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On the measurability of change in Amazon vegetation from MODIS

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ABSTRACT

The Amazon rainforest is a critical hotspot for bio-diversity, and plays an essential role in global carbon, water and energy fluxes and the earth's climate. Our ability to project the role of vegetation carbon feedbacks on future climate critically depends upon our understanding of this tropical ecosystem, its tolerance to climate extremes and tipping points of ecosystem collapse. Satellite remote sensing is the only practical approach to obtain observational evidence of trends and changes across large regions of the Amazon forest; however, inferring these trends in the presence of high cloud cover fraction and aerosol concentrations has led to widely varying conclusions. Our study provides a simple and direct statistical analysis of a measurable change in daily and composite surface reflectance obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) based on the noise level of data and the number of available observations. Depending on time frame and data product chosen for analysis, changes in leaf area need to exceed up to 2 units leaf area per unit ground area (expressed as $m^2\ m^{-2}$) across much of the basin before these changes can be detected at a 95% confidence level with conventional approaches, roughly corresponding to a change in NDVI and EVI of about 25%. A potential way forward may be provided by advanced multi-angular techniques, such as the Multi-Angle Implementation of Atmospheric Correction Algorithm (MAIAC), which allowed detection of changes of about 0.6–0.8 units in leaf area (2–6% change in NDVI) at the same confidence level. In our analysis, the use of the Enhanced Vegetation Index (EVI) did not improve accuracy of detectable change in leaf area but added a complicating sensitivity to the bi-directional reflectance, or view geometry effects.

1. Introduction

The importance of tropical vegetation for the earth system is undisputed (Atkinson, Dash, & Jeganathan, 2011; Malhi et al., 2008; Phillips et al., 2009), however, responses of tropical forests to changes in climate are only poorly understood (Samanta et al., 2010). Spaceborne remote sensing is often the only practical way to observe such changes at useful spatial and temporal scales (Shukla, Nobre, & Sellers, 1990), but the scientific community has been struggling to interpret existing satellite data in the presence of large cloud cover fraction and aerosol concentrations, which led to conflicting evidence over sensitivity for instance to prolonged drought events and thresholds of forest dieback. As a prominent example, the severe Amazon drought in 2005 provided an opportunity to investigate vegetation response to extreme events, but inferences based on remote sensing observations were inconsistent with those based on field studies. Using observations from 55 long-term monitoring plots, Phillips et al. (2009) concluded that the Amazon basin lost an estimated 1.2–1.6 Pg of carbon as a result of this drought. In contrast, Saleska, Didan, Huete, and da Rocha (2007) reported greening of the Amazon forest, suggesting increased photosynthetic activity based on the Enhanced Vegetation Index (EVI) from the 16-days MODIS surface reflectance (SR) MOD13 product.

In addition to inter-annual changes, seasonal variability of tropical vegetation has also been actively debated. A substantial body of literature (Asner, Nepstad, Cardinot, & Ray, 2004; Brando et al., 2010; Graham, Mulkey, Kitajima, Phillips, & Wright, 2003; Huete et al., 2006; Hutyra et al., 2007; Myneni et al., 2007; Nemani et al., 2003; Restrepo-Coupe et al., 2013; Samanta et al., 2012b) supports the view that photosynthetic activity initially increases during the dry season in response to an increase in incident PAR while water supply is maintained through deep root systems (Nepstad et al., 1994). In contrast, Morton et al. (2014) argued that MOD09-derived observations of seasonal greening of tropical vegetation are an artifact of the sun-sensor geometry, concluding that tropical forests maintain consistent greenness and structure throughout dry and wet seasons.

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Since its launch in 2000, MODIS has been the workhorse of Amazon remote sensing due to its superior data quality when compared to AVHRR (Huete et al., 2002). Surface reflectance is routinely derived from top of atmosphere measurements, using pixel-based atmospheric correction and cloud screening (Vermote & Kotchenova, 2008). However, errors in the estimation of atmospheric aerosol loadings (Grogan & Fensholt, 2013; Samanta, Ganguly, Vermote, Nemani, & Myneni, 2012a; Samanta et al., 2010) and deficiencies in cloud screening (Hilker et al., 2012) can introduce variability in estimated surface parameters unrelated to actual changes in vegetation (Zelazowski, Sayer, Thomas, & Grainger, 2011) which may lead to incorrect inferences of vegetation trends (Samanta et al., 2012a). Alternative processing techniques, such as the recently developed Multi-Angle Implementation of Atmospheric Correction Algorithm (MAIAC) (Lyapustin et al., 2011) hold promise to overcome some of these limitations by providing more accuracy in cloud screening, atmospheric correction and accounting for BRDF effects (Hilker et al., 2012). However, statistical analysis of quantifiable change is currently missing. Such analysis will be needed if we are to reconcile remote sensing observations with field studies and in order to determine potentials and limitations for using satellite derived evidence for change over tropical forests.

