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Detecting leaf phenology of seasonally moist tropical forests in South America with multi-temporal MODIS images

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Abstract

Leaf phenology of tropical evergreen forests affects carbon and water fluxes. In an earlier study of a seasonally moist evergreen tropical forest site in the Amazon basin, time series data of Enhanced Vegetation Index (EVI) from the VEGETATION and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors showed an unexpected seasonal pattern, with higher EVI in the late dry season than in the wet season. In this study we conducted a regional-scale analysis of tropical evergreen forests in South America, using time series data of EVI from MODIS in 2002. The results show a large dynamic range and spatial variations of annual maximum EVI for evergreen forest canopies in the region. In tropical evergreen forests, maximum EVI in 2002 typically occurs during the late dry season to early wet season. This suggests that leaf phenology in tropical evergreen forests is not determined by the seasonality of precipitation. Instead, leaf phenological process may be driven by availability of solar radiation and/or avoidance of herbivory.

Keywords: Vegetation indices; MODIS; Plant phenology; Climate

1. Introduction

Forest canopies interact with the atmosphere and play an essential role in maintaining biodiversity and physiological processes (Ozanne et al., 2003). Because mature tropical forests are tens of meters tall, rich in species, and have high leaf area index (LAI, >4 m^2/m^2), phenological studies in the field are challenging. Consequently, there are a limited number of field-based phenological studies for evergreen forests in tropical South America (Van Schaik et al., 1993; Wright & van Schaik, 1994).

Satellite remote sensing at moderate spatial resolution provides frequent observations that may reveal seasonal changes of vegetation. Numerous remote sensing studies have focused on the structural properties of forest canopies, including LAI and the fraction of photosynthetically active radiation (PAR) absorbed by vegetation canopy ($FPAR_{canopy}$) (Myneni et al., 2002). $FPAR_{canopy}$ is highly correlated with Normalized Difference Vegetation Index (NDVI) (Goward & Huemmrich, 1992), which is calculated as a normalized ratio between red and near infrared bands (Tucker, 1979), and NDVI is widely used to estimate LAI (Asrar et al., 1992; Sellers et al., 1992). Mature evergreen tropical forests usually have large values of LAI (>4 m^2/m^2), which results in saturation of $FPAR_{canopy}$ and NDVI. Regional-scale seasonal variations of NDVI in tropical forests of Amazon region are primarily caused by variations of atmospheric conditions associated with aerosols and clouds (Kobayashi & dye, 2005).

The Enhanced Vegetation Index (EVI) is an improved vegetation index that accounts for the effects of residual atmospheric contamination and soil background (Huete et al., 2002). We recently examined the seasonal dynamics of EVI for a stand of seasonally moist tropical evergreen forest in the central Amazon, using satellite images from the VEGETATION sensor onboard the SPOT-4 satellite and the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor

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onboard the NASA Earth Observing System (EOS) Terra platform (Xiao et al., 2005c). The EVI data showed little or no saturation over a year, had a peak in late dry season to early wet season, and tracked the seasonal dynamics of the forest canopy associated with the fall of old leaves and the emergence of new leaves. This observed phenological pattern suggests a higher photosynthetic potential in the dry season and corresponds to the seasonal dynamics of net CO_2 exchange in the site, which absorbs carbon in the dry season and releases carbon in the wet season (Saleska et al., 2003).

In this paper, we ask whether similar phenological patterns can be observed over the range of tropical evergreen forests in South America. We conducted a regional-scale analysis of MODIS images in 2002 with the objective of quantifying spatial and temporal variability of leaf phenology of forest canopies across the evergreen forests of tropical South America.

2. Data and methods

2.1. MODIS images in 2002

We used satellite images from the MODIS sensor. This sensor has 36 spectral bands, seven of which are designed for the study of vegetation and land surfaces: blue (459–479 nm), green (545–565 nm), red (620–670 nm), near infrared (NIR_1: 841–875 nm; NIR_2: 1230–1250 nm), and shortwave infrared ($SWIR_1$: 1628–1652 nm, $SWIR_2$: 2105–2155 nm). Daily global imagery is provided at spatial resolutions of 250-m (red and NIR_1) and 500-m (blue, green, NIR_2, $SWIR_1$, $SWIR_2$). The MODIS Land Science Team provides a suite of standard MODIS data products to the users, including the 8-day composite MODIS Surface Reflectance Product (MOD09A1). Each 8-day composite (MOD09A1) includes estimates of surface spectral reflectance for the seven spectral bands at 500-m spatial resolution. In the production of MOD09A1, atmospheric corrections for gases, thin cirrus clouds and aerosols are implemented (Vermote & Vermeulen, 1999). MOD09A1 composites are generated in a multi-step process that first eliminates pixels with a low observational coverage, and then selects an observation with the minimum blue band value during the 8-day period (http://modis-land.gsfc.nasa.gov/MOD09/MOD09ProductInfo/MOD09_L3_8-day.htm).

