human actions. Phenological response studies at regional and global levels are important in understanding how the climate acts over different natural, agricultural and urban ecosystems at various temporal scales (Myneni et al. 2001).
The exchanges of energy and CO₂ between the biosphere and atmosphere through biogeochemical cycles are strongly influenced by vegetation phenology, primarily through variations in the onset, cessation and the length of the growing season (Ferreira et al., 2003, Huete et al. 2006). For example, there are important phenologic phases in the dynamics of terrestrial primary productivity and the global carbon cycle including the photosynthetically active period, associated with increases in canopy biomass and periods of constrained soil water availability, which limits above ground biomass growth in many canopies (Williams et al. 1998, Lee et al. 2002, Wang et al. 2003).

Vegetation index images are the most frequently used satellite data to monitor natural vegetation dynamics. In recent decades, vegetation monitoring at regional and global scales has been done with Advanced Very High Resolution Radiometer (AVHRR) sensor data converted to Normalized Difference Vegetation Index (NDVI) images (Spanner et al. 1990, Reed et al. 1994, Royer et al. 1996, Batista et al. 1997, Duchemin et al. 1999, Azzali and Menenti 2000, Lu et al. 2003). With the launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua Earth Observing System (EOS) platforms, temporal vegetation indices derived from data with improved spatial, spectral and radiometric resolutions became freely available and made possible a more accurate monitoring of the Earth’s surface. Two vegetation indices are systematically derived from MODIS: NDVI and the Enhanced Vegetation Index (EVI), distributed as part of the MOD13 product. NDVI has been extensively studied and its limitations are well understood. These include saturation in closed canopy and sensitivity to atmospheric aerosols and soil background. EVI was developed to minimize these effects, including the blue band for atmospheric correction, computed as in equation (1):

\[
EVI = 2.5 \times \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + (6 \times \rho_{\text{Red}} - 7.5 \times \rho_{\text{Blue}}) + 1},
\]

where \(\rho_{\text{NIR}}\) is reflectance in the near-infrared (NIR) spectral band, \(\rho_{\text{Blue}}\) is reflectance in the blue spectral band and \(\rho_{\text{Red}}\) is reflectance in the red spectral band.

While NDVI is more sensitive to the absorbing chlorophyll bands (red), EVI is more sensitive to canopy structural variations, including Leaf Area Index (LAI; Huete et al. 1997, 2002).

Spectral mixture analysis (SMA) is a potential tool for detecting and monitoring changes in vegetation structure and phenology, and has already been successfully tested for chaparral vegetation in North America (Dennison et al. 2003). This technique is based on the selection of endmembers (pure pixels) to generate fraction images by the application of spectral mixture models. Each resulting fraction image represents the fractional abundance of endmembers in each pixel. Therefore, in this approach the spectral response of the pixel in any spectral wavelength can be considered as a linear combination of the spectral responses of each component inside the pixels (Shimabukuro and Smith 1991).

The aim of the current study is to evaluate the potential of fraction images derived from the linear spectral mixing model for detecting seasonal changes in three characteristic land cover types (open tropical forest, cerrado grassland and soybean area)
in the Brazilian Amazon using MODIS data. Initially, we describe the phenological changes detected by the fraction images and vegetation indices for each land cover type, and the relationship between the change in phenology and rainfall seasonality. We then investigate the relationships between vegetation fraction images and vegetation indices to better understand the relative merits of both sets of information. Finally, we compare the ability of the fraction images to capture the temporal dynamics of the three vegetation types.

2. Study area

The study was carried out within the limits of Mato Grosso State (900,000 km²) in the southern part of the Brazilian Legal Amazon, lying between the latitudes 06° 00′ and 19° 45′ south and longitudes 50° 06′ and 62° 45′ west (figure 1). The diversity of vegetation types found in this area is largely a result of natural ecosystem processes, specifically spatial-temporal variations in climate, which include length of the dry
season, terrain features and rainfall patterns. Human activities are also important
determinants of land cover patterns in this region. For instance, Mato Grosso is
located in the ‘arc of deforestation’ region, and was the Brazilian state that had the
highest deforestation rates in 2002, 2004 and 2006, mainly due to pasture expansion
and mechanized agriculture of crops such as soybeans (INPE 2007).

Rainfall is not equally distributed throughout the year, and more than 70% of the
total cumulative rainfall occurs from November to March (summarized in table 1).
The wettest months in the northern region are from January to March, while in the
central region they occur from December to February, and from November to
January in the southern part. By contrast, the winter (June to August) is excessively
dry throughout the region (table 1).

