

## Climatic variability and vegetation vulnerability in Amazônia

L. R. Hutyra,<sup>1,2</sup> J. W. Munger,<sup>1,2</sup> C. A. Nobre,<sup>3</sup> S. R. Saleska,<sup>4</sup> S. A. Vieira,<sup>5</sup>  
and S. C. Wofsy<sup>1,2</sup>

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[1] Models of climate change predict close coupling between increases in aridity and conversion of Amazonian forests to savanna. Here we assess the vulnerability and resilience of Amazonian vegetation to climate change by analyzing observed climate-vegetation relationships using climate data, observed vegetation distributions, and evapotranspiration rates inferred from eddy flux data. We found that drought frequency is an excellent predictor of the forest-savanna boundary, indicating the key role of extreme climatic events for inducing vegetation change, and highlighting particularly vulnerable regions of Amazônia. **Citation:** Hutyra, L. R., J. W. Munger, C. A. Nobre, S. R. Saleska, S. A. Vieira, and S. C. Wofsky (2005), Climatic variability and vegetation vulnerability in Amazônia, *Geophys. Res. Lett.*, 32, L24712, doi:10.1029/2005GL024981.

### 1. Introduction

[2] Vegetation change in Amazônia has long been recognized as a potentially significant component of climate change [Gash *et al.*, 1996]. Early studies focused on climate change induced by deforestation [e.g., Nobre *et al.*, 1991], whereas coupled changes of climate and vegetation [e.g., Cox *et al.*, 2004] are the current interest. Roughly 50% of Amazon precipitation is evaporated from the forest [Salati and Vose, 1984], so that changes in either vegetation or climate propagate through the entire vegetation-climate system. Large departures from mean climate conditions have been shown to result in increased tree mortality [Williamson *et al.*, 2000], forest fires [Nepstad *et al.*, 2004], and global atmospheric CO<sub>2</sub> anomalies [Clark *et al.*, 2003], hence both mean climate and climate variability are important.

[3] It is very difficult to capture the variability of natural systems in models. Both climate and vegetation can have multiple states that are persistent and resilient [Holling, 1973; Sternberg, 2001]. Many natural systems show hysteresis and lags. After small perturbations, the system returns to the initial state, but a large disturbance may cause a shift to a new persistent state. The perturbation needed to return the system to a prior long-term state may be larger than the one that triggered the shift. For example, Amazon

forests have expanded during moist periods of the Holocene and contracted in dry periods [Oliveira and Marquis, 2002]. The last contraction, in a brief mid-Holocene dry interval, persisted despite the return of wetter conditions [Ledru *et al.*, 1998].

[4] Changes in the frequency or magnitude of disturbance [Katz and Brown, 1992], and covariance between perturbing factors (e.g. temperature, precipitation, sources of ignition) may make vegetation change inevitable and irreversible, but initially nothing may happen. Vegetation change can be unannounced, catastrophic, and persistent [Scheffer *et al.*, 2005].

[5] Climate and weather are primary mechanisms for disturbance and principal determinants of the size, age, and species structure of ecosystems [Connell, 1979]. The ratio of potential evapotranspiration to precipitation (PET/P) is a key determinant of vegetation in the tropics, with PET/P < 1 typically observed in biologically rich, closed-canopy forests and PET/P > 1 associated with sparser, fire-adapted vegetation [Holdridge, 1947]. Cox *et al.* [2004; cf. Huntingford *et al.*, 2004] predicted dramatic shifts in vegetation and global temperature increases of ~5°C in part due to increased aridity, whereas Friedlingstein *et al.* [2003], whose model incorporated static vegetation distributions, inferred a warming of only ~3°C. This divergence highlights the importance of understanding the resilience of Amazonian vegetation and the factors regulating the vegetation assemblage.

