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SEASONAL BIOPHYSICAL DYNAMICS ALONG AN AMAZON ECO-CLIMATIC GRADIENT USING MODIS VEGETATION INDICES

ALFREDO HUETE [1]
PIYACHAT RATANA[1],
KAMEL DIDAN[1],
YOSIO SHIMABUKURO[2]
HUMBERTO BARBOSA
LAERTE FERREIRA[3]
TOMOAKI MIURA[1]

[1]University of Arizona – Department Soil, Water, Environmental Science
P.O. Box 210038 – Tucson - AZ 85721, U.S.A.
{ahuete, piyachat, kamel, humberto, tomoaki}@ag.arizona.edu

[2]INPE – Instituto Nacional de Pesquisas Espaciais
Caixa Postal 515 - 12201-970 - São José dos Campos - SP, Brasil
yosio@ltid.inpe.br

[3]Universidade Federal de Goias
Caixa Postal 131 - 74001-970 - Goiania - GO, Brasil
laerte@iesa.ufg.br

Abstract. We utilized the Terra- MODIS Vegetation Index (VI) products to characterize the variability in seasonal and spatial patterns of photosynthetic vegetation activity along an eco-climatic gradient extending from the diverse Brazilian cerrado to the seasonal tropical forest at Tapajos National Forest, including transitional biomes at Santana do Araguaia and land conversion areas. The NDVI and EVI at 500-m and 1-km were used to generate the seasonal profile curves with the aid of quality assurance (QA) parameters for noise removal and data filtering. The seasonal patterns of the cerrado were pronounced with distinct dry and wet seasonal trends. We observed decreasing dry-wet seasonal patterns northward along the transect and in the transitional areas near Santana do Araguaia. However, we observed a reversed seasonal pattern at Tapajos National Forest in which vegetation activity increased during the shorter dry season. This was attributed to the flush of new leaf growth in the dry season and the influence of epiphyll-covered, older leaves in the wetter periods.

Keywords: MODIS, vegetation index, phenology, cerrado, Amazon.

1. Introduction

Seasonal measurements of vegetation activity and associated ecosystem fluxes of carbon, nitrogen, and water are difficult to obtain over the Amazon Basin. Seasonal and spatial patterns of vegetation variability are crucial in understanding how the dynamics of rainfall patterns interact with land cover types and soils to control carbon fluxes (Potter et al., 1998). Satellite data sets such as the Pathfinder Advanced Very High Resolution Radiometer (AVHRR) Land (PAL) data have been used successfully for studies of temporal and interannual behavior of surface vegetation and to derive estimates of spatial variations in annual net primary production (NPP). However, the low spatial resolution and large errors inherent in the AVHRR normalized difference vegetation index (NDVI) time series data sets (poor sensor calibration, insufficient cloud screening, variable acquisition geometry) have been major impediments to their effective utilization, particularly in the Amazon Basin where extreme levels of cloud contamination afford limited views of the surface vegetation (Goward et al., 1991). The Landsat TM and ETM+ imagery offer much better quality data sets, particularly for spectral differentiation of land cover types, but at infrequent intervals to capture their seasonal dynamics.

The recently launched Terra MODIS instrument with newly developed terrestrial products, at 250m, 500m, and 1km resolutions, may contribute significantly to further investigations and monitoring of the Earth's vegetation. In comparison to the AVHRR sensor, the MODIS sensor offers improved cloud screening, finer spatial resolution, and atmosphere correction with no water vapor influence. This may better depict the regional seasonal behavior of the various Amazon land cover types for improved carbon metabolism studies and improved discrimination of the components of interannual variability, and improved land cover differentiation.

The seasonality of a specific biome or land cover type is a combination of several factors including changes in leaf physiology (chlorophyll content, water and nutrient availability, leaf aging, flowering), leaf morphology, canopy structure, specific leaf area (SLA), leaf area index, and the proportions of woody, herbaceous, and understory vegetation. Seasonal patterns of vegetation variability as well as NPP have been found to vary inversely with duration of the dry season. Deep rooting and drought tolerance by trees in seasonally dry evergreen forests of the Amazon maintains primary production during dry seasons.

