Remote Sensing of Tropical Forest Phenology: Issues and Controversies

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ABSTRACT:

Different coarse spectral resolution satellite products collected at high temporal frequencies from the AVHRR, SeaWiFS, and MODIS platforms show variable and inconsistent seasonal patterns over tropical rainforests with some sensor products showing canopy drying in the dry season and negative forest responses to drought, while other products show leaf flushing and greening in the dry season and a positive response to drought. Large inconsistencies have been reported in cross- satellite product comparisons (that include MODIS and AVHRR) for tropical evergreen broadleaf forests and inconsistencies have been reported among MODIS products and tropical field observations for LAI-related products. In this study, we investigate various remote sensing processing methods, from leaf to canopy scale, for deriving spatial and temporal patterns of photosynthetic metabolism in tropical environments, using the Brazilian Amazon and Monsoon Asia tropical forests as study areas. We also consider the role and uncertainty played by atmospheric artifacts from highly seasonal cloud cover and aerosol loads in tropical atmospheres, which render the task of decoupling the surface vegetation phenology from atmosphere influences quite challenging.

1. INTRODUCTION

The vulnerability of tropical forest systems to climate change depends not just on the physical climate system, but on biological response of forests to initial climate changes. While much attention has focused on the Amazon die-back scenario (Betts et al. 2004), other models imply forest persistence. Differing modeled fates of the forest are due to model differences in representation of forest function, not just differences in representations of climate. Current knowledge is insufficient to determine which representations of vegetation function are most consistent with real forest ecosystems, but continuing observations from satellites and from the network of eddy flux towers provide tools that can rigorously test mechanisms of forest-climate interactions on observable timescales.

Recent studies using MODIS remote sensing products have detected positive '*greening*' vegetation responses to seasonal drying (Huete et al. 2006; Myneni et al. 2007) and interannual drought (Saleska et al. 2007) which if accurate, suggest that tropical vegetation, by apparently responding to increased dry-period light availability, is more complex, and possibly more robust than most ecosystem models suggest, with implications for long-term vulnerability to climate change. Prior to these studies, models have assumed that tropical forest canopies exhibited no seasonality, in part, because seasonal remote sensing in the tropics is undermined by poor atmospheric conditions (Kobayashi & Dye, 2005). Other models represented browning vegetation and decreased activity in periods of drought (dry seasonal periods and interannual droughts, such as ENSO; Tian et al. 1998; Botta et al. 2002).

Various hypotheses for forest response to climatic variability include: (1) Light limitation, in which tropical forest growth is primarily limited by availability of photosynthetically-active radiation (PAR), with access to deep soil water via deep tree roots minimizing oft-modeled water stresses; (2) Diffuse radiation enhancement of Light-Use Efficiency (LUE), which is the amount of photosynthesis that takes place per amount of PAR absorbed by the forest canopy; (3) Leaf growth phenology.

However, issues remain in the interpretation and understanding of remote sensing data. Different coarse resolution satellite products collected at high temporal frequencies from the AVHRR and MODIS platforms show variable and inconsistent seasonal and interannual patterns over tropical rainforests, with some sensor products showing canopy drying in the dry season and negative forest responses to drought, while other products show leaf flushing and greening in the dry season and a positive response to drought (Huete et al. 2008). Large inconsistencies have been reported in cross- satellite product comparisons (that include MODIS and AVHRR) for tropical evergreen broadleaf forests (Garrigues et al. 2008). At local tower site scales, Doughty and Goulden (2008) showed *in situ* LAI measurements differed markedly from seasonal cycles of the MODIS LAI product (MOD15). Hutrya et al. (2007) showed MODIS LAI and EVI products not in phase with each other. There is a great need to better relate satellite products with canopy functional processes in tropical forests in order to understand what changes in *greenness* signify.

Remote sensing methods directly detect photosynthetic pigments in vegetation, and could be a powerful tool for investigating spatial and temporal patterns of photosynthetic metabolism in challenging tropical environments, but uncertainty remains about atmospheric artifacts from highly seasonal cloud cover and aerosol loads in tropical atmospheres. Some argue that the observed remote sensing responses are due to artifact. Kobayashi and Dye (2005) analyzed the GIMMS AVHRR- NDVI time series over the Amazon and found the

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seasonal signal to be primarily dominated by cloud and aerosol contamination. Samanta et al (2010) suggest that apparent tropical forest greening during the Amazon drought of 2005 (as reported in Saleska et al. 2007) is in fact due to atmospheric aerosol contamination of the surface reflectance, rather than a true vegetation response.

We have previously argued (Huete et al. 2006; Saleska et al. 2007) that by choosing satellite products that correlate with measurements on the ground (e.g. satellite EVI with ecosystem scale photosynthetic fluxes measured from towers), and by a combination of appropriate selection of high quality data from relatively uncontaminated pixels and correction for residual contamination, we arrive at observations that are robust to the problems cited above (for example, because MODIS EVI uses atmospherically-corrected surface reflectances and an aerosol resistance term, we believe it is minimally affected by residual aerosols up to optical depths of over 1) (Fig. 1). However, this argument is in need of further testing and the subject of this study.

