Climate change and thresholds of biome shifts in Amazonia

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[1] We examine potential critical thresholds for biome shift in the Amazonian tropical forest by forcing a potential vegetation model with prescribed climate anomalies and projections from global and regional climate models and different levels of CO_2 fertilization effect under the SRES A2 scenario (2070–2099). The results indicate that tropical forests might be replaced by seasonal forests or savanna over eastern Amazonia with temperature increases of 2–3°C (4–5°C), when CO_2 fertilization effect is not considered (partially considered), depending on precipitation anomaly. A precipitation decrease greater than 30% would trigger the shift from tropical forest to drier biomes, such as savanna and shrubland in southeastern Amazonia. The projected decrease in precipitation during the dry season and the increase of temperature are the main mechanisms driving calculated biome changes. However, biome changes are considerably smaller when the optimum fertilization effect is included. **Citation:** Salazar, L. F., and C. A. Nobre (2010), Climate change and thresholds of biome shifts in Amazonia, *Geophys. Res. Lett.*, *37*, L17706, doi:10.1029/2010GL043538.

1. Introduction

[2] The Amazon forest plays an essential role in the global atmospheric circulation [*Malhi et al.*, 2008] and the southward atmospheric moisture flow out of the region may represent a significant moisture source for precipitation in some areas in South America [*Marengo et al.*, 2004; *Nobre et al.*, 1991]. In recent decades, the warming rate in Amazonia has been about 0.25°C/decade [*Victoria et al.*, 1998; *Malhi and Wright*, 2004] and the climate change projections indicate a mean increase of 3.3°C under an intermediate emissions scenario for the end of 21st century [*Salazar et al.*, 2007; *Nobre and Borma*, 2009]. Precipitation projections, though without consensus in relation to the sign of the annual anomaly [*Li et al.*, 2006], indicate precipitation decrease in the dry season. This is the most critical factor for the forest sustainability in the future [*Salazar et al.*, 2007; *Malhi et al.*, 2008; *Nobre and Borma*, 2009]. These changes might impact not only biological and socio-economical aspects, but also amplify the global climate change due to respiration increase and reduced carbon uptake [*Cox et al.*, 2004]. Over the Amazon forest, a drier and warmer climate (due to climate change, land use changes, or combined effects) would allow an equilibrium climate condition with vegetation more resistant (e.g., savannas) to the multiple stresses caused by high temperatures, droughts, and fire increase [*Nobre et al.*, 1991; *Salazar et al.*, 2007; *Nobre and Borma*, 2009].

[3] Some studies [e.g., *Cox et al.*, 2004; *Scholze et al.*, 2006; *Cook and Vizy*, 2008; *Salazar et al.*, 2007], based on different models and under different emission scenarios, project a total or partial reduction in the tropical Amazon forest by the end of the 21st century. Other studies do not show significant changes in vegetation [e.g., *Cramer et al.*, 2001; *Alo and Wang*, 2008; *Sitch et al.*, 2008] or show a shift of tropical forest to seasonal forest [e.g., *Lapola et al.*, 2009; *Malhi et al.*, 2009] under certain climate change scenarios.

[4] *Oyama and Nobre* [2003] show that the eastern Amazon could have two equilibrium vegetation-climate states. The difference between them would depend directly on atmospheric forcing or indirectly, on changes on land use. *Lenton et al.* [2008] and *Kriegler et al.* [2009] analyze critical thresholds of some elements in the climate system. The study shows a critical threshold with a temperature increase of 3–4°C in Amazonia. A key point for the consequences of climate change in biome distribution is the effect of higher atmospheric CO_2 in carbon uptake through the CO_2 fertilization effect [*Curtis and Wang*, 1998; *Prentice et al.*, 2001; *Lapola et al.*, 2009]. The magnitude of the fertilization effect has been validated with field experiments in temperate ecosystems [*Norby et al.*, 2005], but the impact on tropical forest has remained uncertain. In this study we go further on this type of analysis by consideration of the simultaneous effects of temperature increase and precipitation changes brought about by different global warming scenarios, and different levels of CO_2 fertilization effect (under A2 SRES scenario) using a regional potential vegetation model to evaluate critical thresholds to biome shift in Amazonia.