Standard MODIS products are organized in a tile system with the Sinusoidal projection; and each tile covers an area of 1200 × 1200 km (approximately 10° latitude × 10° longitude at equator). In this study we acquired MOD09A1 data for 2002 (forty-six 8-day composites in a year) from the USGS EROS Data Center (EDC; http://edc.usgs.gov/). Fifteen tiles (from h10v08 to h14v10) are needed to cover the study area ranging from 10° N to 20° S. By exclusion of MODIS tiles east of 40° W we have excluded the limited areas of Atlantic evergreen tropical and subtropical forest from our study domain.

2.2. Vegetation indices

For each 8-day composite image, we calculated EVI (Huete et al., 2002) and Land Surface Water Index (LSWI; (Xiao et al., 2005c)) using surface reflectance values from the blue, red, NIR (841–875 nm) and SWIR (1628–1652 nm) bands.

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{nir}} + \rho_{\mathrm{red}}} \quad (1)$$

$$\mathrm{EVI} = 2.5 \times \frac{\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{nir}} + 6 \times \rho_{\mathrm{red}} - 7.5 \times \rho_{\mathrm{blue}} + 1} \quad (2)$$

$$\mathrm{LSWI} = \frac{\rho_{\mathrm{nir}} - \rho_{\mathrm{swir}}}{\rho_{\mathrm{nir}} + \rho_{\mathrm{swir}}} \quad (3)$$

The SWIR band is sensitive to leaf water and soil moisture. LSWI is sensitive to equivalent water thickness (EWT, g H_2O/m^2) (Maki et al., 2004; Xiao et al., 2005b), and has been used for mapping forests and agriculture (Boles et al., 2004; Xiao et al., 2005a). The blue band is sensitive to atmospheric conditions and is often used for atmospheric correction. EVI directly adjusts the reflectance in the red band as a function of the reflectance in the blue band (Huete et al., 2002, 1997).

The vegetation canopy can be conceptually partitioned into separate components based on biochemical properties. From this biochemical perspective, the vegetation canopy consists of (1) chlorophyll and (2) non-photosynthetic vegetation (NPV) components (Xiao et al., 2004, 2005b,c; Zhang et al., 2005). NPV includes both canopy-level (e.g., stems, branches, senescent leaves) and sub-leaf level materials (e.g., cell walls, veins and non-chlorophyll pigments within a green leaf). Correspondingly, $FPAR_{canopy}$ is partitioned into the fraction of PAR absorbed by chlorophyll ($FPAR_{chl}$) and by NPV ($FPAR_{NPV}$), respectively. EVI is closely related to $FPAR_{chl}$ (Xiao et al., 2004, 2005b, 2005c; Zhang et al., 2005).

The MOD09A1 files include quality control flags to account for various image artifacts (e.g. clouds, cloud shadow). In addition, we used blue band reflectance to further eliminate contaminated observations. Those observations with blue band reflectance values >0.20 were assumed to be contaminated observations and eliminated from the analysis (Xiao et al., 2006). After screening out contaminated observations (clouds, aerosols, etc.), we selected annual maximum values of EVI for pixels from all the remaining good observations in a year, and recorded the dates for annual maximum EVI. In this study we use both (1) annual maximum values of vegetation index (magnitude) and (2) date of annual maximum vegetation index (timing) as a measure for leaf phenology of evergreen forests.

2.3. The map of evergreen tropical forests

A map of evergreen forests in the tropical South America was needed for statistical analysis of leaf phenology. We examined three global land cover maps that provide information on tropical evergreen forests in South America at 1-km spatial resolution. Each was derived from a different set of satellite data: AVHRR (Loveland & Belward, 1997; Loveland et al., 2000), VEGETATION (Eva et al., 2004), and MODIS (Friedl et al., 2002). In order to have a map of evergreen forest at 500-m spatial resolution that is consistent with the vegetation indices