On the other hand, Roberts et al. (1998) conducted leaf optical measurements of a series of tropical broadleaf species near Manaus in the Amazon Basin and found NIR reflectances to decrease with leaf aging. Older, primary forests had lower NIR reflectances and broadleaf trees with the older leaves had the lowest reflectances, while second growth forests and new leaf growth 'flushes' had the highest NIR reflectances. Although not synchronous between plants and species (genetic variability), leaf flush tend to occur approximately 1 month after the start of the dry season. Roberts found leaf flush was restricted to the dry season. With rapid changes due to the natural maturation of leaves over the first ~2 months.

In the humid tropics, leaf optical properties also vary due to colonization by epiphylls (fungi, lichens, algae, bacteria) that cover the mature leaf surfaces and reduce light transmission and limit photosynthesis. Spectral differences among species, in comparison to differences between epiphyll cover categories was relatively minor (Roberts et al. 1998).

In the Terra Firme tropical forest with high species diversity, there would be considerable variation in phenology, leaf turnover, and susceptibility to epiphylls. The impact of leaf aging and epiphyll cover on vegetation indices should be significant but remain unresolved. The resulting VI behavior would further impact estimates of ecologically significant parameters including NPP, APAR, canopy resistance, and photosynthetic capacity.

In this study, we evaluated the utility of the MODIS VI products for moderate resolution land surface monitoring and ecology over Amazonia. We investigate the performance of MODIS in characterizing the seasonal patterns and dynamics of the cerrado, transition, and forested biomes.

2. Methods & Study Sites

The MODIS VI products ingest the level 2G (gridded) daily surface reflectances (MOD09 series), which are corrected for molecular scattering, ozone absorption, and aerosols. Two VI's, the NDVI and the enhanced vegetation index (EVI), are produced:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}} \quad (1)$$

$$EVI = G \times \frac{\rho_{NIR} - \rho_{Red}}{L + \rho_{NIR} + C_1 \times \rho_{Red} - C_2 \times \rho_{Blue}} \quad (2)$$

where ρ_{NIR}, ρ_{Red}, and ρ_{Blue} are the surface reflectances in their respective sensor bands; L is a canopy background adjustment that addresses non-linear, differential NIR and red radiant transfer through a canopy, and C_1 , C_2 are the coefficients of the aerosol term, which uses the blue band to correct for aerosols in the red band. We used the coefficients adopted in the MODIS EVI standard product, L=1, C_1 = 6, C_2 = 7.5, and G (gain factor) is 2.5 (Huete et al. 2002). Whereas the NDVI is chlorophyll sensitive and responds mostly to the visible or 'red' band variations, the EVI has been shown to be more 'near-infrared' (NIR) sensitive and responsive to canopy structural variations, including LAI, canopy type, and canopy architecture (Gao et al. 2000). The two VI's may complement each other in global vegetation studies and improve upon the extraction of canopy biophysical parameters.

Currently, the MODIS VI compositing algorithm utilizes the constrained view angle-maximum value composite (CV-MVC) criterion, whereby the NDVI value with the view zenith angle closest to nadir from the two highest NDVI values is selected. Once all 16 days of observations are collected, the MODIS VI algorithm applies a filter to the data based on input quality analysis (QA), cloud, and viewing geometry. Cloud-contaminated pixels and extreme off-nadir sensor view angles (± 55°) are considered lower quality, while cloud free, nadir-view pixels with no residual atmospheric contamination represent the best quality pixels. The composited VI product contains a variable number of 'Science Data Sets' that include the 16-day NDVI and EVI along with output quality assurance (QA), geometry of observation (view zenith, solar zenith, and relative azimuthal angles), and four residual reflectances (band 1-red, band 2-near-infrared, band 3-blue, band 7- middle-infrared) from the selected, composited pixels.

In contrast to the AVHRR-NDVI datasets with interpolation and reconstruction methods added, the MODIS data sets offer a QA-based scheme to enable the filtering of data to provide spatial and temporal consistency in VI values on an operational basis. Each observation over a 16-day period is evaluated and given an internal quality measure ranked from 0 (best) to 6 (worst), based on the input quality information of cloud, shadow, aerosol, snow/ice, and band reflectances. The per-pixel input quality information is incorporated in the output QA of each pixel in a product to meet the user's needs.