[6] In this paper, we assess the vulnerability and resilience of Amazonian vegetation to climate change by analyzing observed climate-vegetation relationships in a statistical framework using climate data, observed vegetation distributions, evapotranspiration rates based on eddy flux data (ET, includes evaporation of surface water and soil moisture, and transpiration by vegetation [Oke, 1987]), and water balances. We re-evaluate the Nix [1983] criteria for forest-savanna boundaries, and formulate a drought criterion to capture the influence of climatic variability on vegetation.

#### 1.1. Measurements and Empirical Model

[7] Common formulas for ET [e.g., Monteith, 1983; Gash, 1979; Hodnett *et al.*, 1996] could not be used for our analysis of drought because required data are not available from climate reconstructions. Hence we derived a similar formula for Amazonian forest ET, using only temperature, by analyzing eddy flux data that we collected in Tapajós National Forest (54°58'W, 2°51'S, near km 67 of the Santarém-Cuiaba highway, BR-163). This site was selected for study in the Brazilian-led Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA-ECO) because it lies at the dry end of the climate zone supporting evergreen equatorial forests.

[8] Data for water fluxes and temperature [Saleska *et al.*, 2003], from January 2002 through November 2004, were

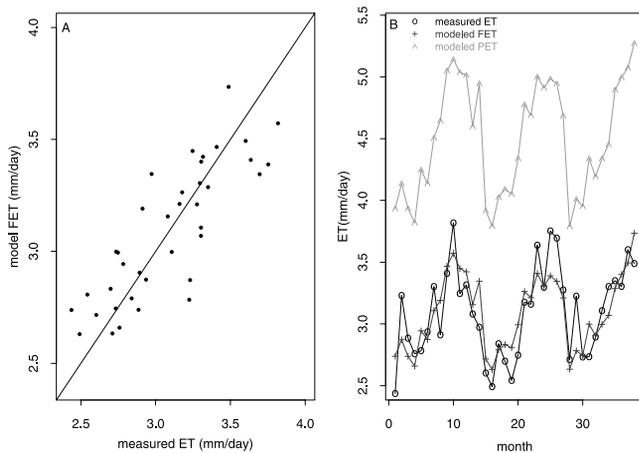
<sup>1</sup>Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA.

<sup>2</sup>Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA.

<sup>3</sup>Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, Brazil.

<sup>4</sup>Ecology and Evolutionary Biology, University of Arizona, Tucson, Arizona, USA.

<sup>5</sup>Laboratório de Ecologia Isotópica, CENA/USP, Piracicaba, Brazil.



**Figure 1.** (a) Observed and modeled forest ET for the Santarém study site,  $R^2 = 0.68$ ; (b) time series for measured forest ET, the FET model (1), and modeled PET [Thornwaite, 1948].

combined to develop a model of actual ET for evergreen Amazonian tropical forest, denoted forest evapotranspiration (FET):

$$\text{FET}(\text{mm/day}) = -6.7084 + 0.3764 \cdot T, \quad (1)$$

where  $T$  is monthly mean temperature (C). When fit to 38 months of environmental measurements, equation (1) explained 68% of the total variance (Figure 1; see section 2.1).

[9] We used the Climate Research Unit's (CRU) 100-year gridded ( $0.5^\circ \times 0.5^\circ$ ) time series for temperature and precipitation [New *et al.*, 1999; Mitchell *et al.*, 2003], in which monthly mean and variance fields are interpolated separately (Figure S1<sup>1</sup>). For the few points (7.7%) where the CRU temperature was outside the range observed at Tapajós ( $24^\circ$ – $28^\circ\text{C}$ ), FET was set to 75% of PET as given by Thornwaite [1948], the mean ratio of equation (1) to PET across the Basin. PET exceeds actual ET because it does not account for soil and vegetation limitations on water exchange, but our observed ET is a nearly constant fraction of PET (Figure 1b).