3. Dataset description and processing

3.1 MODIS data

3.1.1 Description. MODIS files are available in hierarchical data format–Earth
Observing System (HDF-EOS) format, projected in sinusoidal (SIN) or integerized
sinusoidal (ISIN) coordinate system. MODIS MOD13A1 product is a composition of
16-days with a quality analysis filter and processes by a constrained view angle–maximum
value composite (CV-MVC) algorithm (Huete et al. 1999). The product collection 4 (SIN)
was used, acquired for the period January to December 2002. Apart from October, which
has only one image acquisition, there are two composites images per month. A total of 23
sixteen-days composites were acquired at 250-m spatial resolution for each of the six tiles
(path/row) necessary to cover the entire Mato Grosso state, totalling 138 MOD13A1
images. The data include: 250m 16-day NDVI, EVI, NDVI Quality, EVI Quality, average
view zenith angle, average sun zenith angle, average relative azimuth angle and the red
(band 1, centred at 645 nm), NIR (band 2, centred at 858 nm), blue (band 3, centred at 470
nm) and mid-infrared (MIR) (band 7, centred at 2130 nm) spectral bands, associated with
the calculation of the Vegetation Index (VI). Bands 1 and 2 are at a spatial resolution of
250 m while bands 3 and 7 are available at a spatial resolution of 500 m.

3.1.2 Pre-processing. The pre-processing steps of the MODIS images involve the use
of the MODIS Reprojection Tool (MRT) free software for mosaicking the six images
that cover the study site into one image per 16 days, altering the geographic coordinate
system to geographic, datum WGS84, and re-sampling the three and seven spectral
bands to 250 m, using the nearest neighbour resampling algorithm (MRT 2008).

Monthly composite images were generated based on the highest NDVI pixel value
of two 16-day images corresponding to each month. This approach ensures that
cloudy and off-nadir pixels are less likely to be selected for the final monthly compo-
site (Carreiras et al. 2003).
3.1.3 Applying the linear mixture model. The linear spectral mixing model estimates the proportion of each component within pixels by minimizing the sum of squares of the errors. In this approach, the number of components must be less than the number of spectral bands, the proportion values must be non-negative, and their sum must equal one (Shimabukuro and Smith 1991).

The model was run for three endmembers: vegetation, soil and shade, using red (1), NIR (2), blue (3), and MIR (7) spectral bands. Non-photosynthetic vegetation (NPV) plays a major role in low tree density physiognomies (van Leeuwen and Huete 1996, Dennison and Roberts 2003, Xiao et al. 2005); however, due to the number of spectral bands and the characteristics of the study area, the use of NPV as an endmember would not necessarily provide a better representation of the physically based fraction estimates.

The proportion of each component varies from 0% to 100%, and these endmembers were selected directly from the image (image endmember approach) by choosing the pixel with the spectral response closest to the theoretical spectral curve expected for a pure endmember (Haertel and Shimabukuro 2005). In using the image endmember approach for MODIS data, it was assumed in this study that there is at least one pure pixel for each component over the study area, such as large areas of agriculture, or bare soil in the dry season, as well as large water bodies to represent the shade endmember.

The vegetation pure pixel was selected from a homogeneous vegetation cover of soybean area. The soybean plantations are larger than 200 ha in size, and are relatively homogeneous in height, soil and spectral signature. The pure soil pixel was selected from large agricultural bare soil areas in the dry season, when there is no vegetation present. Variations in soil reflectance may result from changes in soil roughness and water content, however the spectral signature shape and pattern for the soil will remain the same, and we can assume that our soil endmember is representative of a dry soil (Foody 1991, Muller and Décamp 2001). The shade pure pixel was selected from clean water bodies considering the spectral similarity between shade and water targets and the invariance of shade (Shimabukuro and Smith 1991).

From the 12 spectral mixing models generated (one for each month), the three endmember responses closest to the ideal theoretical curve were used to generate a unique annual model, which was then applied to the whole temporal series. The final soil and shade endmembers were selected from the dry season months, while the vegetation endmember was selected from the wet season months (figure 2). In this study, we hypothesized that the pure endmembers do not change their spectral characteristics during the period studied (pseudo-invariant targets), and thus the changes observed in the proportion of the components are due to variations in the vegetation phenology.

3.2 Land cover map

The land cover map for the study area was generated based on the same multi-temporal data series (Anderson et al. 2005). They have used statistical analysis to determine the months and spectral bands that would detect and separate the higher number of land cover class. July, August, September and November fraction images and vegetation indices were used as input for the classification algorithms, with a kappa coefficient of 0.89. The land cover classes which presented lower omission and commission errors were selected for this study: Open tropical forest, cerrado grassland, and soybean areas (figure 3(a)).

