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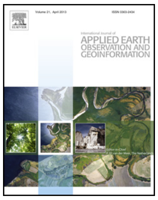

Consistency of vegetation index seasonality across the Amazon rainforest

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ABSTRACT

Vegetation indices (VIs) calculated from remotely sensed reflectance are widely used tools for characterizing the extent and status of vegetated areas. Recently, however, their capability to monitor the Amazon forest phenology has been intensely scrutinized. In this study, we analyze the consistency of VIs seasonal patterns obtained from two MODIS products: the Collection 5 BRDF product (MCD43) and the Multi-Angle Implementation of Atmospheric Correction algorithm (MAIAC). The spatio-temporal patterns of the VIs were also compared with field measured leaf litterfall, gross ecosystem productivity and active microwave data. Our results show that significant seasonal patterns are observed in all VIs after the removal of view-illumination effects and cloud contamination. However, we demonstrate inconsistencies in the characteristics of seasonal patterns between different VIs and MODIS products. We demonstrate that differences in the original reflectance band values form a major source of discrepancy between MODIS VI products. The MAIAC atmospheric correction algorithm significantly reduces noise signals in the red and blue bands. Another important source of discrepancy is caused by differences in the availability of clear-sky data, as the MAIAC product allows increased availability of valid pixels in the equatorial Amazon. Finally, differences in VIs seasonal patterns were also caused by MODIS collection 5 calibration degradation. The correlation of remote sensing and field data also varied spatially, leading to different temporal offsets between VIs, active microwave and field measured data. We conclude that recent improvements in the MAIAC product have led to changes in the characteristics of spatio-temporal patterns of VIs seasonality across the Amazon forest, when compared to the MCD43 product. Nevertheless, despite improved quality and reduced uncertainties in the MAIAC product, a robust biophysical interpretation of VIs seasonality is still missing.

1. Introduction

Seasonal cycles of the Amazon rainforest strongly affect global climate, hydrology and atmospheric composition (Aragão et al., 2014; Cox et al., 2013; Spracklen et al., 2012). For instance, structural changes in the forest canopy can alter the land surface albedo and, therefore, change Earth's radiation balance. Likewise, seasonal changes in vegetation functioning and chemical composition have impacts on carbon emissions and water flux.

Monitoring these seasonal patterns in vast and heterogeneous tropical ecosystems is a complex task, which largely relies on satellite data. During the past decades, numerous studies have used remote sensing for describing forest phenology in the Amazon (Brando et al., 2010; Guan et al., 2015; Huete et al., 2002; Myneni et al., 2007; Samanta et al., 2012b). In particular, vegetation indices (VIs) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) have been an important resource for providing

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data at temporal and spatial resolutions suitable for monitoring large ecosystems.

However, the reliability of seasonal patterns described by remote sensing data has been challenged in recent years. Studies have demonstrated that artefacts associated with clouds, aerosols and Bidirectional Reflectance Distributions Function (BRDF) effects can produce misleading seasonal variations on MODIS observations (Galvão et al., 2011; Maeda and Galvão, 2015; Maeda et al., 2014; Morton et al., 2014; Samanta et al., 2010). Against the backdrop of these recent findings, it is currently unclear whether or not VIs obtained from satellites can provide a reliable description of forest phenology in the Amazon.

Cloud and aerosols contamination can cause apparent greening and browning anomalies, leading to erroneous interpretations of the response of vegetation to climatic variations (Samanta et al., 2010). Previous studies estimate that, even in the dry season approximately 80% of MODIS pixels over the Amazon forest have at least one of the six 16-day VI composites corrupted (Samanta et al., 2012a). Given the high frequency of cloud cover in the Amazon forest, overly restrictive cloud masking algorithms may result in insufficient data to describe seasonal patterns.

Artefacts related to BRDF effects are also a critical issue to be addressed. Although this type of interference on remote sensing data has been studied for decades, correcting this problem still involves complex algorithms and distinguishing real spectral signals from artefacts often leads to uncertainty. The influence of sun-sensor geometry artefacts on artificial greening patterns of the Amazon forest has been reported in recent years (Galvão et al., 2011; Moura et al., 2012). These evidences was later used by Morton et al. (2014), who argued that, after removing BRDF artefacts in MODIS data, there was no evidence of seasonal vegetation greening. After combining these results with orbital LiDAR observations, they concluded that the Amazon forest maintains consistent canopy structure and greenness during the dry season. Nevertheless, recent assessments show that significant seasonal patterns are still present in EVI datasets using a standard MODIS Collection 5 BRDF corrected product (MCD43) (Maeda et al., 2014). Seasonal patterns in VIs were also reported in studies using MODIS data processed using the Multi-Angle Implementation of Atmospheric Correction algorithm (MAIAC) (Lyapustin et al., 2012), which applies state-of-the-art cloud screening, atmospheric and BRDF effects correction (Bi et al., 2015; Hilker et al., 2014; Jones et al., 2014).