## 1.2. Drought Assessment

[10] To derive a measure of drought occurrence, we computed the quantity of soil water available to trees (Plant Available Water, or PAW; units:  $\text{mm H}_2\text{O}$ ),

$$\text{PAW}_i = \text{PAW}_{i-1} + P_i - \text{FET}_i, \quad (2)$$

where  $i$  indexes the month of the 100 year record. Values exceeding  $\text{PAW}_{\text{max}}$  were assumed lost as runoff. The spatial distribution of  $\text{PAW}_{\text{max}}$  was adapted from Kleidon [2004], who applied inverse methods to a land surface model optimizing photosynthesis (Figure S2a). This  $\text{PAW}_{\text{max}}$  applies to current vegetation assemblages, under current climate. PAW in 1900 was set to  $\text{PAW}_{\text{max}}$  at all grid cells.

[11] A drought was assessed at any grid cell where PAW declined to less than 75% of  $\text{PAW}_{\text{max}}$  for 5 or more months

in a year, implying a dry period exceeding 6 or 7 months, longer than the mean dry season for most evergreen Amazon forests. Similar results were obtained using shorter intervals of more extreme dryness, e.g.  $\text{PAW} < 0.25 \cdot \text{PAW}_{\text{max}}$  for 1 month (Figure S2).

[12] The spatial distribution of estimated drought frequencies in 100 years was compared with vegetation in the legal Brazilian Amazon, classified using Landsat data from the early 1980s (prior to most forest clearing). These data were produced by the Tropical Rainforest Information Center (TRFIC), Michigan State University, without any reference to climate data. We aggregated 9 classes to 3 vegetation types: fire-adapted savanna and woodlands, seasonal transitional forest, and equatorial evergreen forest. Riparian zones were excluded and Caatinga in the NW basin was grouped with evergreen forests.

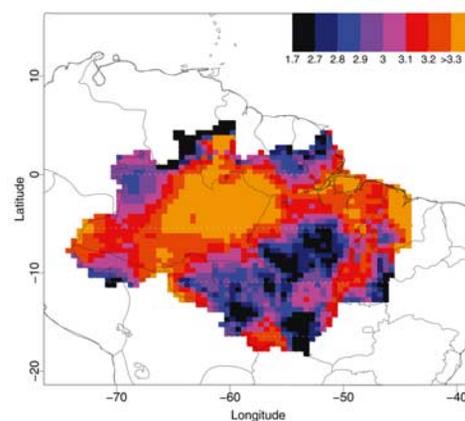
## 2. Results

### 2.1. Forest Evapotranspiration

[13] Equation (1) predicts significant spatial variation of mean annual FET (1.72–3.6 mm/day, Figure 2), highest near the Equator. Variability of FET is greatest in the southern portion of the Amazon (Figure S1). Few accurate multi-year measurements are available to test Figure 2. Near Santarém ( $2.75^\circ\text{S}$ ,  $54.75^\circ\text{W}$ ), Manaus ( $2.75^\circ\text{S}$ ,  $59.75^\circ\text{W}$ ), and Ji-Paraná ( $10.75^\circ\text{S}$ ,  $61.25^\circ\text{W}$ ) mean FET values are  $3.1 (\pm 0.34, 1 \sigma)$ ,  $3.5 (\pm 0.24)$ , and  $2.9 (\pm 0.37)$   $\text{mm day}^{-1}$  respectively, in good agreement with observations ( $3.07$  (this work) and  $3.51$  [da Rocha *et al.*, 2004],  $3.05$  [Malhi *et al.*, 2002] and  $3.45$  [Shuttleworth *et al.*, 1984], and  $3.69$  (wet season) and  $3.83$  (dry season) [Von Randow *et al.*, 2004], respectively). Both FET and measured ET maximize in the dry season when incident radiation and vapor pressure deficits are highest.