Open tropical forest (39% of the study area—354 756 km²), cerrado grassland (17% of the study area—152 466 km²) and soybean areas (5% of the study area—41 198 km²)
were chosen as the focus of the study due to their lower confusion in the validation of the
land cover map with field data and high vegetation structural dissimilarity (Anderson
et al. 2005). The open tropical forest is considered a transitional forest at the southern limits of
the Amazon tropical rainforest. This forest is adapted to a dry period per year and
during 2002 there were six months with rainfall lower than 100 mm. It is primarily
composed of phanerophyte ombrophilous and sparse lianas and bamboo patches.
The cerrado grassland region is strongly geographically constrained by rainfall
patterns. The soil is shallow and the edaphic water is the most important factor
associated with the distribution of the cerrado formations (RADAMBRASIL 1982). It is predominantly composed of grass and shrubs with sparse trees or patches of
woodland. The cerrado grassland formation is subject to distinct seasonality which is
characterized by gradual changes in leaf coverage. However, there is no period in which
the shrubs and sparse trees are completely without leaves (RADAMBRASIL 1982).
Soybean areas are increasing in the Brazilian Central-West Region, and are respon-
sible for over half of the nation’s crop. In Mato Grosso during the period 2001 to 2004
direct conversion of forest to cropland totalled more than 540 000 ha, peaking at 23%
of 2003 annual deforestation (Morton et al. 2006).

3.3 Rainfall data

3.3.1 Description. Daily rainfall data for 2002 were acquired from the Agência
Nacional das Águas (ANA), derived from 125 meteorological ground stations in
Mato Grosso.

3.3.2 Pre-processing. The meteorological ground-station data were imported to a
geographic information system (GIS) and total rainfall was calculated for each
month. Then a regular grid was generated through interpolation using a weighted
average considering the Z-values and quadrant regions algorithm in order to provide
a spatial distribution map (equations (2)–(4)). The interpolation results showing the
cumulative rainfall for 2002 are presented in figure 3(b).
Figure 3. (a) 2002 land cover map for Mato Grosso based on annual signatures in NDVI, EVI and fraction images time series and (b) annual cumulative precipitation surface generated based in the ANEEL ground stations (the Brazilian Electricity Regulatory Agency).
\[ d = \sqrt{(x - x_0)^2 + (y - y_0)^2}, \quad \text{(2)} \]

where \( d \) is the Euclidian distance from the interpolation point.

\[ w(x, y) = \left( \frac{1}{d} \right)^u = 1, \quad \text{(3)} \]

where \( u = 1 \) is the exponent of weighted function.

\[ \int (x, y) = \frac{\left( \sum_{i=1}^{8} w(x_i, y_i) \right) \times z}{\left( \sum_{i=1}^{8} w(x_i, y_i) \right)}, \quad \text{(4)} \]

where \( w(x, y) \) is the weighted function, and \( \int (x, y) \) is the interpolation function.

In the present study the dry season was defined as months with rainfall lower than 100 mm, associated with the mean evapotranspiration and water balance assumed for the Amazon (Malhi et al. 2002).

The water deficit (WD) for each month was calculated using equation (5) based on Aragão et al. (2007).

\[
\begin{align*}
\text{if} \quad & WD = (WD)_{n-1} - E + P_n < 0; \\
\text{then} \quad & WD_n = (WD)_{n-1} - E + P_n; \\
\text{else} \quad & WD = 0
\end{align*}
\]

where \( n \) is the month, \( E \) is evapotranspiration, fixed at 100 mm month\(^{-1}\), and \( P \) is the total monthly rainfall.

### 3.4 Forest inventory data

RADAMBRASIL (1980) inventories were used to aid the interpretation of structural changes in the open tropical forest canopy. Project RADAM, created in 1970 by the Brazilian Ministry of the Mines and Energy, was originally conceived as an integrated survey of natural resources of the Brazilian Amazon using a side looking airborne radar (SLAR) and was subsequently expanded to include the whole of Brazil. In addition to the radar images the RADAM project used a combination of aerial photographs and field surveys to generate detailed information of geology, geomorphology, pedology, vegetation and potential land use. The radar and aerial photographs were combined to generate phyto-geographic unit maps. The data for the open tropical forest, covering the north of Mato Grosso, used 272 inventories of 1 ha for detecting floristic composition, volume measurement and species with economic value. In relation to species composition, the RADAM data compiled trees with a diameter at breast height (DBH) higher than 30 cm. In the current study, the RADAM species list of the most common species for the open tropical forest physiognomy was used. This approach ensures that the species list is more likely to be representative of all forest sub-type mosaics presented in this forest formation. The open tropical forest is considered a mature old growth tropical forest, and is therefore assumed to be in equilibrium. Although species composition is unlikely to have changed markedly due to natural conditions, forest degradation, such as selective logging, fires and deforestation have been increasing in this region.
3.5 Statistical analyses