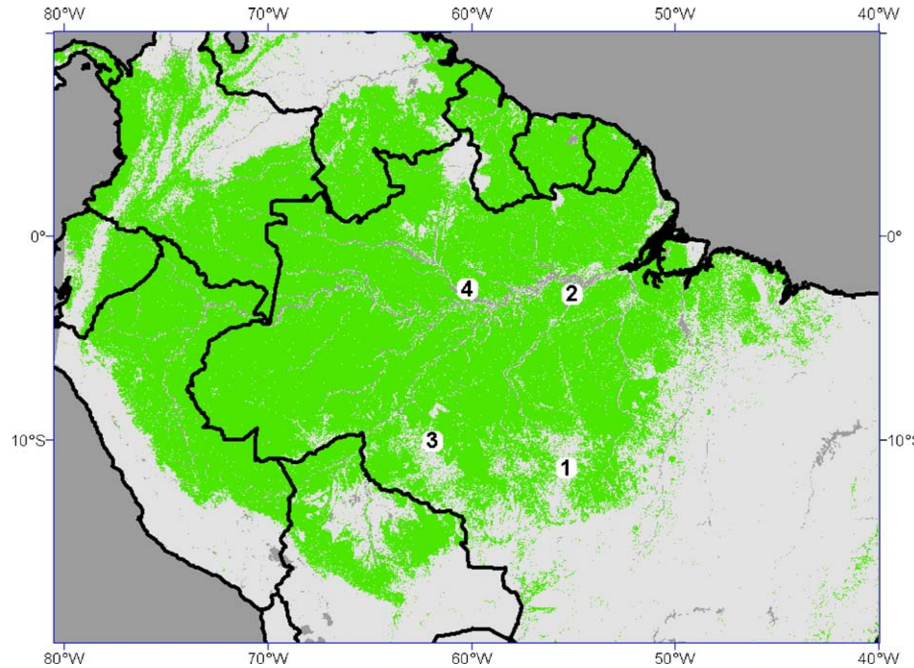

Fig. 1. The spatial distribution of evergreen tropical forests in the South America, as derived from a procedure that uses time series data of Land Surface Water Index (LSWI) at 500-m spatial resolution. Symbols 1–4 represent locations of the four blocks (each consists of 37 by 37 MODIS pixels and is centered on a CO_2 eddy flux tower site.) in Amazon basin: 1 – Mato Grosso (11.41230° S, 55.32470° W); 2 – Para (2.85500° S, 55.03639° W); 3 – Rondonia (10.07830° S, 61.93360° W); 4 – Amazonas (2.60907° S, 60.20917° W). The latitude and longitude of CO_2 eddy flux tower sites, as measured from global positioning system (GPS) receivers, are included here.

data used in this study, we developed an approach that uses LSWI in 2002 to identify evergreen vegetation in the study area. Earlier studies showed that LSWI values rarely go below 0.0 for a pixel with evergreen vegetation (Boles et al., 2004; Xiao et al., 2005a). In this study, a MODIS pixel was defined as evergreen vegetated land if none of the valid 8-day composites in 2002 has a LSWI value of <0.0. The resultant map estimates about 6.41 million km^2 of evergreen vegetated land surface in the study area (Fig. 1). We compared our area estimate to the area estimate of evergreen broadleaf forest in the International Geosphere and Biosphere (IGBP) classification scheme derived from the standard MODIS 1-km Land Cover data (Friedl et al., 2002). The IGBP classification estimate was about 2.9% higher than that of the LSWI-based forest map at 500-m spatial

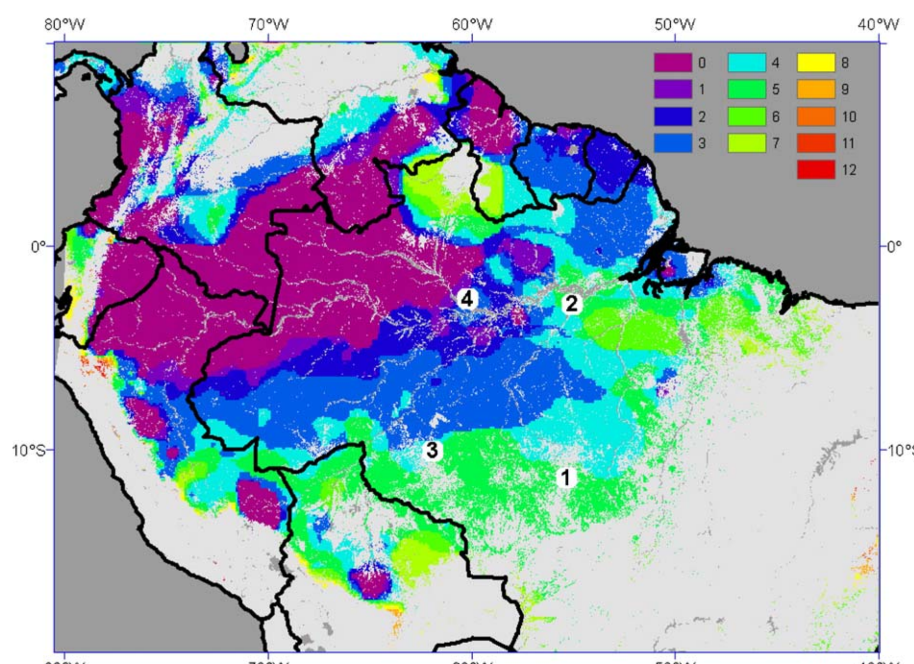

Fig. 2. Spatial distribution of the dry season (defined as number of months with precipitation < 100-mm/month) in tropical South America. The monthly precipitation data are from the South American Precipitation Dataset (Willmott & Webber, 1998), and provided by LBA-Hydronet.