3. Study Area

The eco-climatic transect includes the major cerrado formations, cerrado-Amazon forest transition, and forested areas as well as their land use converted areas. We extracted windows along the transect at Tapajos, Araguaia, and Brasilia sites with the 1 km MODIS composites, and plotted their seasonal profiles using the QA filter criteria to delete pixels that were labeled cloud contaminated and selected pixels of the medium and highest quality labeling. Two years of data were analyzed, the 2000 and 2001 growing seasons. The first set of study sites, near Brasilia, are located in the Brasilia National Park (BNP) and surrounding areas. These sites include undisturbed typical cerrado vegetation formations (grassland, shrub land, and woodland) and disturbed, land-converted pasture and agricultural sites. A second set of study sites is located in the Tapajos LBA core site near Santarem, which has primary and secondary forests, pasture areas, and selective logged areas. The last set of study areas are located near Santana do Araguaia (woodland/ semi-deciduous broadleaf forest), serving as a transition area between the above two, cerrado and forest endpoints.

4. Results

Monthly composites of maximum value composite (MVC) based, 8-km NDVI from the AVHRR PAL dataset were acquired along the eco-climatic transect and averaged over a 20 year period (1982-2001) (**Figure 1**). The datasets are corrected for Rayleigh scattering and ozone absorption and are smoothed with low pass filters and Fourier analysis and interpolations in order to remove anomalous NDVI signals (Los et al. 1994) resulting in a more complete cloud-free NDVI seasonal response profile.

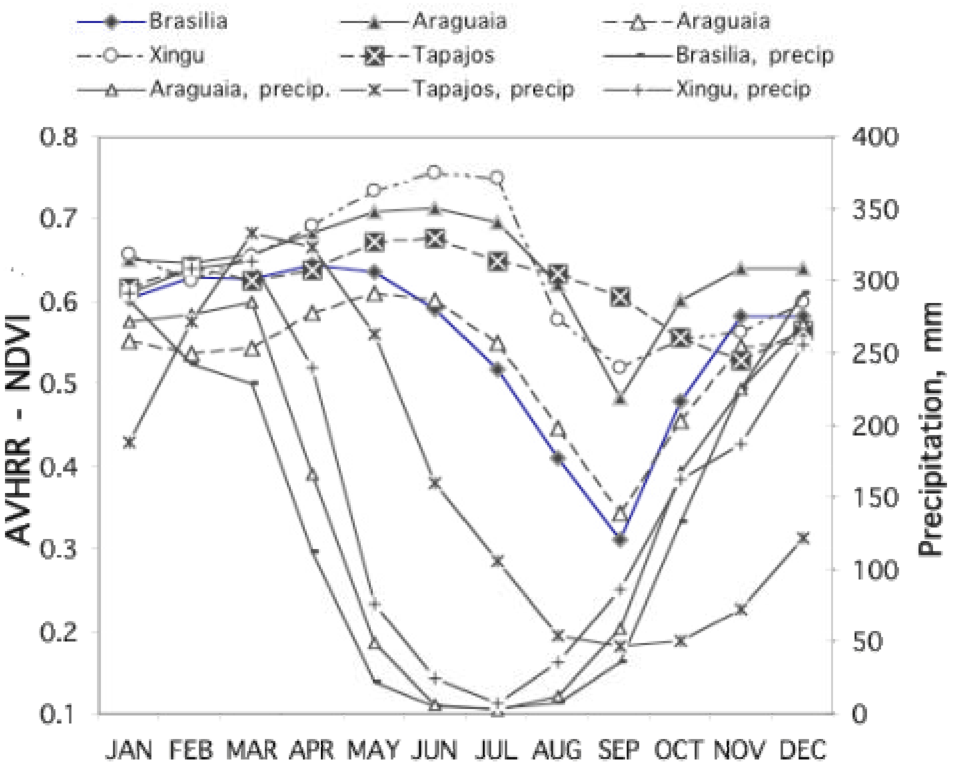

Figure 1. 20-year average of AVHRR-NDVI for each month and average monthly precipitation along the eco-climatic transect sites.