The Kolmorogov–Smirnov test corrected by the Lilliefors test was carried out to test for normality of the vegetation indices. The number of points tested for each land cover type for each month was 461,300 for the open tropical forest; 97,847 for cerrado grassland and 119,508 for soybean plantations. EVI was used as a proxy for testing the normality of the data, and the skewness value for each month for the EVI was close to zero; therefore the data was considered normally distributed.

Linear regression analyses were carried out to compare the monthly mean value of the vegetation indices and the fraction images for corresponding land cover classes (Du Plessis 1999) and to assess the relationships of the vegetation indices and fraction images to rainfall (monthly and monthly lag response). Previous studies have reported a lag in vegetation response to rainfall, mainly due to soil characteristics, vegetation adaptation to dry conditions, and plant physiology in different vegetation physiognomies (Du Plessis 1999, de Wasseige et al. 2003, Poveda and Salazar 2004, Xiao et al. 2005).

4. Results and discussion

4.1 Phenology detection in the fraction images and rainfall relationships

4.1.1 Open tropical forest. EVI and VF (vegetation fraction) appear to be sensitive to changes in the canopy structure during the dry season (April to September), particularly in the months of August and September (the last month with precipitation lower than 100 mm), when there is a peak in index values (figure 4(a)). Huete et al. (2006) related the

Figure 4. Monthly mean derived from the linear mixing model (soil, shade and vegetation fraction images) and the vegetation indices NDVI and EVI for the land cover classes: (a) open tropical forest, (b) cerrado grassland, and (c) soybean areas. (d) Precipitation pattern for 2002, for each land cover type.
increase of the EVI with the flushing of new leaves and intensification of chlorophyll activity during the dry season in central Amazon forests. Saleska et al. (2007) also found an increase in EVI values during an anomalous dry period in central Amazonia in 2005 and related it to the flushing of new leaves and increased canopy photosynthetic activity. These explanations are based on the fact that drier and sunnier periods, without water limitation, can lead to an increase in photosynthesis due to greater light availability (Saleska et al. 2003). However, it has also been demonstrated that the changes in the green (or vegetation) and shade fractions could also be related to structural changes in the canopy of tropical forests (Aragão et al. 2005, Jiang et al. 2006).

The open tropical forest region evaluated in this study, in the southern limits of the Amazon forest, has a different structure and species composition from those in central Amazonia, as studied by Huete et al. (2006) and Saleska et al. (2007). It has been shown that in Mato Grosso forests, the variations in rainfall and soil water availability can influence rates of CO₂ exchange by directly limiting rates of respiration and photosynthesis, and by altering canopy structural properties such as LAI and litterfall production (Vourlites et al. 2004). In this region, a decline of canopy LAI by almost 1 m² m⁻² between the wet and the dry season has been observed (Vourtilis et al. 2001). Leaf litter production reaches a seasonal maximum between August and September, probably in response to a decline in soil water availability (Scott et al. 1992, Wieder and Wright 1995), and exhibits a large pulse of leaf and stem fall at the end of the dry season (Vourlitis et al. 2001). Based on these studies, carried out in the same region of the present study, it is hypothesized that the seasonality observed in the EVI and vegetation fraction in August and September (figure 4(a)) is more likely to be related with structural changes in the canopy (see discussion in section 4.2). The leaf shedding of emergent trees in the dry season changes the canopy structure (top-of-canopy ‘topography’), decreasing the roughness and shading effects, as they are a function of canopy structure. This directly leads to an increase in the vegetation index response. Moreover, leaf fall in the end of the dry season reduces self-shading, resulting in more sunlight penetrating into the canopy, with a higher proportion of below-emergent canopy leaves being detected by the satellite.

Based on RADAM’s field survey, within the study area 43.7% of all trees inventoried are semi-deciduous and 28.1% are deciduous. In relation to canopy positioning, 34.3% of all trees are emergent, with a density of 3.04 deciduous and 8.88 semi-deciduous individuals per hectare (table 2). Most of the emergent trees that are deciduous or semi-deciduous shed their leaves in the dry season. Based on the high density of deciduous and semi-deciduous emergent trees in this area, it is expected that they can considerably change the roughness of canopy in the dry season. This pattern can also explain the significant relationships between shade fraction and the three-month rainfall lag ($R^2 = 0.75, p < 0.05$) (table 3). Specifically, the lowest shade fraction was found in September: three months after the lowest rainfall and during the maximum cumulative meteorological water deficit of 345 mm (assuming a threshold of 100 mm for evapotranspiration) (Aragão et al. 2007).