resolution. The spatial distribution of the LSWI-based map was also consistent with that of the standard MODIS 1-km Land Cover map (not shown here). In this study the LSWI-based forest map at 500-m resolution was used for the statistical analysis of leaf phenology.

2.4. Spatial and temporal variations of wet- and dry-seasons

Although annual precipitation is high (>1500 mm/yr), there still exist distinct dry and wet seasons for a large portion of Amazon region (Keller et al., 2004; Poveda & Salazar, 2004). In this study we used long-term monthly precipitation data at 0.5° (latitude and longitude) spatial resolution (Willmott & Webber, 1998) to delineate the spatial distribution of dry season in tropical South America. The length of dry season, defined as the number of months with <100 mm precipitation (Saleska et al., 2003), varied substantially across the study region, with most areas ranging from zero to 5 months in a year (Fig. 2). The starting and ending months of dry season also varied across the study region (Fig. 3).

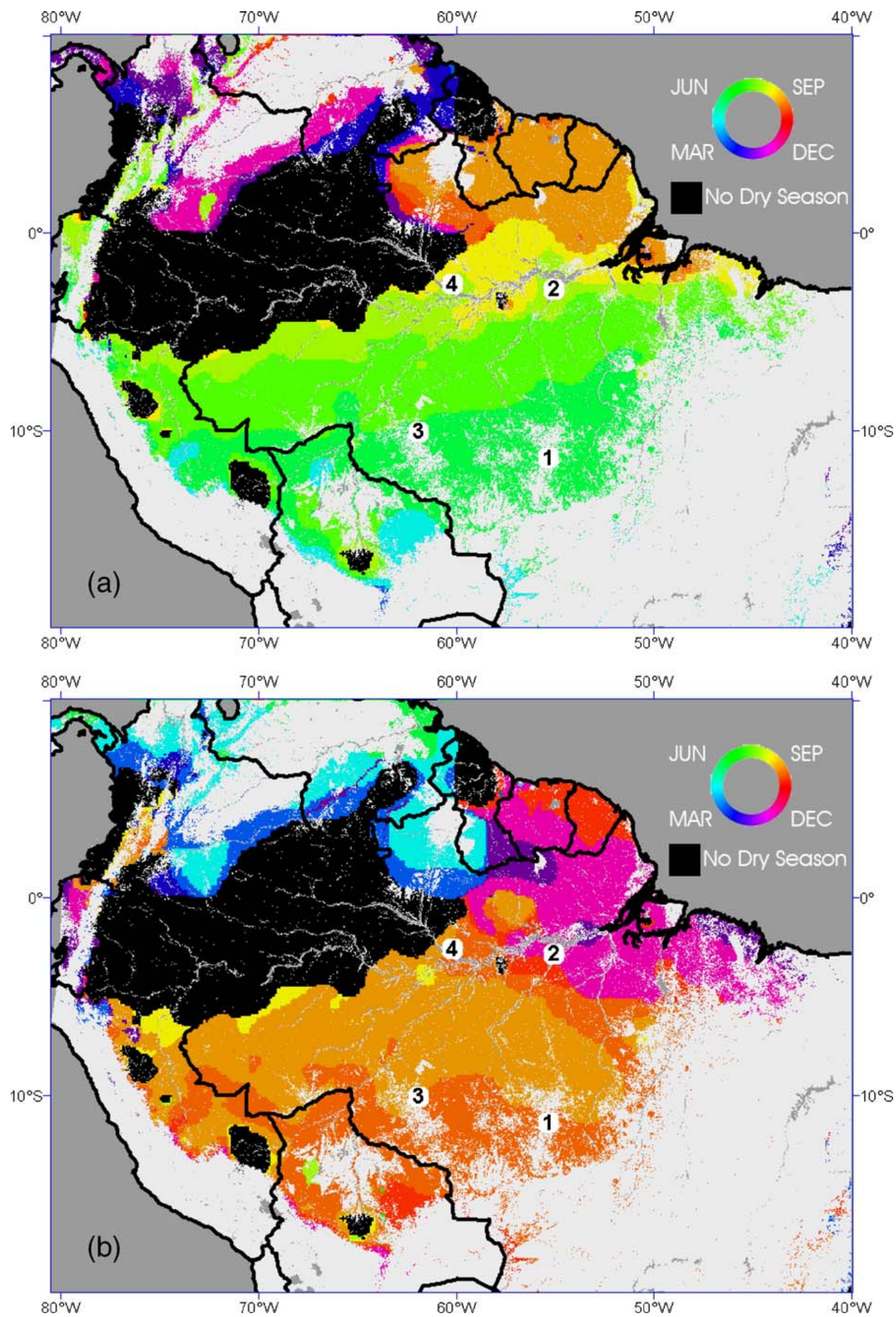

Fig. 3. Spatial distribution of (a) the starting month (the first month with monthly precipitation < 100 mm) and (b) the ending months (the last month with monthly precipitation < 100 mm) of the dry season in the tropical South America. The monthly precipitation data are from the South American Precipitation Dataset (Willmott & Webber, 1998), and provided by LBA-Hydronet.

We selected four blocks in areas of evergreen forests with different length (3 to 5 months) and timings of dry season for analysis of vegetation indices in relation to precipitation. Each block consists of 37 × 37 MODIS pixels, and is centered on a CO_2 eddy flux tower site in the states of Rondonia, Para, Mato Grosso and Amazonas, respectively. We calculated time series of the mean EVI values in 2002 for the four blocks individually.

3. Results