2. Material and Methods

[5] The potential vegetation model used is the CPTEC-PVM2.0Reg [*Salazar*, 2009], a regional version of CPTEC-PVM2.0 [*Lapola et al.*, 2009]. The CPTEC-PVM2.0Reg considers seasonality as a determinant factor for the delimitation of forests and savannas. It also takes into account physiological responses of vegetation to seasonality (such as primary productivity) under variable atmospheric CO_2. The biome allocation relies mainly on the optimum net primary productivity (NPP) values for a given grid cell. The determination of biome distribution through NPP is based on numerous studies showing that different biomes have typically different average NPP [e.g., *Turner et al.*, 2006]. However, NPP can be quite similar among biomes in some cases, and hence variables other than NPP are used for biome allocation. As a non-dynamic model, the CPTEC-PVM2.0Reg calculates only equilibrium solutions based on long-term mean monthly climate variables. This is done

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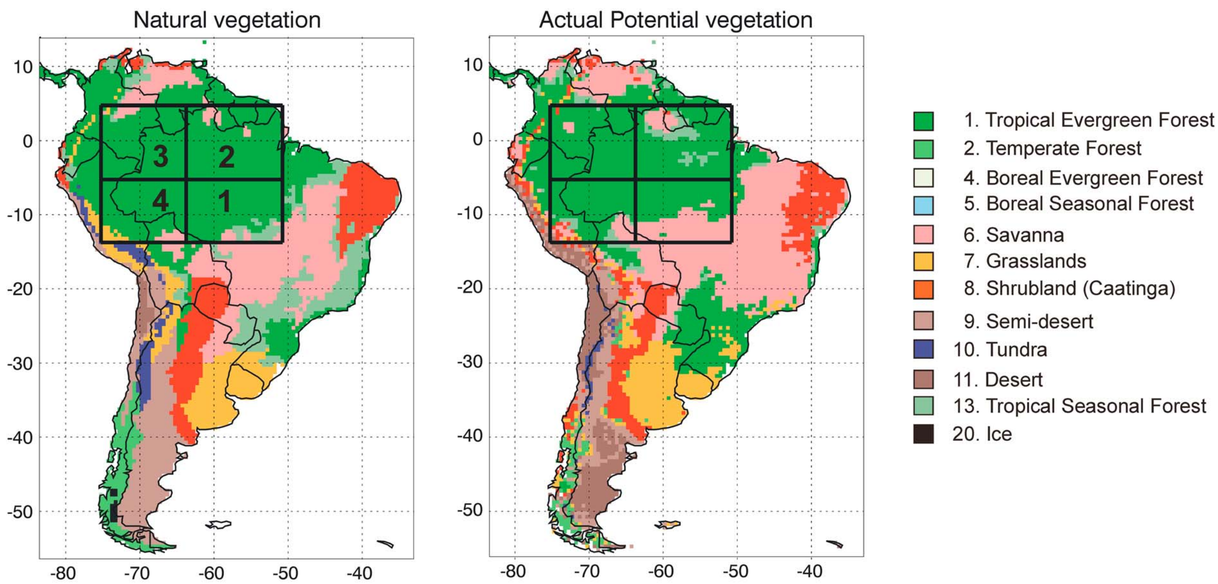

Figure 1. Natural vegetation reference map [*Salazar*, 2009] and actual potential vegetation simulated by CPTEC-PVM2.0Reg model under the 1961–1990 mean climate. The division of the Amazon domain is indicated by the continuous box in the natural vegetation map. Region 1: Southeast (5.25°S–13.75°S; 50.75°W–63.75°W); Region 2: Northeast (4.75° N–5.25°S; 50.75°W–63.75°W); Region 3: Northwest (4.75°N–5.25°S; 63.75°W; 75.25°W); Region 4: Southwest (5.25°S–13.75°S; 63.75°W–75.25°W).

concomitantly by a water balance sub-model using climatological values of surface temperature and precipitation (1961–1990 (C. J. Willmott and K. Matsuura, Terrestrial air temperature and precipitation: Monthly and annual climatologies, University of Delaware, Newark, 1998, http://climate.geog.udel.edu/~climate/html_pages/archive.html)), intercepted photosynthetically active radiation (I_{PAR}) (1986–1995 [*Raschke et al.*, 2006]), soil classes [*Food and Agriculture Organization of the United Nations*, 1991], and atmospheric CO_2 concentration [*IPCC*, 2007] as inputs.