There was no significant relationship between the EVI and rainfall, however a significant correlation was found ($R^2 = 0.66, p < 0.05$) for the NDVI versus one month lag precipitation (table 3).

The annual mean of the NDVI (0.86) is higher than the value (0.53) reported by Batista et al. (1997) for Northern Brazil. The difference between the results could be attributed to two factors: the temporal series analysed and the sensor/data characteristics. Batista et al. (1997) used data from 1981 until 1991 (10-year monthly mean), which included two El
Niño years (1982/83 and 1986/87), that affected the rainfall pattern. They also used data provided by the AVHRR sensor, which is at 1-km spatial resolution, and could have been affected by sensor degradation, navigation error, and atmospheric attenuation thereby influencing their results (Los 1993, Gutman and Ignatov 1995). The higher NDVI values
found in this study could be related to the better spatial and spectral characteristics of the spectral bands of the MODIS sensor, the systematic atmospheric correction with more accurate parameters for these data (Vermote et al. 2002), and the vegetation map used here that excludes the disturbed forests and deforested areas.

4.1.2 Cerrado grassland. The spectral response of open canopies, such as cerrado grassland, also incorporate soil substrate, leaf litter and NPV to varying extents (Roberts et al. 1993). Here, NPV response is represented in the signal as a mixture of vegetation and soil response. It is characterized by weak chlorophyll absorption in the visible spectrum and increased reflectance in the shortwave infrared (SWIR).

The vegetation fraction gradually changes from its maximum during the wet season (44% in January) to its lowest in the dry season (16% in August), but does not drop to zero due to the presence of evergreen shrubs and treelets (figure 4(b)). Ferreira et al. (2003) found 40–46% of green cover during the wet season and 25–18% in the dry season for the same vegetation formation in Central Brazil using integrated field transects and airborne, nadir-look digital images. The values obtained in both studies are similar for the vegetation, and the differences in their range can be attributed to the spatial resolution of the data used.

The shade fraction progressively increased until June (49%) and then gradually decreased (38% in December). During the year, the shade fraction values are higher and more constant than the soil and vegetation fraction values due to the layers formed by this vegetation structure. As expected, the soil fraction image showed its lowest values during the wet season (8% in January), when the vegetation is more vigorous, and it increased during the dry season up to 35% in August—the peak was two months after the lowest rainfall. Ferreira et al. (2003) found a 15% soil difference between wet–dry seasons in MODIS data, while in this study a difference of 27% was found. This discrepancy could be due to the selection of the endmember in a bare soil area in this study, while in Ferreira et al. (2003) some mixing could have occurred. The increase of the soil response in dry conditions could also be related to the increase of the content of NPV during water deficit conditions (Denninson and Roberts 2003).

The relationship between the cerrado grassland (NDVI, EVI and Fraction images) and rainfall is shown in table 4. The soil and vegetation fractions and also the NDVI and EVI were significantly ($p < 0.05$) correlated for all the rainfall variables tested (monthly, 1-month lag, 2-months lag and 3-months lag). The strongest relationships found were with NDVI (1-month lag: $R^2 = 0.84$) and soil fraction (2-month lag: $R^2 = 0.81$).

Batista et al. (1997) found a minimum NDVI value of 0.36 and a maximum of 0.41 for a 10-year monthly mean in cerrado areas. Du Plessis (1999), using AVHRR data from rainy season periods for 1993/94, 1994/95 and 1995/96, found a minimum value

| Shade fraction | 0.06 | 0.01 | 0.19 | 0.75* |
| Vegetation fraction | 0.00 | 0.04 | 0.04 | -0.74 |
| NDVI | 0.31 | 0.66* | 0.47 | 0.45 |
| EVI | 0.2 | 0.01 | 0.05 | -0.61 |

Note: *$p < 0.05$
of 0.02 and a maximum of 0.4 in the NDVI for the Namibia savannah region. In this study a higher annual mean (0.67) for NDVI in cerrado grassland was found. The minimum value found was 0.50 in August and a maximum value of 0.81 in January. The EVI had an annual mean of 0.40, with a maximum of 0.49 in January and a minimum of 0.27 in August. All the maximum and minimum values found for the vegetation indices and vegetation fraction occurred during the same months, in both seasons. Ferreira et al. (2003) found a 30% MODIS NDVI seasonal relative difference for cerrado grassland, and in this research a 37% NDVI range from the maximum to the minimum values was found. In relation to the MODIS EVI, Ferreira et al. (2003) found a relative difference of approximately 38%, and a 44% EVI difference was found in this study from wet to dry seasons. Interestingly, the results from this study and the one carried out by Ferreira et al. (2003) present a similar proportional difference for vegetation indices.