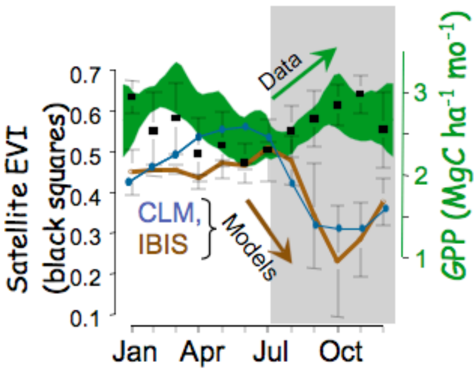

Figure 1. Contrasting model, flux tower, and satellite data forest responses to seasonal drought periods.

2. 2005 DROUGHT

In 2005, large areas of the southwestern Amazon basin experienced one of the most intense droughts of the last 100 years (Marengo et al. 2008). During the 2005 drought, satellite observations showed short-term (3 mos) increases in MODIS EVI, suggesting increased forest photosynthetic capacity (Saleska et al. 2007), while Phillips et al. (2009), using field measurements, showed a longer-term decline in the rate of biomass accumulation, slowing or reversing previous trends, primarily due to an increase in tree mortality. It is not currently understood whether these seemingly divergent responses (short term increase in photosynthetic capacity during the peak months of drought, encompassed by excess mortality integrated over several years) may in fact be reconciled by accounting for differing time scales and effects of time lags. The divergent responses, however, sharply pose specific questions, including: (1) What is the role of light vs. water limitation in controlling vegetation response to drought; (2) What are the causes for variation in forest responses to the same drought event (while most areas greened up, distinct "brown-down" regions were also observed (Fig. 2); (3) How does a drought response interact with nominal patterns of seasonal drought, given the varying nature of seasonal drought responses (Fig. 2)

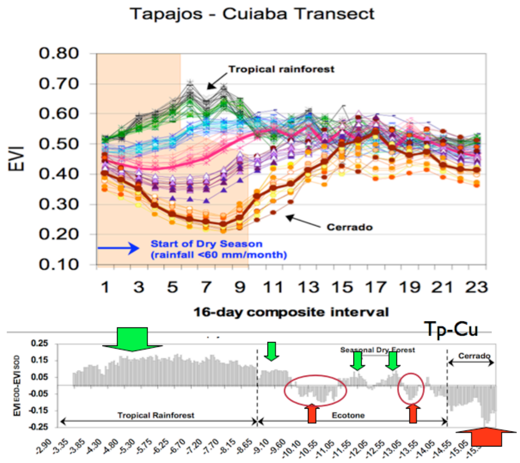

Figure 2. Varying tropical forest responses to seasonal drought along a transect from northern to southern Amazon forests and the cerrado region.

3. METHODS

We analyzed the spatio-temporal tropical forest responses to seasonal and interannual drought events with 10 years of MODIS enhanced vegetation index (EVI) satellite data. We used the 500m and CMG versions of MODIS EVI (MOD13A1 and MOD13C1) and used the quality assurance (QA) filters to screen for and remove cloud and aerosol contaminated pixels, as in Saleska et al. (2007).

We tested a wide variety of methods to process the MODIS EVI time series data and found consistent patterns throughout our analysis, further confirming the Amazon green-up hypothesis.

4. RESULTS & DISCUSSION

All datasets, time periods, and methods of analysis show that valid pixels in the drought region exhibited a statistically significant anomalous *increase* in EVI. MODIS EVI anomalies of the 2005 drought remain statistically significantly skewed towards greenness. The method of Samanta et al. (2000) eliminates much of the drought region but even so, a disproportionate number of remaining pixels are anomalously green. We further show that the full time series shows that *the strongest positive EVI anomaly of the entire satellite record* corresponds to *the strongest drought of the entire record* (2005). This observed time series stands in strong contrast to model simulations (Fig 1).

Separate tests were made to determine whether it was possible for aerosols to have contaminated our results. We found that even in the worst-case periods, surface reflectances flagged as contaminated by high aerosols hardly intersected the drought region at all, and played no role in the outcome of this analyses. Thus, high aerosols were, for the most part, not in the drought area.

In conclusion, the patterns of anomalous greening was found to be robust across different versions and processings of the MODIS dataset, and across a range of analysis methods. If drought had the expected negative effect on canopy photosynthesis, it should have been especially observable during extreme drought events, when anomalous interannual drought coincided with the already seasonally low precipitation. The observations of intact forest canopy “greenness” in the affected areas, however, are dominated by a significant increase, not a decline.

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