EFFECTS OF TROPICAL FOREST DEGRADATION ON AMAZON FOREST PHENOLOGY

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ABSTRACT

Anthropogenic disturbances in tropical forests cause short- and long-term alterations in forest structure, species composition, and successional processes. However, improved understanding of the impacts of disturbance on forest functioning is needed to support forest management and conservation. In this study, we investigated the phenological responses of two sites in the Brazilian Amazon to forest degradation (selective logging and forest fires). We used MODIS-derived time-series to assess pre- and post-disturbance trajectories of two vegetation indices: Normalized Burn Ratio (NBR) and Enhanced Vegetation Index (EVI). We found that our study sites present different VI seasonality, and that selective logging did not cause phenological shifts. Fires, on the other hand, caused explicit EVI shifts in the transition from wet to dry season in the driest site and barely no shifts in the wettest site, and year-long NBR shifts compared to intact forests at both sites. Changes in the magnitude and timing of phenological events highlight human-induced changes in tropical forests functioning. If widespread, these shifts may have large-scale implications for carbon sink stability in tropical regions.

***Index Terms* —** Amazon forest, logging, fires, phenology, MODIS

1. INTRODUCTION

The abundant carbon stocks of tropical forests are vulnerable to land use changes [1], and are especially sensitive to forest degradation agents, such as selective logging and forest fires [2]. The drivers and intensity of forest degradation vary by region, but their impacts can be seen at several scales, from global climate change to declining economic value of forest resources and biodiversity that can threaten local livelihoods [3]. Tropical forest degradation alters forest structure and species composition, causing impacts that may last for many years or even decades [4, 5], but impacts of degradation in tropical forest ecosystem function remain poorly understood.

Phenology is a key component of forest functioning, and relates to seasonal variations in land-atmosphere gas exchange, including photosynthesis and transpiration, due to the dependence of these fluxes on leaf area and physiology [6]. In evergreen tropical forests, precipitation, temperature and radiation patterns are less seasonal than forests in sub-tropical and temperate zones. However, their canopy experiences seasonal variations in leaf area and photosynthetic capacity, led by differential leaf development and demography [7]. Early assessments of seasonal vegetation dynamics with coarse resolution satellite measurements in the tropics showed no seasonal variation [8], but later improvements in both sensor capabilities and spectral indices have shown a positive 'greening' forest response to increased light availability in the dry season [9, 10].

When scaled-up by remote sensing, land surface phenology can show potentially significant vegetation changes in both time and space. The wide-spatial and high-temporal coverage of satellite observations offers the opportunity for multiscale phenological monitoring that is unfeasible with any other source. The temporal dynamics of spectral Vegetation Indices (VI), such as the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI), provide means to characterize tropical vegetation phenology patterns [9, 11, 12], and assess whether anthropogenic disturbances have altered these patterns .

The strong interplay between forest structure and functioning is affected by forest community composition, climate variability and natural or anthropogenic disturbances. However, these effects are not well understood at the different temporal and spatial scales they operate. To address this knowledge gap, the objective of this study is to investigate the effects of fires and selective logging on the phenology patterns of two evergreen forest sites experiencing distinct dry season severity. We gauge these effects using MODIS observations at 250m resolution aggregated at the stand level.

2. MATERIALS AND METHODS

2.1. Study areas

Two study regions were selected: Paragominas municipality (PRG), Pará State, in the Eastern Amazon; and Feliz Natal municipality (FNA), Mato Grosso State, in the Southeastern Amazon (Figure 1). Both sites are covered by evergreen forests and have similar mean annual precipitation (approximately 1900 mm/year), but they differ in the severity of the dry season: under a 100mm/month precipitation threshold [13], PRG has a 6-months dry season while FNA has a 5-months dry season. However, if a threshold of <50mm/month is adopted, FNA has a 6-months dry season, while PRG has a 3-months dry season. Both regions exhibit intense land use, with high rates of deforestation (Figure 1), predominantly for agriculture and pastures, and high occurrence of fires and selective logging. Each study area has approximately 5 million hectares.

2.2. Disturbance history assessment

We analyzed MODIS data time-series from 2002 to 2014. We didn't include more recent years to avoid the intense fires in 2015/16 El-Niño-induced drought in the Amazon [14].

A multi-source approach was implemented to assess the disturbance history of our study sites, as their spatio-temporal disturbance dynamics is very diverse. Four disturbance treatments were defined, based on the most common agents of forest degradation in the Amazon region [15]: once-burned forest, twice-burned forests, selectively logged forests, and intact forests as control. We used an existing fire dataset produced by Morton et al. [16], ranging from 2000 to 2010, based on MODIS data. For each study site, the two most burned years according to Morton's dataset were inferred, and the polygons for only those years were selected. We implemented additional filters to rule out areas previously or subsequently degraded or deforested during the MODIS time-series period.

Selectively logged areas were mapped through visual interpretation of yearly fitted Landsat-based NBR images. Logging detection and mapping were based on images of the first year of the largest fire disturbances, to ensure the same breakpoint for all disturbance treatments. One hundred 100-hectare polygons of intact forests were randomly sampled inside indigenous territories, which are widely recognized as deforestation barriers (Figure 1).