Among the four blocks with the length of dry season ranging from 3 to 5 months, the time series data of EVI showed a distinct trend of increasing EVI values from the end of wet season to late dry season (Fig. 4). Annual maximum EVI values occurred mostly in the late dry season.

Fig. 5a shows the spatial variations of annual maximum EVI values in 2002. Annual maximum EVI varied considerably across the evergreen forest region. The histogram of annual maximum EVI for forests had a wide range of variation (Fig. 6a). EVI had a bell-shape distribution, with 95% (29, 865, 835) of MODIS pixels in the evergreen tropical forest ranging from 0.5 to 0.9.

Fig. 5b shows the spatial distribution of the dates of annual maximum EVI occurring in 2002. The histogram for the dates of annual maximum EVI for all evergreen forest pixels had a bi-modal distribution (Fig. 6b). The larger peak of annual maximum EVI that occurred from September through December (Fig. 6b) corresponds to the larger area of evergreen forests in the portion of the study region mainly south of the equator (orange-to-red colored area in Fig. 5b). The secondary peak from January through March (Fig. 6b) corresponds to the evergreen forests mostly located north of the equator in northwestern part of the study region (see purple-to-blue colored area in Fig. 5b), where the dry season is non-existent or has short duration (1 to 2 months) (Fig. 2).

4. Discussion

At first glance, it is surprising that a large portion of the evergreen forests in the tropical South America are greener in the late dry season when the trees are more likely to suffer from drought stress due to relatively low precipitation. This unexpected timing of peak greenness indicates that seasonality of leaf phenology in seasonally moist tropical forests is not driven by the seasonality of precipitation (wet/dry seasons). The existence of a regional phenological pattern that favors highest chlorophyll levels during the dry season may be explained in two ways: (1) high chlorophyll and photosynthetic capacity during the dry season favors photosynthetic carbon uptake when radiation is abundant; and (2) flushing of new leaves

