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Modelling of the decrease of tropical-forest resilience in Amazonia as affected by deforestation and fires

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Abstract:
Biome models of the global climate-vegetation relationships indicate that most of the Brazilian Amazon has potential for being covered by tropical forests. From current land-use processes observed in the region, however, several areas of natural forests were lead to different states dominated by degraded and secondary forests or even savannas. This may happen because deforestation and presence of ignition sources frequently cause nearby forests to burn. Fire is a major disturbance in tropical forests, which may substantially increase the mortality of trees and other native species. In a first attempt to generally represent the potential for tropical forest degradation due to fires in Brazilian Amazon, we analysed large-scale data on fire occurrence and climate factors. Fire-activity information are based on remote-sensing detections with the Tropical Rainfall Measuring Mission - Visible and Infrared Scanner (TRMM-VIRS). Climate information are summarized by a wetness index used as an estimate of dry/wet climate conditions, and a soil-moisture seasonality index. Our results have important implications for evaluating the resilience of tropical forests in the Brazilian Amazonia by presenting general relations between climate and the occurrence of fires/deforestation, which can help to refine the estimates of the allocation of forest-savanna boundaries based on the likelihood for land-use fires in the region.

Keywords: Fire detection, remote-sensing fire data, deforestation, Amazonia, tropical forest, resilience

Introduction

Biome models of the global climate-vegetation relationships indicate that most of the Brazilian Amazon has potential for being covered by tropical forests (Prentice et al., 1992; Haxeltine & Prentice, 1996; Oyama & Nobre, 2004). Large-scale datasets derived from remote sensing support those estimates by reporting similar broad extent of these rainforests (Eva et al. 2004). Together with field surveys (Nepstad et al. 1999), however, these datasets also document how the region is diverting from its original state as a result of changes in land use. In the past decades, processes such as logging, agriculture and pasture formation lead to the removal of a substantial fraction of the primary forests of the Amazon in Brazil (INPE 2008). These modifications are concentrated in the south-southeast portion of the region, an area called “Arc of Deforestation”.

In addition to the rapid (~yearly) removal of the original vegetation by direct deforestation, other processes can also contribute to the impoverishment and replacement of these forests by secondary and degraded vegetation or even savannas. Fires, for example, are such a dominant process normally associated to the current land-use practices observed in the region (Fig. 1). Combined, fuel from deforestation and presence of ignition sources frequently cause nearby forests to burn consuming surface litter and understory vegetation and substantially increasing the mortality of trees and other native species (Uhl & Kauffman, 1990; Cochrane & Schulze, 1999).