The Brasilia cerrado profiles displayed the sharpest seasonal contrasts due to the early and pronounced dry season encountered in Brasilia (see **Figure 1** for monthly NDVI and monthly precipitation). As we proceed northward toward the Araguaia transition area, we note a shift in the onset of the dry season and a less lower seasonality contrast as denoted by the NDVI. The northernmost site at Tapajos has a dry season that commences approximately 2 months later (July) and a rainy season that starts in November or 2 months after the rainy season starts in Brasilia. The NDVI profile at Tapajos has the least contrast and reaches a minimum value in November which is about 2 months after the Brasilia minimum NDVI period (September). All sites showed a decrease in NDVI values at the onset of the dry season as well as an increase in NDVI following the initiation of the rainy season with a time lag of about 2 months (**Figure 1**). One surprising result was that the wet season NDVI values were lower at Tapajos relative to both Xingu and Araguaia, a pattern that reversed in the dry season.

The structure of the MODIS extract, global VI histograms of the Amazon basin also reveal the strong seasonal patterns of this region, particularly in the cerrado boundaries, but also in the tropical seasonal forests of the eastern Amazon (**Figure 2**). The strong cerrado – forest seasonal contrast appears fairly markedly in the EVI histogram as a secondary peak of EVI values during the cerrado dry periods (2000-177, 2000-241). In the wet season the cerrado peak disappears. The primary peak in the EVI histograms is the more highly vegetated forest biome and exhibits a much smaller degree of seasonality. In the case of the EVI, there is a slight shift toward higher values in the dry period of the seasonal tropical forest (2000-241, 2000-305), while in the case of the NDVI, the wet periods (2001-065, 2001-113) show the highest NDVI values. However, overall there are less structural features in the NDVI histograms which appear skewed and saturated at the upper end of NDVI values. There is also no secondary, cerrado peak evident (**Figure 2**, top).

The seasonal profiles for the year 2000 and 2001 at the 3 major sites along the transect are depicted in **Figure 3** for the NDVI and EVI. The Brasilia cerrado has the most dramatic seasonal contrast in both NDVI and EVI with the Araguaia cerrado (transition area) following a similar profile but with a much lower dry-wet seasonal contrast. The Tapajos forest site and Araguaia forest site both showed the least seasonality, appearing nearly flat in the NDVI while demonstrating an increase in EVI over the dry season (~DOY 200 – 300) (**Figure 3**). The Araguaia forest area also had a lower EVI value than the Tapajos site, whereas they were indistinguishable in the NDVI seasonal data. The increase in EVI over the dry season at Tapajos and Araguaia support the finding in the regional histogram extracts (**Figure 2**) in which EVI was maximum over the dry season. There was also a sharper contrast between the forest sites and the cerrado sites with the EVI data. In the NDVI seasonal dataset, the cerrado values nearly were equal to the forest values in the wet season and between the Araguaia sites.

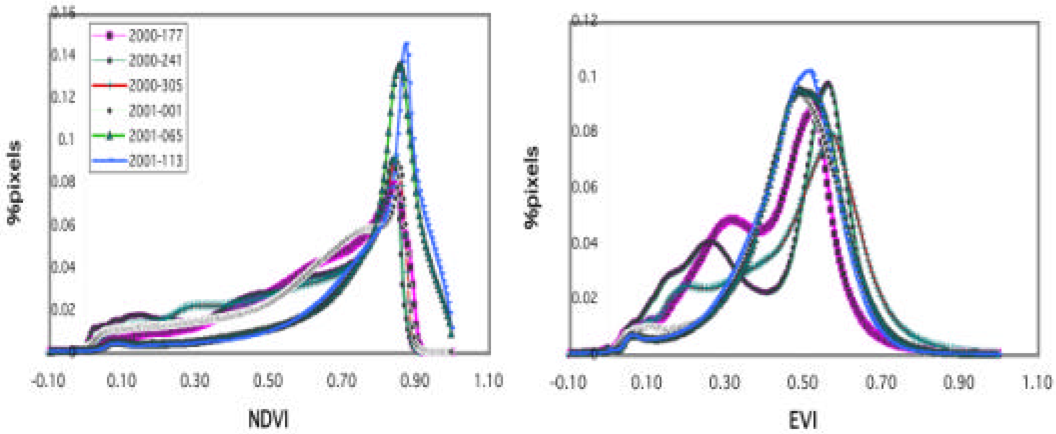

Figure 2. Seasonal 16-day histograms of the MODIS-NDVI (top) and MODIS-EVI (bottom) for the entire Amazon Basin (2000-2001).