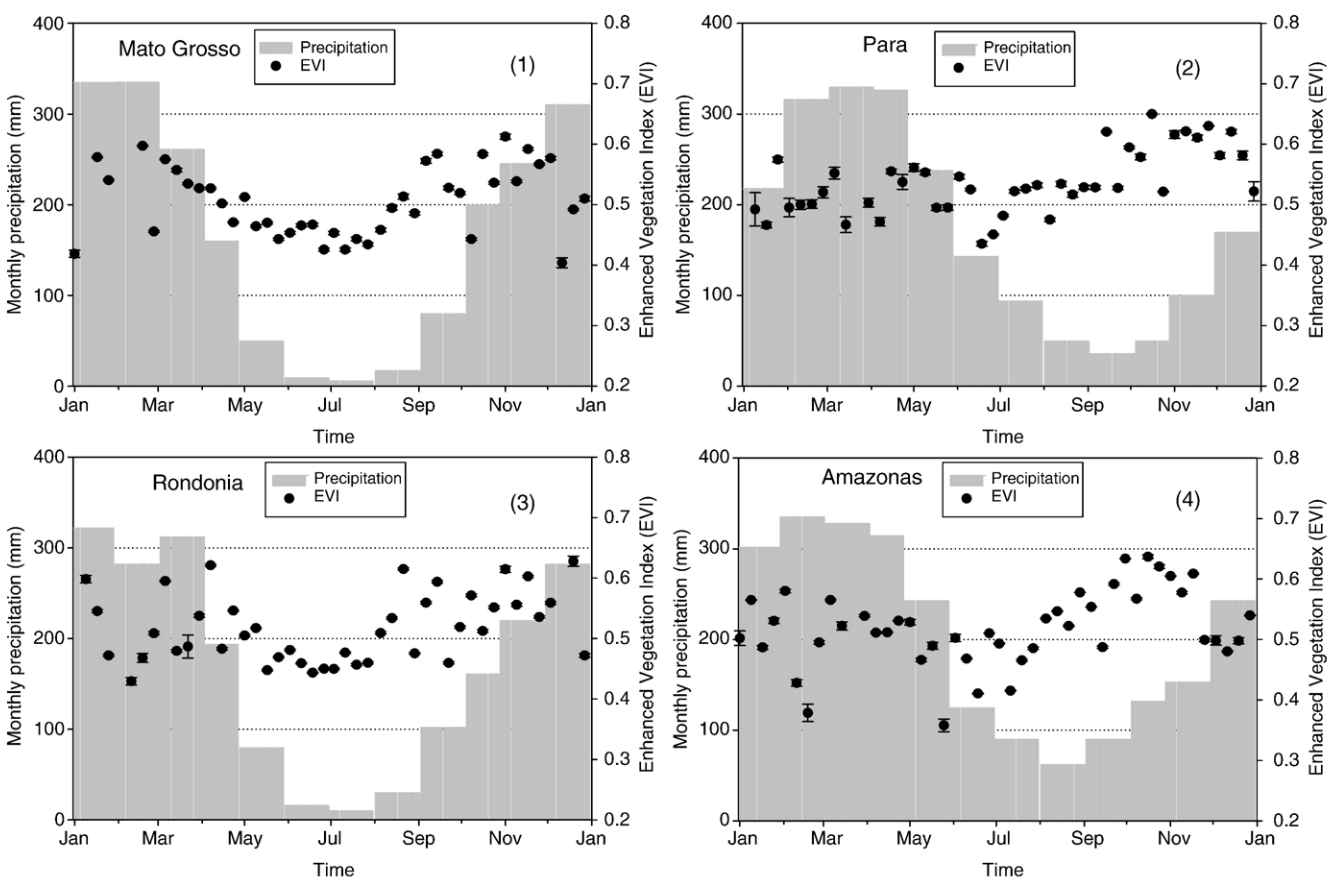

Fig. 4. Seasonal dynamics of Enhanced Vegetation Index (EVI) in the four blocks (designated as 1, 2, 3, and 4 in Fig. 1) and precipitation. Error bars for EVI represent one standard error of the mean. The monthly precipitation data are from the South American Precipitation Dataset (Willmott & Webber, 1998), and provided by LBA-Hydronet.