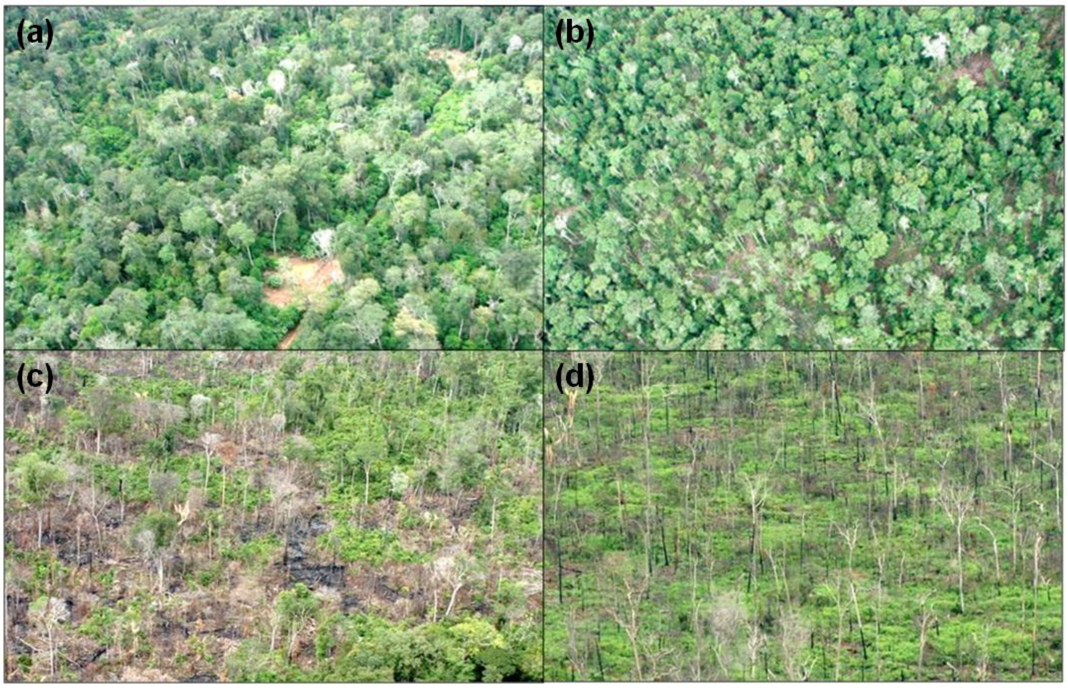

Figure 1 – Example of tropical-forest areas in the Brazilian Amazon progressively declining due to deforestation and fire. The process usually starts with selective logging (a), followed by progressive openings in the understory (b), which cause plant mortality, fuel build up, increase of flammability and the occurrence of fires (c). In (d), an area where surface species are recovering while trees present fire scars and absence of most of canopy, indicating substantial damage to native vegetation. Persistence of fires in these areas can rapidly decrease resilience leading to replacement of primary forests by degraded/secondary vegetation and savannas. Picture: Gilberto Câmara (INPE).

In a first attempt to generally represent the potential for tropical forest degradation due to fires in Brazilian Amazon, we searched for relations between fire occurrence and climate factors used to determine the establishment of these forests by the Brazilian Center for Weather Forecast and Climate Studies - Potential Vegetation Model (CPTEC-PVM) (Oyama & Nobre 2004). The relations we found provide new information that can be used, for example, to adjust the climate thresholds used in vegetation models to estimate the occurrence of tropical forests and savannas to be functions of the potential for land-use fires in the region.

Material and methods

Tropical forest coverage

Our analyses are concentrated over the Brazilian portion of original tropical forests of Amazonia (Fig. 2), as determined by the CPTEC-PVM (Oyama & Nobre 2004). This model was built for studying long-term climate-vegetation equilibrium states, and is able to correctly represent most of the natural (without land use) vegetation features globally, at ~2° spatial resolution. Inputs of the CPTEC-PVM include prevailing climate conditions (surface air temperature and precipitation) and other environmental variables (soil water and evapotranspiration) derived from simple water balance modeling (Oyama & Nobre 2004).

Wetness and seasonality indexes

The analyses here explore two factors used in the CPTEC-PVM. One is a wetness index (H) used as an estimate of dry/wet climate conditions, and other is a soil-moisture seasonality index (D) (Oyama & Nobre 2004), according to:

$$H = \frac{\sum_{i=1}^{12} g_i E_i}{\sum_{i=1}^{12} g_i Em_i} \quad ; \quad D = 1 - \frac{\sum_{i=1}^{12} F(0.5 - w_i)}{6} \qquad (1),$$

$$g = \begin{cases} 1, & \text{unfrozen} \\ 0, & \text{frozen} \end{cases} \quad , \text{ and } F(x) = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (2),$$

where E is the actual and Em is the maximum evapotranspiration, w is soil water degree of saturation (the ratio between soil water storage and availability), and i is a month index (1=January, …12=December). Note that both indexes have no dimensions, and are higher for wetter conditions. Along with surface temperature-derived quantities (growing degree days and mean temperature of the coldest month), the wetness and seasonality indexes are used to determine the potential distribution of major biomes (e.g. desert, savannas, forests, etc.) globally. For these specific indexes in the CPTEC-PVM formulation, tropical forests require $H > 0.8$ and $D > 0.81$ (Oyama & Nobre 2004).

Active-fire information

Fire-activity information are based on detections with the Tropical Rainfall Measuring Mission - Visible and Infrared Scanner (TRMM-VIRS) (Fig. 2). The product used reports monthly fire occurrence in the tropics (38°N to 38°S), from 1998 to 2005 at 0.5° spatial resolution (Giglio et al. 2003). The data were aligned to the CPTEC-PVM estimates by aggregating the total number of active-fire detections at the model's spatial resolution. As shown, overall patterns of fire activity generally match the location of major land-use features such as roads and deforestation, and are in good agreement with other sources of fire data for the region (e.g. Setzer & Malingreau 1996; Prins et al. 1998; Justice et al. 2002). In addition, TRMM-VIRS detects fire activity at different returning overpass times, thus avoiding a potential diurnal cycle of fire activity in the region (Justice et al., 2002, Cardoso et al. 2005), and favoring the long-term representativeness of the data.