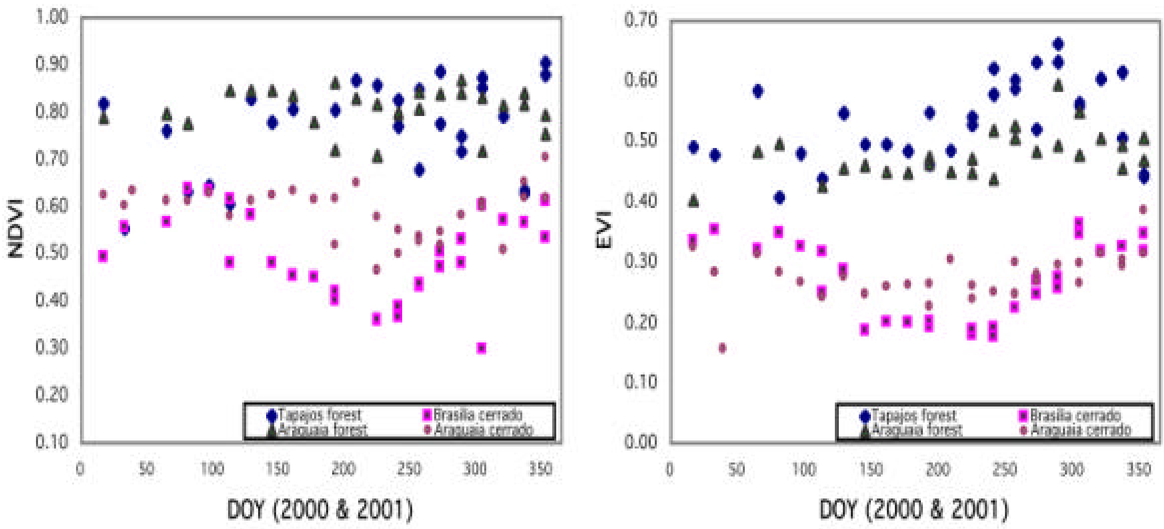

Figure 3. MODIS NDVI and EVI seasonal profiles for years 2000 and 2001 at the three major sites along the eco-climatic transect.

We carried out a more detailed analysis of the behavior of the EVI at the Tapajos National Forest by using the QA filter to select only pixels with the highest two levels of quality and by plotting the reflectances associated with the compositing results. **Figure 4** shows that for both the 2000 and 2001 years, the MODIS enhanced vegetation index (EVI) significantly increased in value over the dry season from July to November. The EVI seasonal profiles run counter to the seasonal precipitation profile with a 6-7 month phase difference (**Figure 4**). The visible reflectance bands (blue and red) showed no obvious trend over the entire measurement period, however, the near-infrared (NIR) reflectance values also significantly increase in value at the onset of the dry season. These results are in agreement with Roberts et al. (1998) findings of a 'green flush' in new leaf growth starting approximately one month into the dry season. The new leaf growth does not contain the large presence of epiphyll growth characteristic of the older leaves (personal observation) and have higher NIR reflectances than the NIR-absorbing epiphyll covering of the old leaves. Now the NDVI is more responsive to the red channel and hence is less affected by the dynamics of NIR reflectance and more responsive to the absorption behavior of the red channel which is not as impacted by leaf aging and epiphyll activity (Roberts et al., 1998).