### 4.1.3 Land cover: soybean areas.

The spectral response of this crop was separable from the other land cover and land use types in this region due to the high amplitude difference between wet and dry season values. The vegetation fraction profile ranged from a peak of 80% in January to its lowest value of 0.7% of vegetation in August (figure 4(c)). NDVI and EVI also presented higher and lower values in the same months: the EVI varied from 0.7 to 0.2 and the NDVI from 0.8 to 0.3, and for both indices, this land cover type is the one that showed higher differences between seasons. Therefore, the vegetation indices and vegetation fraction measurements from January and August could be potentially used to spectrally differentiate this land use from the other land cover types. During the dry season, the soil fraction varied from 29% in May to 58% in August, while the shade fraction varied from 42% in May to 39% in August, with a peak in June (44%)—two months before the soil fraction peak.

In table 5, the relationships between the soybean areas (NDVI, EVI and fraction images) and rainfall are summarized. Vegetation indices and fraction images showed significant correlations with all the rainfall patterns presented here, but not the shade fraction image with 2-month lag. There was also no significant correlation for all the variables studied with 3-month rainfall lag \( p < 0.01 \). The highest correlation coefficient found for this land cover type was NDVI, soil fraction and EVI with a 1-month rainfall lag: \( R^2 = 0.82 \), \( R^2 = 0.82 \) and \( R^2 = 0.81 \), respectively \( p < 0.01 \).

Wardlow et al. (2007) using an intra-annual temporal series of MODIS 250-m spatial resolution found that soybean is spectrally separable from winter crops traditionally grown in Kansas, USA. However, it exhibits some classification confusion with corn, the other summer crop examined. In their study, the soybean peak in the growing
season occurred in July (NDVI \( \approx \) approximately 0.83)—the opposite crop calendar to Brazil due to the summer period in the two hemispheres. Presumably the use of fraction images could improve the differentiation between the summer crops, due to the vegetation fraction image being characterized by a higher amplitude than NDVI between seasons. In addition, soil and shade fraction could play a major role in determining the phenology of the studied crops due to the characteristics of both species.

### 4.2 Relationships between fraction images and vegetation indices

Linear regression analysis was used to evaluate the relationship between the vegetation fraction and vegetation indices (figure 5). These results are based on one year of data in a ‘normal’ rainfall condition for this region. Although the use of a intra-annual time series may not be sufficient for capturing the total variation that the vegetation formations may exhibit in response to changes in climate and rainfall patterns (such as during El Niño years or droughts due to the rise in sea surface temperatures (SSTs) in tropical North Atlantic events) it is extremely important to document and characterize the response of the vegetation in detail for a non-anomalous year in relation to the rainfall. Therefore, due to the marked intra-annual seasonality in this region, it is argued that the relationships found in this study are valid. Open tropical forest had a significant correlation between the vegetation fraction and EVI \( (R^2 = 0.84, p < 0.01) \), but not with NDVI. A significant correlation with both vegetation indices and the vegetation fraction for the other landscapes analysed was also found.

It was observed that even with a significant correlation between NDVI and the vegetation fraction, there is a poor adjustment and a higher data scatter then in the relationship with EVI. This result suggests that the vegetation fraction is associated more with structural changes in the canopy, such as EVI, rather than with chlorophyll, which is better described by NDVI (Huete \textit{et al.} 2002). In addition, NDVI might be more saturated than EVI in this forest type, suggesting that the vegetation fraction, such as EVI, is more sensitive to variations in closed canopies than NDVI. This is understandable in the context of the intercept of the regression equation for the soybean relationships. NDVI and EVI intercept the \( y \)-axis at 0.33 and 0.18, respectively and the vegetation fraction interception is 0.74. In addition to the saturation problems related to NDVI, the EVI and vegetation fractions are characterized by lower values due to the partitioning of the vegetation signal by the correction factor and use of the blue channel in EVI, and estimation of the soil and shade influence in the vegetation fraction.