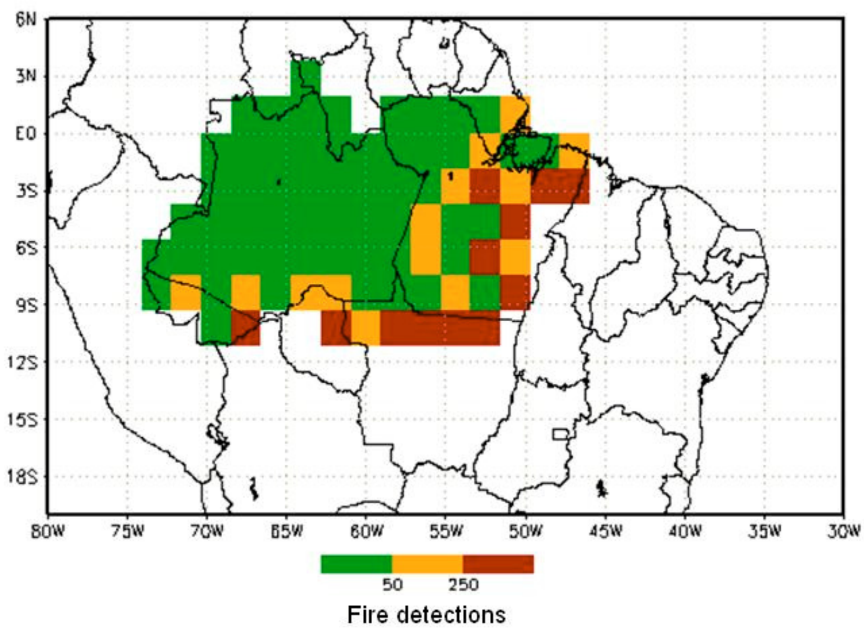

Figure 2 – Potential tropical forest coverage in the Brazilian Amazon and fire activity during 1998-2005, at ~2° spatial resolution. Non-white cells correspond to natural (not considering land use) tropical forests determined by the CPTEC-PVM in the Brazilian Amazon. Fire occurrence detected with TRMM-VIRS (Giglio et al. 2003) was classified in three levels. The number of active-fire detections was ≤ 50 in green areas, between 50 and 250 in orange, and ≥ 250 in red areas. Fire levels were determined based on 5% and 25% of the maximum number of detections verified in the study region.

Results

Relations between fire activity and indexes H and D

We first related fire activity to environmental conditions by simply plotting the total number of fire detections against *H* and *D* (not shown here). We verified that in the majority of the grid cells, the number of fire detections decreased for higher values of both indexes. Based on the indication that fires preferably occurred at lower values of *H* and *D*, we built distributions of the values of both indexes under different fire frequencies, in parallel to the levels of fire occurrence discussed in the section above. In Fig. 3, (a) displays the distribution of H values and (b) the distribution of D values for the whole region (black dashed line), and for grid cells that presented low (≤ 50), medium (between 50 and 250), and high (≥ 250) number of fire detections.

For both indexes, most common values decreased for grid cells that presented higher fire occurrences. For example, in Fig. 3a, while most (61%) of the grid cells with low fire activity correspond to values of *H* between 0.84 and 0.88, 86% of the grid cells with medium fire levels presented values of H < 0.84, and 75% of grid cells with high fire occurrence had values of *H* between 0.80 and 0.82. Similar patterns were also verified for *D*. Figure 3b shows that while 66% of the grid cells with low fire occurrence had maximum (0.97-1.00) values of *D*, 65% of the grid cells with medium fire levels presented *D* values between 0.88 and 0.94, and 75% of the grid cells with high fire activity had *D* values smaller than 0.91. As expected, given their similarity in areal extent and level of fire activity generally, curves for the whole region (black dashed) and for grid cells with low fire activity (green) were similar.