Detectable change in surface reflectance depends on noise and sampling frequency. Independent estimates of measurement noise are difficult across vast areas such as the Amazon basin, however, a first approximation may be obtained from high frequency changes in observed surface reflectance, when assuming little change in vegetation over short periods of time. While this simple approach has limitations, high frequency changes in surface reflectance mostly characterize processing errors from clouds and aerosols as a pixel, unless disturbed by logging or fire, would not be expected to change from one day to the next (Hilker et al., 2012). Common approaches to mitigate noise include compositing of best available pixels, these techniques however, significantly reduce the number of observations.

The objective of this paper is to evaluate detectable changes in vegetation greenness given statistical properties of noise driven by cloud cover, aerosol loading and other effects including bi-directionality of surface reflectance. The tradeoffs of using daily vs. composited surface reflectance are being discussed and detectable changes are quantified. We also evaluated the usefulness of Aqua vs. Terra observations, a question related to the diurnal cycle of early afternoon cloud development. Our hope is to provide a sounder statistical basis for the recent discussion on seasonal and inter-annual changes in Amazon vegetation.

2. Methods

2.1. MODIS MOD09/MYD09 observations

Our study encompasses 12 MODIS tiles (h10v08 and h13v10), a land area of 12.25 million km^2, spanning 10°N to 20°S in latitude and 80°W to 42°W in longitude. We used MODIS data from the Terra and Aqua satellite platforms acquired between 2000/02/24 and 2012/12/31 (Terra) and between 2002/07/04 and 2012/12/31 (Aqua). Collection 5 data of the MOD09GA/MYD09GA 1 km daily surface reflectance product were obtained from the reverb data gateway of NASA's Goddard Space Flight Center (reverb.echo.nasa.gov) as well as 1 km vegetation index (VI) composites from MOD/MYD13A2. Clouds were masked by means of the 'state_1km' scientific dataset (SDS) included in the MYD09GA product, which is based on two cloud detection algorithms, the MOD/MYD35 cloud mask (Frey et al., 2008) and an additional, internal cloud screening (Vermote & Kotchenova, 2008). In addition to cloud masking, all conventional MODIS data were quality filtered using the MODIS quality (Q_A) and pixel reliability flags and only cloud free pixels with the highest data quality were passed and used for all subsequent analyses. An overview of the quality and cloud flags set is provided in Table 1.

Table 1
Quality/cloud flags of the MYD09GA product used in this study. Flags that are not mentioned were not used (Hilker et al., 2012).

Product	SDS name	Flag	Accepted values
MYD09GA	QC 500 m	MODLAND QA bits	00 (ideal quality — all bands)
		Band 1 data quality	0000 (highest quality)
		Band 2 data quality	0000 (highest quality)
		Atm. corr. performed	1 (yes)
	State 1 km	Cloud state	00 (clear)
		Cloud shadow	0 (no)
		Aerosol quantity	00/01 (climatology/low)
		Cirrus detected	00 (none)
		Internal cloud flag	0 (no cloud)
		Fire flag	0 (no fire)
		Pixel adjacent to cloud	0 (no)
MYD13A2	VI quality	MODLAND QA Bits	00 (VI produced with good quality)
		VI usefulness	0000 (Highest quality) 0001/0010/0100/1000 (Lower quality)
		Aerosol quantity	00/01 (climatology/low)
		Adjacent cloud	0 (no)
		Mixed cloud	0 (no)
		Possible shadow	0 (no)
	Pixel reliability	Rank key	0 (good data — use with confidence)

2.2. MAIAC observations

In addition to conventionally processed daily MODIS data, we also obtained MODIS observations processed with the MAIAC algorithm. MAIAC is a new generation cloud screening and atmospheric correction technique that uses an adaptive time series analysis and processing of groups of pixels to derive atmospheric aerosol concentration and surface reflectance without typical empirical assumptions. In previous work (Hilker et al., 2012), we have demonstrated a 3–10 fold reduction in noise of MAIAC SR, while the algorithm at the same time yields 2–5 times more observations as a result of a more accurate, less conservative cloud mask. Both these properties should make it more suitable to detect changes in the Amazon basin. MAIAC data were obtained for the identical 12 MODIS tiles and time period from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS Web) ftp://ladsweb.nascom.nasa.gov/MAIAC. Recently, also a composited VI product has been provided. Detailed descriptions of MAIAC and quality testing are provided elsewhere (Lyapustin, Wang, Laszlo, & Hilker, 2011, 2012; Lyapustin et al., 2011).

2.3. Approach

Our ability to observe trends and changes in tropical vegetation depends on the number of available clear sky observations and measurement noise. In tropical latitudes, this noise results largely from undetected clouds and cloud shadows (particularly during the wet season) and high aerosol levels during the biomass burning (dry) season (Aragão et al., 2008; Hilker et al., 2012). Typical techniques to overcome high noise levels include best pixel compositing, which effectively increases the data quality at the cost of a reduced number of observations. Analysis of seasonal changes from composited data products is therefore often pursued by combining observations over multiple years (such as averaging multi-year observations acquired during June and comparing them to multi-year observations acquired during October), assuming a regular onset of dry and wet seasons.

We pursued two different approaches for change analysis, one based on daily satellite observations and another based on multi-year averages of VI composites. Composited data are most commonly used for determining change in tropical vegetation, however daily observations would be desirable to better understand changes for instance during