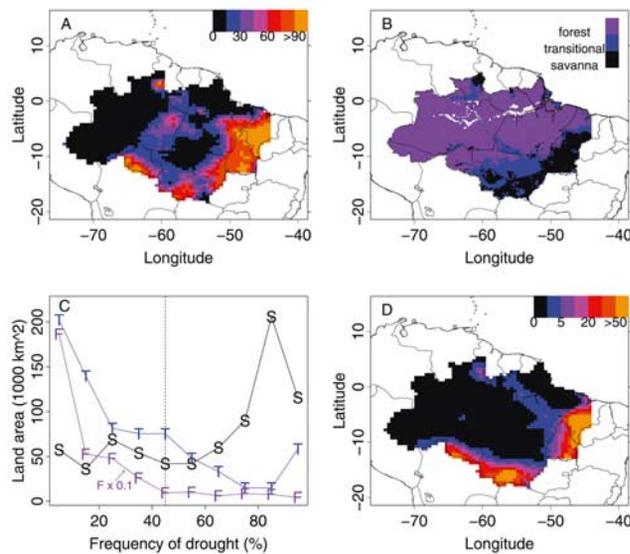
### 2.2. Drought and Vulnerable Vegetation Areas

[14] Our values for drought frequency (Figure 3a) are highest along the southern and eastern edges of the legal Amazon, but less frequent droughts occurred in the central basin. Areas with high drought frequency are associated with regional precipitation minima and/or high temperature variability. The current distribution of vegetation (Figure 3b) strikingly follows drought frequency, with savanna replac-



**Figure 2.** Mean annual modeled FET (mm/day) from equation (1).

<sup>1</sup>Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2005GL024981>.



**Figure 3.** (a) Observed drought frequency (% years); (b) distribution of savanna, transitional vegetation, and forest across the legal Brazilian Amazon; (c) land area (1000 km<sup>2</sup>) of vegetation types for pixels with given drought frequency (%), forest land area is multiplied by 0.1 for scaling; (d) percent attainment of the *Nix* [1983] criteria for savanna vegetation in the last 100 years.

ing forest and transitional vegetation as drought frequencies increase (Figure 3c).

[15] *Nix* [1983] developed seven criteria to predict occurrence of tropical savannas (Table 1). The spatial patterns for attainment of his criteria 2–6 (Figure 3d), utilizing the CRU time series, showed a strong correlation with our PAW drought metric ( $r = 0.69$ ,  $p \approx 0$ ). The fraction of years attaining *Nix* criteria and vegetation type were also correlated,  $r = 0.59$  ( $p \approx 0$ ). Correlations between individual *Nix* [1983] rules and vegetation (Table 1) imply that his most significant criteria are mean rainfall, which excludes very wet areas, and dry season precipitation, his aridity criterion. Since temperatures maximize in the dry season, the similarity with drought occurrence is unsurprising.

### 3. Discussion

[16] Climatic variability is a principal driver for our PAW drought index, and implicitly for the *Nix* [1983] rules. Forest areas with high climate variability are vulnerable to loss of forest with either increased mean temperature, or increased variability in temperature and/or precipitation. Our analysis provides a physical quantity (PAW deficit) to predict vegetation type, and it supports the models of *Oyama and Nobre* [2004] indicating that the seasonality of soil moisture is a critical factor determining forest-savanna boundaries. We support the findings of *Nix* [1983], by testing against the extensive CRU climate record and the TFRIC vegetation map. The apparent role of variability highlights the importance of correctly capturing high order statistical characteristics in coupled vegetation/climate models.