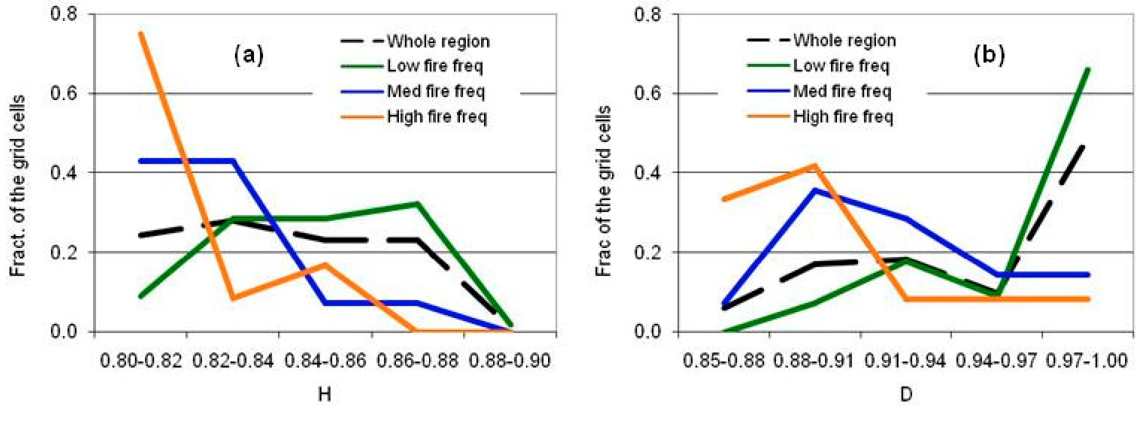

Figure 3 – Distribution of values of the wetness (*H*) and seasonality index (*D*) under different fire frequencies in the Brazilian Amazon. *H* (a) and *D* values (b) are displayed in fraction of the grid cells that presented low (≤ 50, green), medium (from 50 to 250, blue) and high (≥ 250, orange) number of active fires detected from TRMM-VIRS (Giglio et al. 2003). Distributions for the whole study region are in dashed black lines.

Characteristic values of H and D under different fire frequencies

The histograms above confirmed the general pattern indicated by our original simple analysis based only on scatter plots of fires versus *H* and *D* indexes (not shown), and helped to quantify the most typical values of these indexes under the different fire-activity levels we analyzed. In order to summarize the patterns observed in the distributions of Fig. 3, and provide simplistic values to capture the general decrease in common values of *H* and *D* for places that presented relatively higher fire occurrence, we calculated weighted arithmetic means (*H** and *D**) for the distributions in Fig. 3. For example, to represent the distribution of *H* for low fire frequency grid cells, we found the mean of mid-bins values weighted by its relative occurrence (*H**(low)), as:

$H^*(\text{low}) = 0.810\times9\% + 0.830\times29\% + 0.850\times29\% + 0.870\times32\% + 0.890\times2\%$, or

$H^*(\text{low}) = 0.85$.

For representing the distribution of *D* for grid cells with high fire frequency (*D**(high)), we used:

$D^*(\text{high}) = 0.865\times8\% + 0.895\times8\% + 0.925\times8\% + 0.955\times 42\% + 0.985\times 33\%$, or

$D^*(\text{high}) = 0.90$.

The results of applying this simple method are displayed in Fig. 4 below. As shown, the weighted arithmetic means for the wetness index (*H**) and for the seasonality index (*D**) are higher for low than for high fire frequency. *H** values ranged from 0.82 to 0.85, and *D** values from 0.90 to 0.97. Has already indicated by the pronounced maximum values of low- and high-fire distributions of the seasonality index (Fig. 3b), the variation for *D** (0.07) was relatively higher than for *H** (0.03).