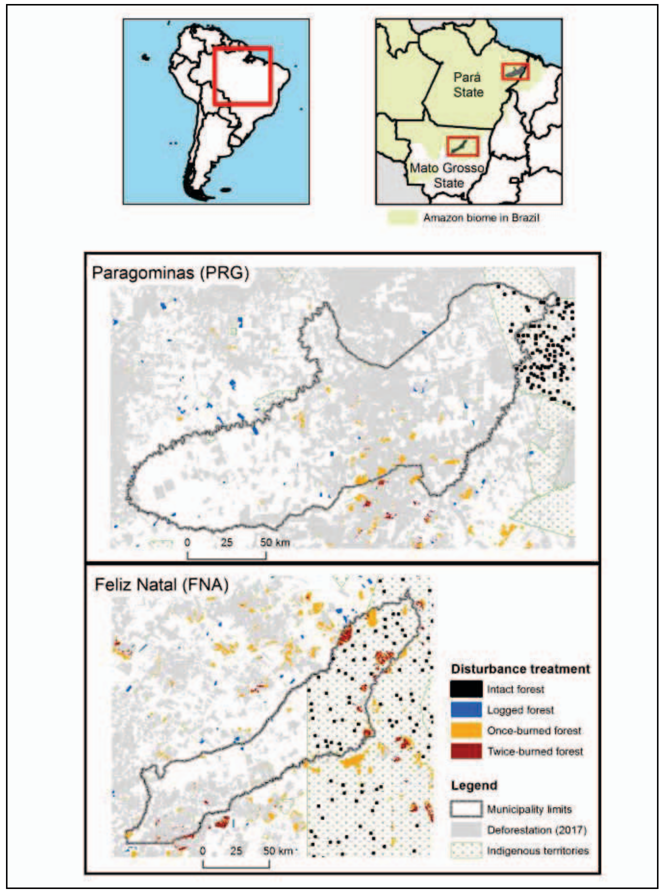

Figure 1. Location and polygons of the disturbance treatments within the study areas. The disturbance treatments only include those forest patches disturbed in the most burned year (logged and once-burned areas) and in the two most burned years (twice-burned areas).

2.3. Remotely sensed data

We used MODIS surface reflectances at 250m resolution, from the MYD13Q1.006 product (MODIS/Aqua Vegetation Indices 16-Day L3 Global 250 m, Version 6). We performed cloud and shadow masking based on the QA band information, and applied a bidirectional reflectance distribution function (BRDF) correction [17] to minimize the effects of seasonal sun angle variations on phenology patterns. In total, 288 MODIS images were used for each site.

From the pre-processed surface reflectance images, EVI and NBR spectral indices were derived. EVI can be calculated as:

$$EVI = G\,x\,\frac{(\rho NIR - \rho Red)}{(\rho NIR + C1\,\rho Red - C2\,\rho Blue\; + L)} \qquad (1),$$

while NBR can calculated by the equation:

$$NBR = \frac{\rho NIR - \rho SWIR2}{\rho NIR + \rho SWIR2} \qquad (2),$$

where G corresponds to a gain factor = 2.5, C1 and C2 corresponds to aerosol coefficients (6 and 7.5, respectively), L corresponds to canopy background adjustment = 1, and ρNIR, ρRed, ρBlue, and ρSWIR2 correspond to surface reflectances of near infra-red, red, blue and distant shortwave infra-red bands, respectively.

To generate temporally consistent, noise-free MODIS EVI and NBR time-series for each disturbance treatment, we 1) extracted the median VI values for each disturbance polygon, and 2) the median VI value for each image date. Subsequently, we 3) filled the missing date values using linear interpolation, 4) smoothed the time-series with the Savitzky-Golay filter [18], and 5) interpolated the data to daily time-stamps. The time-series were 6) split into pre- and post-disturbance periods (according to the breakpoints caused by the first fires in NBR time-series), and finally, 7) aggregated per day of the year (DOY).

3. RESULTS

At FNA site, EVI presented more obvious seasonality than NBR, presenting the lowest values at the start and highest values at the end of the dry season (Figure 2). NBR presented lesser annual amplitude and peaked in the middle of the dry season.

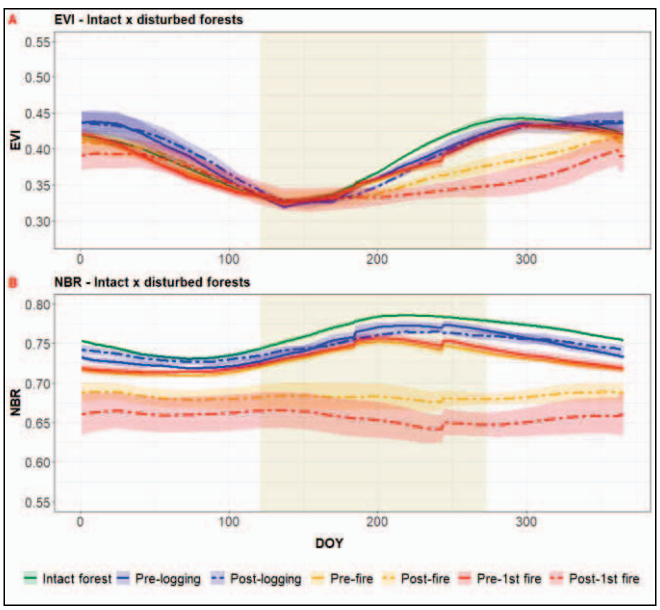

Figure 2. MODIS-derived EVI (A) and NBR (B) seasonal profiles for the disturbance treatments at Feliz Natal site. Bands represent the 95% confidence interval. The beige shade depicts the dry season (months with < 100mm of rain).