[6] In order to evaluate biome shift thresholds in Amazonia, the CPTEC-PVM2.0Reg is integrated with different prescribed precipitation (−50, −40, −30, −20, −10 0, 10, 20, 30, 40 e 50%) and temperature (0, 1, 2, 3, 4, 5, 6 e 7°C) annual anomalies, added to the observed climatology. Furthermore, different levels of CO_2 fertilization effect (fully considered: 100%; partially considered: 25%; and non-existent: 0%) under emissions scenario A2 (mean atmospheric CO_2 concentration of 730 ppmv) are used for the period 2070–2099. We include the fertilization effect in the model scaling the increase in CO2 concentration from 1960–1990 level (350 ppmv) to 2070–2099 projected level (730 ppmv, in A2 scenario) with the percentages analyzed (0%, 25% and 100%). To compare the biome in equilibrium with model projections, we use annual climate anomalies projected from global and regional model scenarios. The regional scenarios taken from regional climate models (RCM) for South America (50 km resolution), integrated in the CREAS project [*Marengo*, 2009; *Marengo and Ambrizzi*, 2006], are: ETA CCS, RegCM3 and HadRM3P. The global scenarios use standard output, available through the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset, from fifteen Coupled Ocean-Atmosphere GCMs for the IPCC AR4: BCCR-BCM2.0, CCSM3, CGCM3.1(T47), CNRM-CM3, CSIRO-Mk3.0, ECHAM5/MPI-OM, ECHO-G, GFDL-CM2.0, GFDL-CM2.1, GISS-ER, INM-CM3.0, IPSL-CM4, MIROC3.2(MedRes), MRI-CGCM2.3.2, and UKMO-HadCM3. The anomalies for global and regional models are calculated as the difference between the present climate (1961–1990) and the future scenario A2 (2071–2100) simulated by each model (this methodology filters out the effect of GCM's systematic errors). We divide the Amazon basin into four quadrants (see Figure 1) due to differences in climate seasonality and climate change projections [*Vera et al.*, 2006]. For each region, we calculate the dominant biome (the highest occupation area in the region) using all combinations of prescribed climate anomalies and CO_2 fertilization effect. Superimposed to Figure 1, we calculated the dominant biome in equilibrium with climate change projections from the regional models, selected global models (GISS-ER, ECHAM5 and HadCM3) and the mean of the fifteen global models. These three global models are selected based on their capacity to simulate current climate in South America [*Covey et al.*, 2003; *Li et al.*, 2006] and also to capture in the analysis the range of somewhat divergent projections (mainly in precipitation).

3. Results

[7] Figure 1 shows the natural vegetation reference map [*Salazar*, 2009] and the biome distribution simulated by the CPTEC-PVM2.0Reg model under current climate. To measure the degree of similarity between the natural and potential maps, the kappa (κ) statistics [*Monserud and Leemans*, 1992] is used. For South America, the κ average value is 0.48 (comparable to other models like BIOME), which is considered an acceptable value. For tropical biomes, the agreement is good for tropical forest (κ = 0.66) and shrubland (κ = 0.57); acceptable for savannas (κ = 0.51) and grasslands (κ = 0.49); and poor for seasonal tropical forests (κ = 0.03).