<table>
<thead>
<tr>
<th></th>
<th>Monthly</th>
<th>1-month lag</th>
<th>2-months lag</th>
<th>3-months lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shade fraction</td>
<td>0.63*</td>
<td>0.44*</td>
<td>0.05</td>
<td>0.21</td>
</tr>
<tr>
<td>Soil fraction</td>
<td>0.68*</td>
<td>0.82*</td>
<td>0.55*</td>
<td>-0.46*</td>
</tr>
<tr>
<td>Vegetation fraction</td>
<td>0.76*</td>
<td>0.79*</td>
<td>0.38*</td>
<td>0.27</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.73*</td>
<td>0.82*</td>
<td>0.51*</td>
<td>0.29</td>
</tr>
<tr>
<td>EVI</td>
<td>0.78*</td>
<td>0.81*</td>
<td>0.41*</td>
<td>0.29</td>
</tr>
</tbody>
</table>

\textit{Note:} *\( p < 0.05 \)
The relationships between shade and soil fractions with the vegetation indices are presented in table 6. The soil fraction was not analysed for the open tropical forest area, as the soil response in closed canopies is insignificant. The shade fraction was significantly related with the EVI, showing a negative correlation. In other words, the higher the EVI, the lower the shade fraction, reinforcing the discussion of changes in the canopy structure presented in section 4.1.1.

The results of the linear regression for cerrado grassland were $R^2 = 0.94$ and $R^2 = 0.74$ for the soil fraction and NDVI and EVI, respectively ($p < 0.05$), but no significant relationship was found for the shade fraction and the vegetation indices. The soybean area analysis, like the results for cerrado grasslands, presented significant and high correlations with the soil fraction for EVI and NDVI and shade fraction with EVI.

Figure 5. Linear regression analysis between monthly mean value for vegetation indices image and vegetation fractions image for the three vegetation formations studied. Open tropical forest: (a) NDVI versus vegetation fraction and (b) EVI and vegetation fraction. Cerrado grassland: (c) NDVI versus vegetation fraction and (d) EVI and vegetation fraction. Soybean areas: (e) NDVI versus vegetation fraction and (f) EVI and vegetation fraction.
4.3 Comparison among vegetation types

The fraction images revealed seasonal patterns that can aid the interpretation of the phenology of the land cover types. In general there were three main trends that can be observed from the fraction images temporal profiles (figure 4). First, the open tropical forest vegetation fraction (VF) was highest in September (62%), as was EVI (0.58) (figure 4(a)). The VF was significantly correlated with EVI for all three vegetation physiognomies analysed. However, NDVI was significantly correlated with VF only for the cerrado grassland and soybean areas \((p < 0.05)\).

Second, the shade fraction (SF) showed higher values in the beginning of the dry season for open tropical forest (May and June) and cerrado grassland (March) \((p < 0.05)\). During this period, it is expected that the vegetation has not entered the water deficit phase yet, due to the high rainfall in the previous months. Therefore, the canopy layers are assumed to be vigorous, projecting the shade due to the heterogeneity of the canopy (the deciduous and semi-deciduous trees in the open tropical forest are green and full of leaves, and in cerrado grassland the sparse trees, shrubs and grasses form different layers, resulting in increases in the shade proportion). The lowest shade values were observed in January for soybean (when most of the plants are fully developed reaching the same height) and in December for cerrado grassland and open tropical forest (38% and 36%, respectively). In the open tropical forest as the VF increased the proportion of canopy gaps and shadows decreased. Similarly, in the soybean and cerrado grassland sites, as VF increased, the shade fraction decreased.

Finally, the peak in the soil fraction (SF) occurred in August for the cerrado grassland and soybean sites (58% and 35%, respectively). The soil fraction in open tropical forest was negligible. It is also observed that August was characterized by the lowest VF, NDVI and EVI values for the soybean areas (VF = 0.7%, NDVI = 0.33 and EVI = 0.18) and cerrado grassland (VF = 16%, NDVI = 0.50 and EVI = 0.27). In the open tropical forest physiognomy, the lower VF and EVI were in June (46.6% and 0.47, respectively), and the lowest NDVI was in July (NDVI = 0.83), in the middle of the dry season.

A summary of the intra-annual changes in the response of the land cover types detected in the fraction images is presented in figure 6. It is interesting to observe not only the amplitude but also the direction of the changes for the fraction images. The
soybean areas have the highest amplitude, and the monthly changes are observed in the centre of the diagram. Cerrado grassland presents intermediate variation and the values are grouped closer to the vegetation-shade axis of the diagram. The smallest oscillation was presented by open tropical forest, with varying vegetation and shade proportions between seasons, clustered in one region of the vegetation-shade axis of the diagram. Despite the small variation for the open tropical forest, it is possible to distinguish between the wet and dry seasons in the three vegetation types, which all show maximum vegetation fractions and minimum shade and soil proportions in the wet season. Although a large number of images are necessary for monitoring the phenology, it was possible to detect the key months that present higher separability and higher similarity among the land cover classes evaluated in this study. Based on the monthly values, the most important months to distinguish among the land cover types are during the dry season, specifically in August. In contrast, from April to June, soybean areas and cerrado grasslands presented closer values.