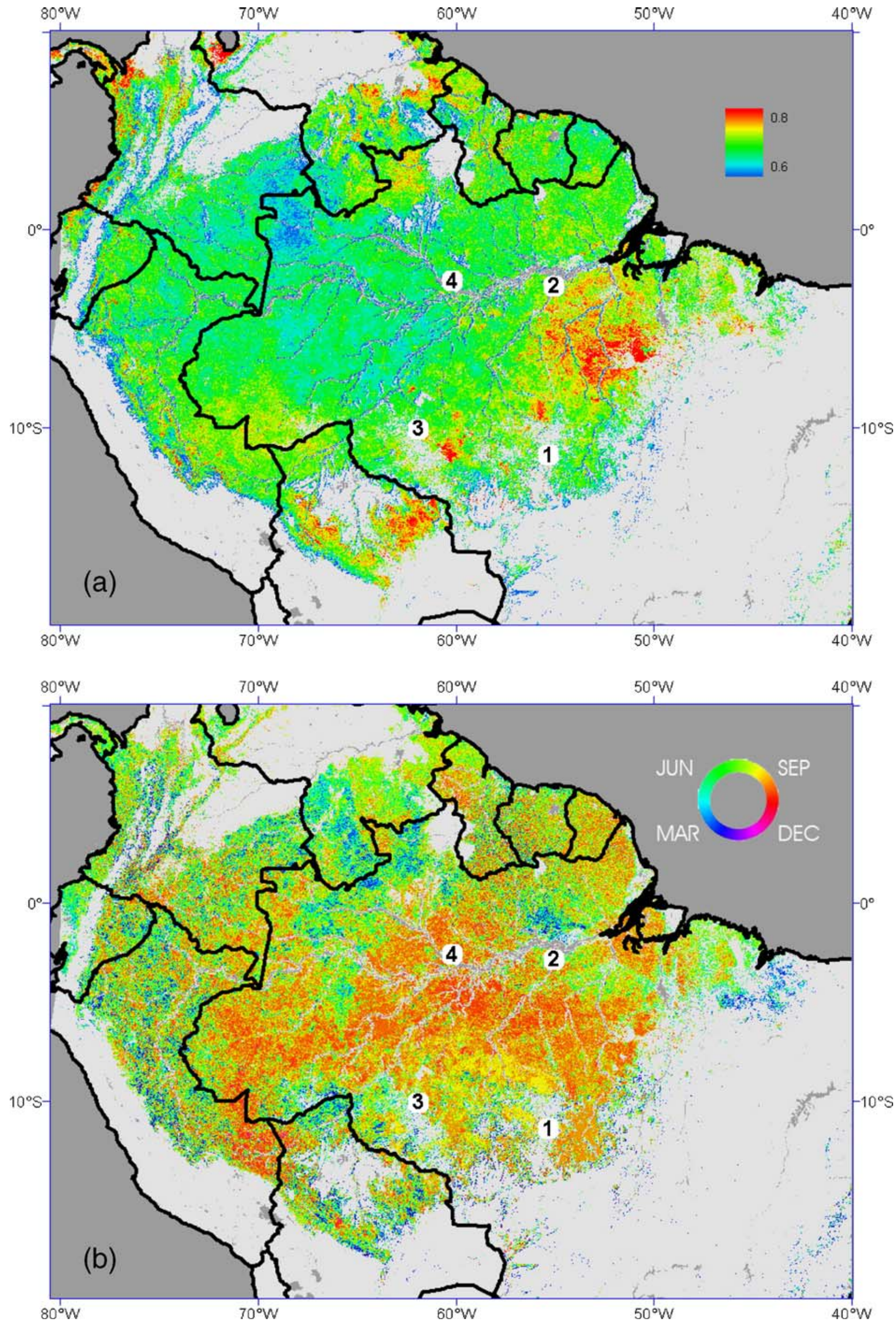

Fig. 5. Spatial distributions of (a) annual maximum Enhanced Vegetation Index (EVI) and (b) date of annual maximum EVI in 2002 over the tropical South America.

during the dry season is an effective widespread strategy for the avoidance of herbivory (Coley & Barone, 1996; Van Schaik et al., 1993). These two explanations are not mutually exclusive.

Field observations in seasonal tropical forests show that many drought-tolerant species with deep roots produce new leaves in the dry season (Van Schaik et al., 1993; Wright & van Schaik, 1994). In a seasonally moist evergreen tropical forest, the seasonal dynamics of EVI in a year is largely determined by the seasonal dynamics of the fall of old leaves and emergence of new leaves (Xiao et al., 2005c). New leaves generally have higher chlorophyll contents and greater maximum photosynthetic capacities than old leaves (Kitajima et al., 1997). Replacement of old leaves by young leaves with higher photosynthetic capacity leads to greater canopy photosynthetic capacity.

In the dry season throughout the evergreen forest regions of tropical South America, potential evapotranspiration exceeds precipitation. Trees remain evergreen and continue to transpire and photosynthesize by tapping deep soil moisture down to 12 m or more (Nepstad et al., 1994). At the Tapajos National Forest near Santarem, Para, Brazil in the Central Amazon, net ecosystem exchange peaked during the dry season because gross productivity remained high even as total respiration diminished (Goulden et al., 2004). Studies at both local and

