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Spectral analysis of amazon canopy phenology during the dry season using a tower hyperspectral camera and modis observations

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ABSTRACT

The association between spectral reflectance and canopy processes remains challenging for quantifying large-scale canopy phenological cycles in tropical forests. In this study, we used a tower-mounted hyperspectral camera in an eastern Amazon forest to assess how canopy spectral signals of three species are linked with phenological processes in the 2012 dry season. We explored different approaches to disentangle the spectral components of canopy phenology processes and analyze their variations over time using 17 images acquired by the camera. The methods included linear spectral mixture analysis (SMA); principal component analysis (PCA); continuum removal (CR); and first-order derivative analysis. In addition, three vegetation indices potentially sensitive to leaf flushing, leaf loss and leaf area index (LAI) were calculated: the Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI) and the entitled Green-Red Normalized Difference (GRND) index. We inspected also the consistency of the camera observations using Moderate Resolution Imaging Spectroradiometer (MODIS) and available phenological data on new leaf production and LAI of young, mature and old leaves simulated by a leaf demography-ontogeny model. The results showed a diversity of phenological responses during the 2012 dry season with related changes in canopy structure and greenness values. Because of the differences in timing and intensity of leaf flushing and leaf shedding, *Erisma uncinatum*, *Manilkara huberi* and *Chamaecrista xinguensis* presented different green vegetation (GV) and non-photosynthetic vegetation (NPV) SMA fractions; distinct PCA scores; changes in depth, width and area of the 681-nm chlorophyll absorption band; and variations over time in the EVI, GRND and NDVI. At the end of dry season, GV increased for *Erisma uncinatum*, while NPV increased for *Chamaecrista xinguensis*. For *Manilkara huberi*, the NPV first increased in the beginning of August and then decreased toward September with new foliage. Variations in red-edge position were not statistically significant between the species and across dates at the 95% confidence level. The camera data were affected by view-illumination effects, which reduced the SMA shade fraction over time. When MODIS data were corrected for these effects using the Multi-Angle Implementation of Atmospheric Correction Algorithm (MAIAC), we observed an EVI increase toward September that closely tracked the modeled LAI of mature leaves (3–5 months). Compared to the EVI, the GRND was a better indicator of leaf flushing because the modeled production of new leaves peaked in August and then declined in September following the GRND closely. While the EVI was more related to changes in mature leaf area, the GRND was more associated with new leaf flushing.

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1. Introduction

Terrestrial ecosystems regulate carbon-climate feedbacks by controlling fluxes of mass and energy between the biosphere and the atmosphere (Bonan et al., 2003). In turn, changes of the biosphere's carbon balance (i.e. uptake or losses) affect the climate system (Friedlingstein et al., 2006; Frank et al., 2015). However, detailed knowledge of the processes and mechanisms of the carbon cycle is still lacking. A better understanding of these feedbacks is urgently needed to reduce climate model uncertainties and to allow more accurate predictions of vegetation changes under future climate scenarios. This is particularly important in the tropics, where high plant productivity sustains one of the largest remaining terrestrial carbon pools on the planet (Hilker et al., 2014; Wu et al., 2016a). The ongoing exposure of tropical ecosystems to anthropogenic pressures and climatic changes have led to substantial concerns about the future of tropical forests as a component of the global climate system (Cox et al., 2004; Malhi et al., 2008). While field experiments, networks of flux-towers and remote sensing based studies have improved our understanding on the sensitivity of forests to climate in temperate regions (e.g., D'Odorico et al., 2015; Gamon et al., 2006; Hilker et al., 2010; Richardson et al., 2007, 2012; Yang et al., 2014), this issue is far less understood in the tropics.

Quantifying shifts in phenological cycles, which influences the timing of plant maximum photosynthetic activity, is critical for describing tropical ecosystem metabolism and environmental controls (Cleland et al., 2007; Richardson et al., 2012; Wu et al., 2016a). However, phenological observations in tropical regions have proven challenging (Samanta et al., 2010) and so far have been unable to produce unequivocal evidence for the constraints of vegetation growth in the tropics (Huete et al., 2006; Lee et al., 2013; Borchert et al., 2015; Guan et al., 2015; Bi et al., 2015). Despite the uncertainty associated with the mean seasonality of vegetative growth derived from satellite remote sensing, it is even more controversial when using these remote sensing observations to explore tropical forest response to inter-annual droughts (Myneni et al., 2007; Morton et al., 2014; Saleska et al., 2016). An increase in greenness (higher Enhanced Vegetation Index - EVI) for the 2005 drought was reported by Saleska et al. (2007), whereas a widespread decline in photosynthetic activity (lower EVI) for the 2010 drought was observed by Xu et al. (2011). While remote sensing approaches have shown conflicting results, field-based studies indicate that moisture stress in tropical forests due to extreme events of droughts reduces aboveground biomass growth and increases tree mortality, altering carbon stocks and biodiversity (Phillips et al., 2009).