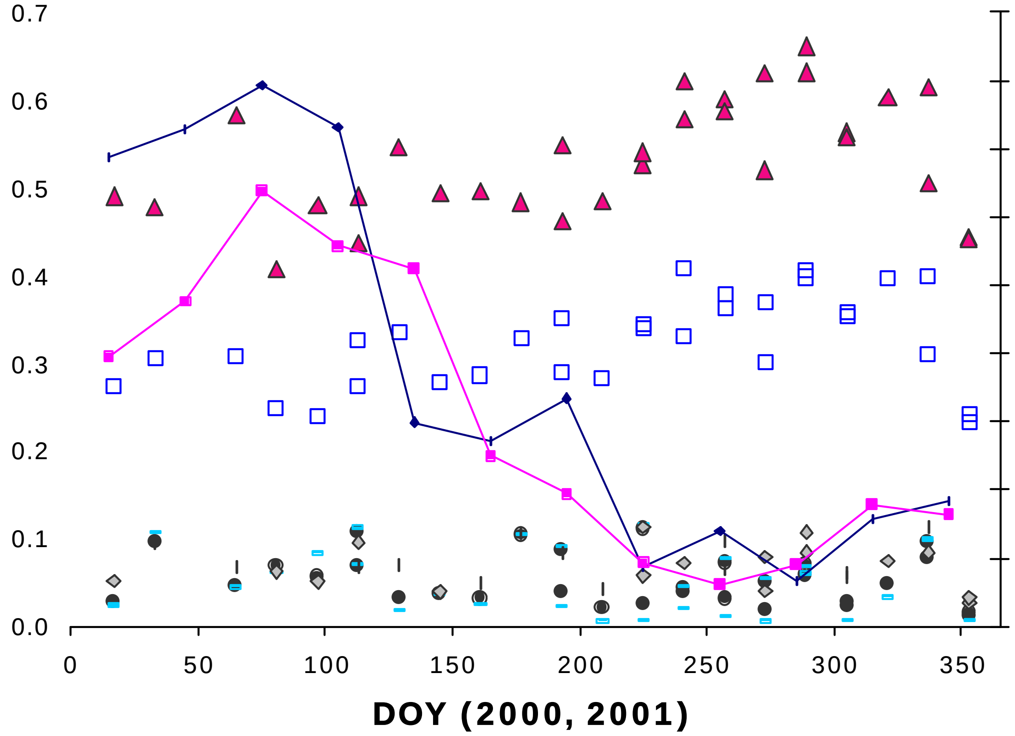

Figure 4. Seasonal plots of MODIS EVI and reflectance 16-day composites for Tapajos National Forest for two years, 2000 and 2001. Annual precipitation from the on-site Belterra meterological station is shown for the year 2000 and 15 year average (1986-2000).

4. Discussion

We found MODIS to be very useful in seasonal monitoring of the Amazon over the full range of land cover types encountered over the eco-climatic transect studied in this paper. We found distinct seasonal behavior in the cerrado zones and more humid forest portions of the transect. The seasonal patterns observed agree with the seasonal patterns of precipitation, however, there were important differences noted. In the transition zone, we note that even under similar precipitation patterns, the cerrado and forested portions near Araguaia had very distinct and variable seasonal profiles. This indicated that other environmental factors, such as topography and soil and physiognomy also play important roles in ecosystem phenolgy and carbon metabolism,

The other important observation encountered in this dataset was the behavior of the EVI during the dry season at the Tapajos forest site. Whereas, the NDVI from the 20-year AVHRR dataset shows a drop in vegetation activity coincident with the dry season, the MODIS EVI showed an increase in vegetation activity at the onset of the dry season. This was attributed to the initiation of fresh, new leaf growth during the dry season, producing a higher NIR signal of which the EVI is particularly sensitive to. This also agreed with the expected lower NIR and EVI signals expected in the wet season as a result of epiphyll activity on the mature leaves. This is in need of further study, given the relevance of remotely-sensed 'greenness' signals in the estimation of carbon fluxes and NPP. The MODIS-NDVI signal showed no obvious seasonal pattern. On the other hand, the decrease NDVI signal noted in the AVHRR data could be the result of inclusion of the land coverted pastures into the larger 8km by 8km pixel size data which was further averaged with a 5x5 window. The pastures presented in the converted lands dry out in the dry season resulting in a decreased VI signal. This further supports the importance of incorporating land surface heterogeneity into studies of vegetation dynamics, phenolgy, and carbon fluxes.

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