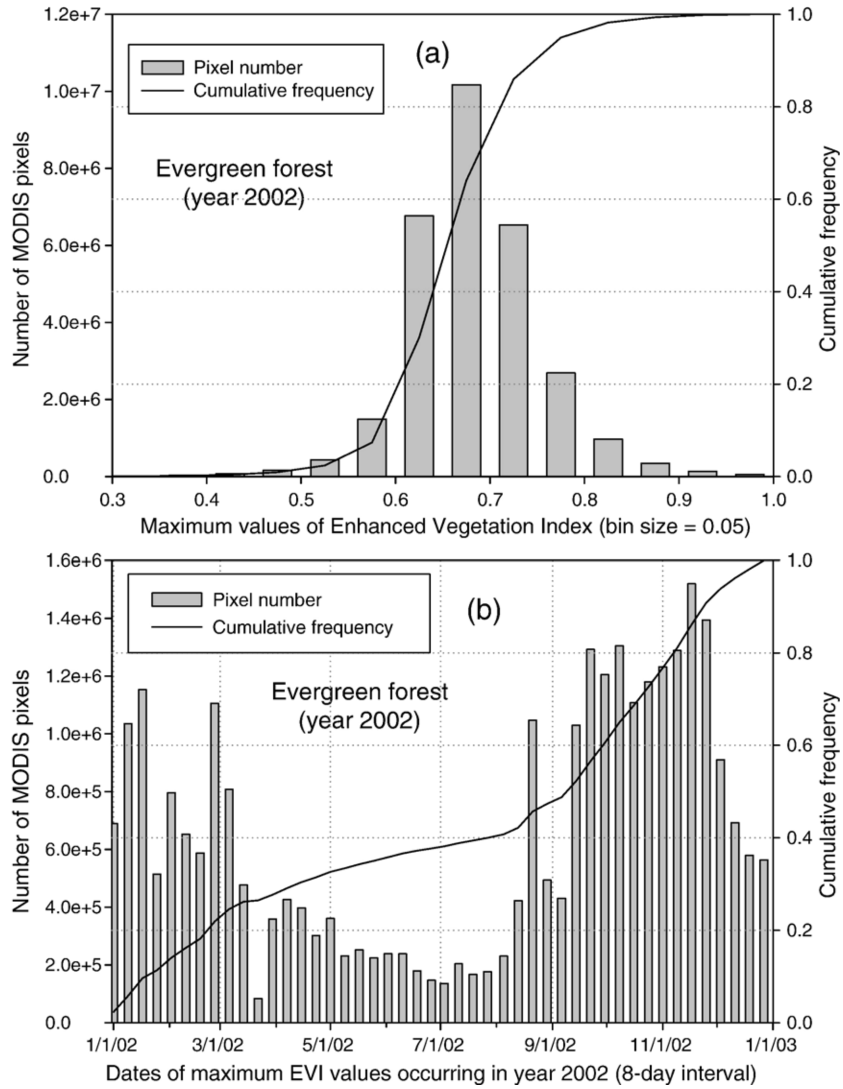

Fig. 6. Histograms of (a) annual maximum Enhanced Vegetation Index (EVI) and (b) date of annual maximum EVI in 2002 for evergreen forests in the tropical South America.

regional/global levels suggest that tropical forests are light limited (Goulden et al., 2004; Graham et al., 2003; Loescher et al., 2003; Nemani et al., 2003). The phenological pattern revealed in this study suggests that trees may flush new leaves throughout a large portion of evergreen tropical forests in South America in order to maximize photosynthetic uptake when cloudiness is at a minimum and light availability is maximized during the dry season.

The studies on plant–herbivore interaction in tropical forests have noted that herbivory rates are higher in tropical forests than in temperate forests and that most of the damage to leaves of tropical plants occurs when they are young and expanding (Coley & Barone, 1996). Other studies suggest that dry season conditions stress insect herbivores, resulting in low density of insect herbivores (Van Schaik et al., 1993). As leaves are most vulnerable to herbivory when they are young and expanding, it is advantageous to flush new leaves when herbivores are absent or diminished (Coley & Barone, 1996).

The observed large spatial variations of the dates of annual maximum EVI values in evergreen tropical forests indicate that there may be large differences in the seasonal dynamics of gross primary production on a continental scale, as has been observed and modeled locally at tropical forest sites (Goulden et al., 2004; Saleska et al., 2003; Xiao et al., 2005c). The biochemical perspective (chlorophyll content and $FPAR_{chl}$) of forest canopies (Xiao et al., 2005c; Zhang et al., 2005), together with advanced optical sensors (e.g., MODIS and VEGEATION), offers new opportunities to examine the contribution of leaf phenology of forest canopies to spatial and temporal variation in carbon and water fluxes of tropical evergreen forests in South America.

It is important to note that optical remote sensing in a moist tropical region faces challenging issues such as frequent cloud cover in the wet season and fire-induced aerosols in the dry season. Additionally, various artifacts generated in the MODIS-data processing stream (e.g., atmospheric correction, cloud removal, surface reflectance retrieval, compositing), the bidirectional reflectance distribution function (BRDF) of different land cover types and variation in sun-angle could also contribute to seasonal variations of surface reflectance and vegetation indices. A recent analysis of MODIS EVI data over 2000–2005 in Amazon basin showed that EVI values in October were higher than in June for evergreen forests (Huete et al., 2006). While we believe that this regional-scale analysis using 8-day composites of MODIS/Terra accurately reflects forest phenology at a continental scale, we acknowledge that future work is needed to improve atmospheric correction and cloud/shadow detection, to combine daily MODIS/Terra and MODIS/Aqua images for constructing high-quality time series MODIS image data, and to develop BRDF-adjusted surface reflectance datasets at 8-day intervals. Improvement in MODIS surface reflectance datasets are likely to lead to better observation of leaf phenology of seasonally moist tropical forests.

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