To date, tropical leaf phenology remains one of the most challenging components to parameterize in ecosystem models (Arora and Boer, 2005). Part of the observational uncertainties has been linked to poor quality remote sensing data because of high atmospheric aerosol loadings and deficiencies in cloud detection and screening (Samanta et al., 2010; Hilker et al., 2014). Progress has been made with the development of more robust atmospheric correction methods (e.g. Multi-Angle Implementation of Atmospheric Correction - MAIAC) (Lyapustin et al., 2011), or the use of higher spatial resolution imagery (Zelazowski et al., 2011). However, a scale mismatch remains between moderate to coarse spatial resolution satellite imagery on one hand, and a sparse network of field observations on the other.

One possible approach to address this mismatch and to help further our understanding of tropical phenology is to use observations from tower-based cameras to consistently link optical signals with biophysical processes. Near surface, camera-based phenology can help bridging the spatial mismatch existing between field and satellite data by using optical principles similar to those used by spaceborne optical sensors, but still allowing interpretations similar to those made at the plot level.

In temperate regions, tower-based optical remote sensing has been used to establish frequent observations of plant phenology (Richardson et al., 2007), to link them to biophysical processes of photosynthesis (Hilker et al., 2010), and to scale-up field observations (D'Odorico et al., 2015). Perhaps most prominently, the phenocam network (Richardson et al., 2007) provides a continental-scale phenological observatory, spanning a range of biogeoclimatic zones in North America. Other networks (Gamon et al., 2006) and individual studies have been undertaken to connect optical measurements and flux tower observations of CO_2 exchange and ecosystem productivity using multi-angular (Hilker et al., 2010; Tortini et al., 2015) and mono-angle spectroscopy (Garbulsky et al., 2008; Garrity et al., 2010).

More recently, tower-based observations of plant phenology have also been established for tropical vegetation using near infrared (NIR)-red-green cameras (Wu et al., 2016a) and simple RGB cameras (Lopes et al., 2016). Increases in dry season "Amazon greening" were linked to synchronous leaf flushing during the dry season in central Amazonia, in response to an increase in available PAR, consistent with previous satellite studies (Huete et al., 2006; Anderson et al., 2011; Guan et al., 2015) and field investigations (Restrepo-Coupe et al., 2013). Increases in vegetation greenness were preceded by abrupt, brief "browning" because of the increased leaf abscission (Lopes et al., 2016). While tower-based observations have improved our understanding of plant phenology in the tropics, a comprehension of its effect on the optical signal observed by hyperspectral instruments in different regions of the electromagnetic spectrum is currently lacking, as is an understanding of the spatial heterogeneity of the observed signal. Such understanding will be critical in order to assess tropical seasonality at broader scales using future orbital hyperspectral missions such as the Environmental Mapping and Analysis (EnMAP), planned for 2019 (Guanter et al., 2015), and the Hyperspectral Infrared Imager (HyspIRI), planned for the near future (Hochberg et al., 2015), both with 30 m spatial resolution.

The objective of this paper was to analyze spectral components of canopy phenology using a tower-mounted hyperspectral camera in an eastern Amazon forest to assess dry season differences existing between individual species. Our analysis was based on hyperspectral data acquired during the 2012 dry season at the k67 flux-tower field station in the Tapajós National Forest (TNF), in Brazil. As far as we know, this is the first hyperspectral remote sensing study using a tower-mounted camera to observe canopy phenology in the Amazon.

Our study was designed to address four research questions: (1) How do individual components (leaves, branches and shade) of tropical species canopy vary throughout the dry season? (2) What are the most important spectral components responsible for the data variance in the hyperspectral signal to describe phenological patterns across species? (3) Are there dry season variations in spectral attributes and metrics between the species? (4) Are the phenological patterns observed from the tower-based hyperspectral data perceptible when evaluating a landscape level data (MODIS observations)?

2. Data acquisition and processing

2.1. Hyperspectral data acquisition

The study area in Brazil is the TNF, located in the eastern Amazon, near Santarém town, in the state of Pará, which is mainly composed of dense ombrophilous forest (Fig. 1). The climate in the