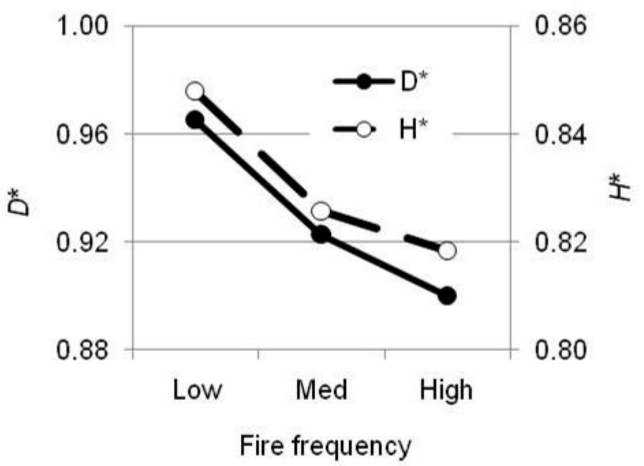

Figure 4 – Variation of the weighted arithmetic means of the wetness (*H**) and seasonality (*D**) indexes for different fire frequencies in the Brazilian Amazon. See text for details.

Discussion

Climate allows for most of the Brazilian Amazonia to be potentially covered by tropical forests, as indicated by vegetation models (Prentice et al., 1992; Haxeltine & Prentice, 1996; Oyama & Nobre, 2004) and other large-scale datasets for the region (Eva et al. 2004, INPE 2008). Resulting from land-use activities (Nepstad et al. 1999), however, substantial deforestation and fire activity have been verified in large portions of the region, particularly along the Arc of Deforestation (INPE 2008). Associated with direct effects of land-use change, indirect impoverishment and replacement of these forests by secondary and degraded vegetation or even savannas may result from unintended fires escaping from managed areas (Cardoso et al. 2003, 2005).

As an initial step for representing the potential for forest degradation due to land-use fires, we analysed fire and climate variables relevant for determining the spatial distribution of tropical forests by the CPTEC-PVM. In this model, a wetness (*H*) and a soil-moisture seasonality (*D*) index (along with other surface temperature-related variables) drive the location of tropical forests. The alignment of fire to *H* and *D* information yielded important details on the relations between these quantities. In particular, we verified that the distributions of the values of these indexes vary depending upon relative levels of fire activity in the region. The most common values of *H* and *D* are higher in grid cells with lower fire occurrence than in grid cells with relatively higher fire frequencies.

For summarizing our results, we calculated weighted arithmetic means for the wetness (H^*) and the seasonality index (D^*) according to different fire frequencies. The values in Fig. 4 summarize the major patterns in the previous distributions analysis by showing that H^* and D^* values also decrease with fire frequency, and by indicating values of *H* and *D* below which deforestation/fire degradation were relatively more frequent in the Brazilian Amazonia. An example for using the values in Fig. 4 is by asserting that a hypothetical region where H^* was higher than 0.83 commonly presented low fire frequencies. Other example is that D^* values smaller than 0.92 were most commonly associated with medium-to-high number of fire occurrences.

The interpretation of H^* and D^* results have thus important implications for building parameterizations of the potential for fires and related degradation of tropical forests in the Brazilian Amazonia. First, these results provide simple quantifications of thresholds of *H* and *D* related to more or less fire activity, which can be used to scale the stability of tropical forests. For example, the likelihood of fire activity (and thus forest degradation) is low for values of *D* close to or higher than 0.94, which is the average between 0.92 (D^* for medium fire frequency) and 0.96 (D^* for low fire frequency). The analogous interpretation for *H* would be a value of 0.84, or the average between H^* values of 0.83 (H^* for medium fire frequency) and 0.85 (H^* for low fire frequency).

Other important implication of the results from this study is their potential for being combined with direct estimates of the likelihood of fires based on relations between land-use patterns and climate/meteorological conditions (e.g. Cardoso et al. 2003). This type of combination can be applied for estimating future conditions of forests in light of changes in land cover and use in the region. For example, the expectation for a short- or medium-term increase in fire occurrence in a hypothetical region may also represent a decrease in medium- or long-term resilience for nearby forests. This may be evaluated by checking if, based on to H^* and D^* results from this study, the *H* and *D* values for the study area would support projected levels of fire frequency.

Concluding, the relations found in our results have important implications for evaluating the resilience of tropical forests in the Brazilian Amazonia by presenting general relations between climate and the occurrence of fires/deforestation, which can help to refine the estimates of the allocation of these forests in the region. In the future, we plan to build a parameterization for the CPTEC-PVM that is able to adjust the original *H* and *D* thresholds for the forest-savanna boundaries in the direction of restraining forests and favouring the occurrence of savannas if there is indication for increase in the potential for land-use fires.

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