Selective logging did not cause major changes in the VI values or seasonal cycle relative to intact forests, while one or two burns caused an explicit decrease in NBR across the year and reductions in EVI from the middle of the dry season to the middle of the wet season. Also, fires dampened the seasonality on both VI.

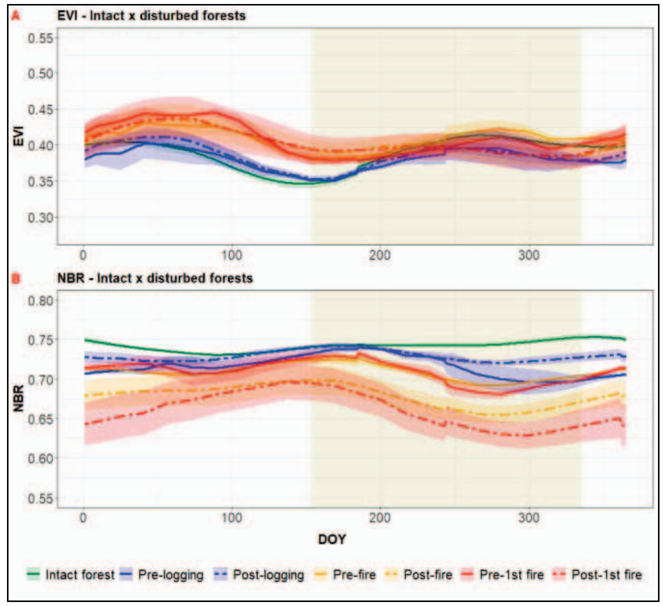

Figure 3. MODIS-derived EVI (A) and NBR (B) seasonal profiles for the disturbance treatments at Paragominas site. Bands represent the 95% confidence interval. The beige shade depicts the dry season (months with < 100mm of rain).

At PRG site, EVI and NBR seasonal variation was less pronounced than at FNA site. Two annual EVI peaks, one in the middle of the wet season, and other at the end of the dry season, were observed (Figure 3). EVI post-disturbance profiles followed the pre-disturbance profiles most of the year, except for the end of the dry season. There was not much differentiation in the EVI seasonal profiles of burned-once and burned-twice forests, but the burned areas failed to reach the second EVI peak during the dry season, whereas in the wet season they maintained values similar to those of the pre-disturbance period. Additionally, the post-burn EVI curves presented less amplitude than intact and pre-burn curves, as opposed to NBR post-disturbance profiles, which presented more seasonality than intact and pre-disturbance curves. Fire disturbance seemed to have caused a year-round VI decrease and amplified seasonal NBR variation.

4. DISCUSSION

Our study corroborated the dry season green-up hypothesis in the Amazon [9]. We also further demonstrated for the first time the effect of different disturbance agents and frequency on Amazon forest phenology. EVI and NBR showed distinct temporal trajectories, indicating that these indices provide independent information about canopy functionality. Canopy greenness, as depicted by EVI, is a composite property of canopy structure, leaf area, and canopy chlorophyll content [19]. Although affected by canopy structure features, such as leaf area and orientation, greenness reflects canopy responses to ecological processes that occur mostly at the leaf scale. NBR, on the other hand, is dominated by the signal of shortwave infra-red, which is affected by processes that happen at the canopy scale instead.

At burned areas, deep-rooted tree mortality reduces access to deep soil water [20], resulting in decreased greenness through the dry-wet season transition and a potential shift to a water-limited ecosystem. Multiple burns may amplify this process. Also, pioneer species that kick off regeneration after disturbance are usually fast-growing and shallow-rooted, use more water and have higher photosynthesis capacity [21], so they are likely to deplete soil water supply earlier. The methods we used to reduce noise also likely reduced the capacity to detect spatially-diffuse selective logging disturbance.

Despite distinct seasonal patterns and magnitude of EVI change between the two sites, all post-fire profiles showed lower values than intact and logged forests towards the end of the dry season. This finding implies that the water supply limitation in burned forests applies to different forest types across the Amazon regardless of length and severity of the dry season. These human-induced phenological shifts have large-scale implications for carbon sink stability in tropical regions.

Acknowledgment: This research was supported by the University of Technology Sydney (UTS) International Research Scholarship (IRS) and UTS President's Scholarship (UTSP), and by the USDA Forest Service Pacific Northwest Research Station and International Programs. The authors are grateful for the constructive comments from M. Keller, M. Longo, W. Cohen and Z. Yang, and the anonymous reviewers.

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