Although the most recent evidence demonstrate the existence of seasonality in MODIS VIs, the uncertainties and errors associated with different processing algorithms have not yet been fully explored. The correlation of MODIS VIs seasonality with other remote sensing datasets, as well as field measurements, still need to be assessed over a larger range of ecoregions, before a robust interpretation of the seasonal patterns can be achieved.

In this study, we evaluate the spatial and temporal consistency of VIs seasonality across the Amazon basin. The following research questions were addressed: Are seasonal patterns of VIs consistent between MODIS products? How do uncertainties in seasonality vary in time and across different bioclimatic conditions? And finally, are VI seasonal patterns consistent with active microwave remote sensing, field measurements of leaf litterfall and Gross Ecosystem Productivity (GEP)?

2. Material and methods

2.1. MODIS MCD43B1 product

Two VIs were evaluated in this study, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). An EVI and NDVI dataset was produced using MODIS BRDF-Albedo Model Parameters product (MCD43B1), which provides model parameters for the kernel-driven BRDF model (Schaaf et al., 2002, 2011). Using the model parameters, it is possible to calculate reflectance for any sun and view-angles:

$$\rho = k_{iso} + (k_{vol} \times f_{vol}) + \left(k_{geo} \times f_{geo}\right) \tag{1}$$

where k_{iso}, k_{vol} and k_{geo} are isotropic, volumetric and geometric-optic weights of the Ross-Thick Li-Sparse (RTLS) BRDF model (Wanner et al., 1995) and f_{vol} and f_{geo} are respective functions (kernels) depending on viewing and illumination geometry. The MCD43B1 product provides RTLS model parameters $\{\mathrm{k_{iso}}, \mathrm{k_{vol}}, \mathrm{k_{geo}}\}$ for each 16-day interval. In this work, we used fixed nadir view and sun zenith angle of 45° for all months of the year. The 3-band EVI was calculated using (Huete et al., 2002):

$$EVI = G \times \frac{(\rho_{NIR} - \rho_{Red})}{(\rho_{NIR} + C1 \times \rho_{Red} - C2 \times \rho_{Blue} + L)} \tag{2}$$

where ρ_{NIR} is the near infrared reflectance factor, ρ_{Red} is the red reflectance factor, ρ_{Blue} is the blue reflectance factor, and the coefficients adopted are: L = 1, C1 = 6, C2 = 7.5, and G = 2.5, following the procedure used in other MODIS-EVI algorithms.

NDVI was calculated as follows:

$$NDVI = \frac{(\rho_{NIR} - \rho_{Red})}{(\rho_{NIR} + \rho_{Red})} \tag{3}$$

2.2. MODIS MAIAC product

MAIAC data were obtained for 12 MODIS tiles (h10v08 to h13v10, spanning 10°N to 20°S in latitude and 80°W to 42°W in longitude) from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS Web: ftp://ladsweb.nascom.nasa.gov/MAIAC). The processing was done using MODIS Collection 6 Level 1 B (calibrated and geometrically corrected) observations, which removed major sensor calibration degradation effects present in earlier collections. We used observations from the Terra and Aqua satellites collected between 2000 and 2012. MAIAC uses an adaptive time series analysis and processing of groups of pixels for advanced cloud detection, aerosol retrievals and atmospheric correction. Contrary to standard MODIS processing which is based on a Lambertian assumption, MAIAC uses a BRDF-coupled radiative transfer solution. It directly derives parameters of RTLS model from the top-of-atmosphere multi-angle observations accumulated for the 16-day interval. MAIAC implements a sliding window approach storing up to 16 days of MODIS observations gridded to 1 km resolution and produces daily BRDF retrievals provided sufficient angular coverage. Among atmospherically corrected products, the mentioned dataset provided both the bidirectional reflectance factors (BRF), often called surface reflectance, and the geometrically-normalized spectral reflectance $\mathrm{BRF_n}$ which were further used to compute VIs. MAIAC also features a dynamic land-water-snow classification and surface change detection algorithm to account for rapid and seasonal changes in surface reflectance of the time series data (Lyapustin et al., 2012). A detailed descriptions of the algorithms is provided in Lyapustin et al. (2012). EVI and NDVI were calculated considering a fixed sun sensor geometry (sun zenith angle of 45° and nadir view angle), using Eqs. (2) and (3), respectively.

2.3. QSCAT/SeaWinds

Seasonal changes in vegetation canopy structure were also assessed using microwave backscatter data from the SeaWinds Scatterometer onboard the QuikSCAT satellite (QSCAT). We used SeaWinds-QSCAT Enhanced Resolution Image Products (version 2), provided by NASA's Scatterometer Climate Record Pathfinder