[17] Fire is likely the event that actually shifts a forest to savanna. Historical records and charcoal found in soils

**Table 1.** Correlation Coefficients Between the Percent Attainment of the *Nix* [1983] Criteria and Observed Vegetation<sup>a</sup>

<i>Nix</i> [1983] Criteria	Correlation Coefficient
1. Annual totals of solar radiation between 6 and 8 GJ m <sup>-2</sup> yr <sup>-1</sup>	NA
2a. Mean precipitation >1000 mm/yr	0.28
2b. Mean precipitation < 1500 mm/yr	0.56
2. 1000 mm/yr < mean Precipitation < 1500 mm/yr	0.56
3. High seasonality in rainfall	NA <sup>a</sup>
4. Precipitation > 600 mm/yr during wettest 6 months	0.05
5. Precipitation < 50 mm/yr during driest 3 months	0.75
6. Mean temperature >24°C	0.08
7. Mean min temperature of coldest month between 13° and 18°C	NA
Parameters 2 and 5	0.59
Parameters 2 through 6	0.58

<sup>a</sup>Satisfied by the whole basin.

show that fires have occurred in many evergreen tropical forests. Trees are sustained during dry periods by deep roots [*Nepstad et al.*, 1994] that access stored water, but small plants and dead organic matter can become combustible. Increased drought frequency would evidently raise susceptibility to ecosystem-transforming fires. Evergreen tropical forests are not fire-adapted, reflecting the long fire return interval. Fire return times of less than 90 years may eliminate rainforest species, and return intervals of less than 20 years may entirely eliminate trees [*Jackson*, 1968].

[18] Other factors may interact synergistically with droughts, exacerbating vulnerability even in a stable climate [*Cochrane and Laurance*, 2002]. Fire frequency and intensity are expected to increase with fragmentation due to land conversion, due to desiccation at fragment edges, and with introduction of anthropogenic ignition sources [*Cochrane and Laurance*, 2002]. Areas of forest proximate to edges or to ignition sources have increased dramatically [*Cochrane*, 2003], and forest disturbance is currently significant in areas with notable climatic variability (e.g., Santarém and Rio Branco; Figure 1 [*Vieira et al.*, 2004]).

[19] *Oyama and Nobre* [2003] have suggested that the Amazon may have an alternate persistent vegetation/climate state, where savannas take over large areas currently in tropical rainforests. A drier climate leads vegetation to rely on deeper water supplies to maintain green canopies, and flammability increases. Once large areas converted to savanna, overall aridity would increase because fire-adapted vegetation transpires much less than forests. Our study supports the view that forests in areas of high drought frequency (>45% drought probability) could shift to transition forests or savanna, if aridity increases as predicted by climate change models [*Cox et al.*, 2004; *Friedlingstein et*

**Table 2.** Areas of the Legal Amazon Within the Two Drought Frequencies Regimes for Each Vegetation Type<sup>a</sup>

	Drought Frequency 0–44	Drought Frequency 45–100
Forest	3,176,751 km <sup>2</sup>	413,900 <sup>a</sup>
Transitional	550,023	197,027 <sup>a</sup>
Savanna	243,655	583,965

<sup>a</sup>Areas vulnerable to degradation with increased aridity. A 45% frequency of drought implies a mean return interval of 2.2 years.

al., 2003]. Potentially at risk are over 600,000 km<sup>2</sup> of forest (Table 2 and Figure 3), >11% of the total area. Savanna vegetation currently present in areas with low drought frequency (<45% droughts) is unlikely to shift to forest if aridity increases. Our maps show that increased aridity may lead to bisection of Amazonian equatorial forests.

[20] The critical links between fire, climate, and land use are highly uncertain in current coupled climate-vegetation models. In order to assess vegetation vulnerability to climate change, models must capture variability of climate, the non-linear, hysteretic behavior of vegetation response to rising drought frequency, the synergistic effect of forest fragmentation and development, and the occurrence of landscape-changing fires.

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L. R. Hutyra, J. W. Munger, and S. C. Wofsy, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA. (lhutyra@fas.harvard.edu)

C. A. Nobre, Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, 12630-000 Cachoeira Paulista, SP, Brazil.

S. R. Saleska, Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ 85721, USA.

S. A. Vieira, Laboratório de Ecologia Isotópica, CENA/USP, PO Box 96 CEP 13400-970, Piracicaba, SP, Brazil.