5. Conclusions

This study investigated the use of the MODIS 250-m vegetation indices and derived fraction images to detect and characterize vegetation phenology on an intra-annual basis. The relationships between MODIS vegetation indices (NDVI and EVI) and the vegetation fraction images were also investigated. A number of conclusions and recommendations are provided below regarding the suitability of the data and methodology for this application.
First, the fraction images derived from the MODIS data can be a useful additional source of information to understand not only natural changes in vegetation phenology due to alterations in canopy structure, but also to highlight seasonality of anthropogenic land cover processes, such as the cultivate maximum growth and harvest phases. Each landscape analysed showed a unique combination of components that better explained its phenology. Open tropical forest was most closely related with the vegetation and shade fractions. Conversely, the cerrado grassland phenology was better explained by the variability of the soil and vegetation fractions. The dynamics of the soybean areas were well discriminated among the three fractions analysed. All the three vegetation types investigated were separable at some point based on their spectral characteristic and temporal differences expressed in the fraction images.

Second, the relationships between vegetation fraction and vegetation indices suggest that the vegetation fraction and EVI respond similarly to seasonal changes in different land cover types. On the other hand, NDVI and vegetation fraction did not show a significant relationship with open tropical forest, most likely to due to NDVI’s spectral saturation. The cerrado grassland and soybean areas showed similar phenological patterns. However, the magnitude of the changes in the spectral response between the dry and wet seasons permitted their characterization.

Third, the shade fraction image can be an important component for the investigation of natural changes in closed canopies vegetations. The shade fraction image had a significant negative relationship with EVI and explained 88% of the open tropical forest variability. Despite the increase in EVI during the dry season that has been previously related with the greening-up of the forest (Huete et al. 2006, Saleska et al. 2007), the use of fraction images in this study suggested that this increase in EVI is more likely to be associated with a modification in the canopy structure. Additional work is required to validate these findings, and the use of field-based measurements on LAI, litterfall, canopy nitrogen and pigments, and phenology of dominant species would be necessary for answering this unresolved question. Furthermore, the relationship between shade and gap fraction in the forest may be related on a intra-annual scale with litterfall seasonality or on a long-term scale with changes in the structure and composition of the forest during extreme natural events, such as blow downs (Chambers et al. 2004), drought (Aragão et al. 2007), or climate change (Phillips et al. 2002, 2009). This could be further tested using high spatial resolution imagery.

In relation to the MODIS vegetation index product, the 250-m spatial resolution showed to be an appropriate scale to assess the fragmented landscape in the southern limits of the Amazon. It is still an open question as to what exactly would be missed in using a dataset with 500-m or 1-km spatial resolution, and this issue deserves further investigation since it could greatly influence space storage, speed of processing, computational power and time.

Finally, the spectral mixture methodology was shown to be a valuable tool for understanding seasonal changes in different vegetation physiognomies and land cover types. The fraction images, such as shade and soil, complement the vegetation indices data, providing additional information about the land cover, land cover change and vegetation structure seasonality. Ongoing research is focusing on the evaluation of the relationships among vegetation indices, fraction images and field observational data of phenology in central Amazonia. The next steps will focus on improved and up-to-date land cover inter-annual datasets of phenology and patterns of land use change.
that can potentially support science and policy applications focused on the understanding of the natural and anthropogenic drivers for environmental change in Amazonia.

**Acknowledgments**

The first author would like to thank the Coordenação de Aperfeicoamento de Pessoal de Nível Superior (CAPES) for the PhD studentship (BEX4018052) and BECA/IEB (BECA-B/2006/01/BDE/04) for financial support. We thank Dr Dalton M. Valeriano and Dr Sassan Saatchi for thoughtful discussions. Data for this study were provided by the Land Processes Distributed Active Archive Center (LP-DAAC) and Agência Nacional de Águas (ANA), information freely available in the World Wide Web at http://edcdaac.usgs.gov and http://ana.gov.br, respectively. The authors would like to thanks the two anonymous reviewers for their comments and suggestions that immensely contributed to improving the manuscript.

**References**


dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences*, 103, pp. 14637–14641.