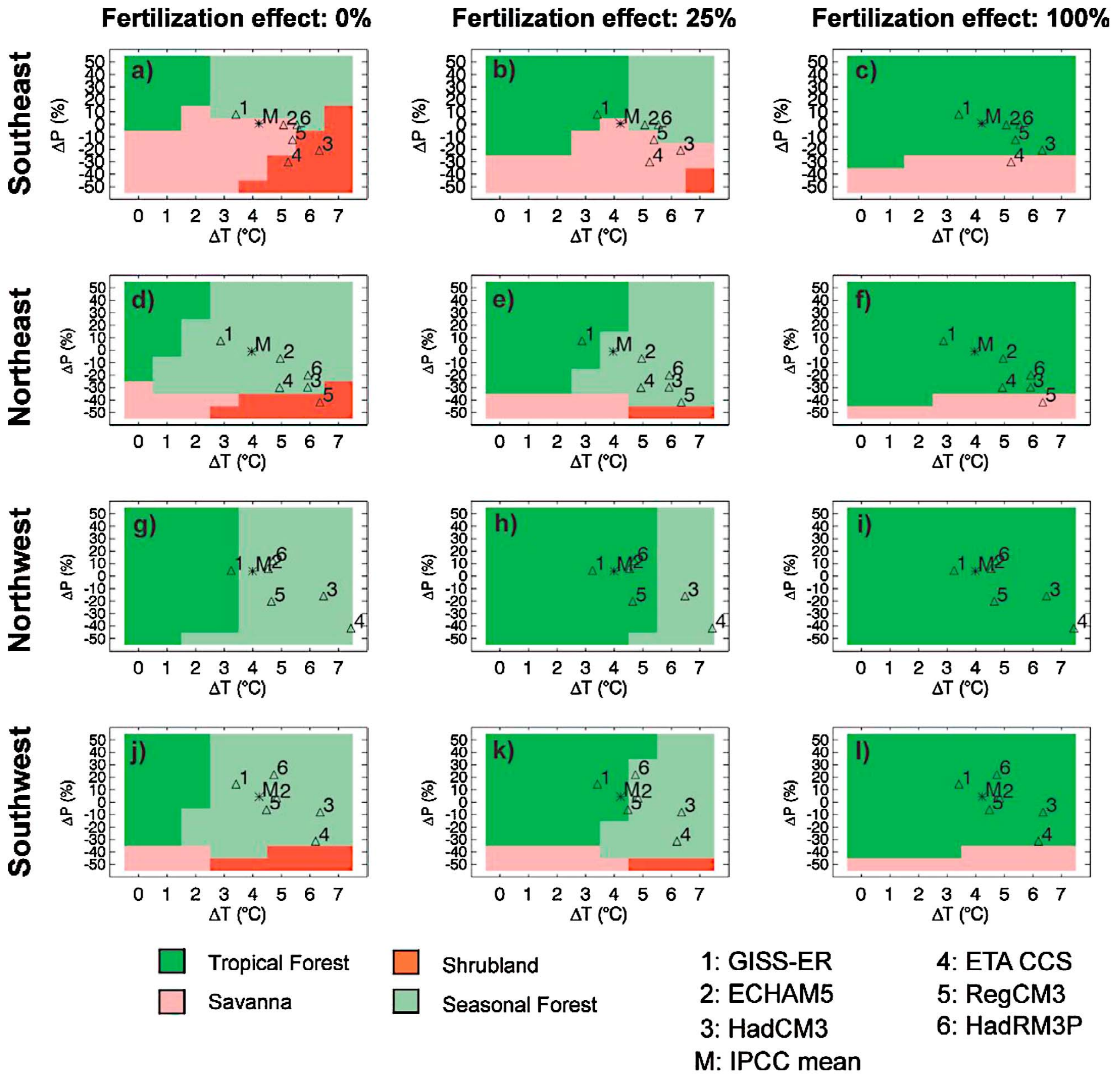

Figure 2. Potential dominant biome simulated by CPTEC-PVM2.0Reg for different temperature anomalies, precipitation changes, and fertilization effects (0%, 25% and 100%) for SRES A2 climate scenario for the period 2070–2099, and for the regions of Amazonia (indicated in Figure 1): (a–c) southeast, (d–f) northeast, (g–i) northwest and (j–l) southwest Amazonia. The climate anomalies projected by regional (ETA CCS, RegCM3 and HadRM3P) and selected global (GISS-ER, ECHAM5, HadCM3 and M: average of fifteen global models from IPCC) models are plotted for each region.

[8] Figure 2 shows the dominant biome in each region when the PVM model is integrated with prescribed climate and fertilization effects. In eastern Amazonia, if the fertilization effect is non-existent (Figures 2a and 2d), there is a shift to savanna when the annual precipitation decrease is greater than 10% or to seasonal forest when the temperature increase is greater than 2°C. In extreme temperature and precipitation anomalies (as projected by HadCM3 and ETA CCS models), the model simulates a dominance of shrubland (caatinga) biome. When the CO_2 fertilization effect is considered at 25% efficiency (Figures 2b and 2e), the shift to seasonal forest (savanna) occurs when the temperature is greater than 4°C (precipitation decrease is greater than 30%). In this simulation, a large increase in temperature alone (>4°C) is sufficient to drive the biome shift through reduced NPP, but not the seasonality (shifting the biome to tropical seasonal forest). In the case of full (100%) fertilization effect (Figures 2c and 2f), the temperature increase does not affect the tropical forest biome (due to the optimal water use by plants in conditions of higher CO_2 concentrations and full fertilization effect), maintaining a critical threshold of 40% in precipitation decrease to replace tropical forest with savanna (due to increase in the dry season length).

[9] Northeast and southwest Amazonia show similar thresholds for biome shift. In all simulations, a precipitation

decrease >40% changes the tropical forest into savanna or shrubland (depending on temperature increase). The critical threshold to replace tropical forest with seasonal forest is 2°C when the fertilization effect is non-existent or 4°C when fertilization effect is partially considered. Northwest Amazonia does not show a biome change to savanna (Figures 2g–2i) and the critical threshold for biome shift to seasonal forest occurs when temperature increase is >3°C (>5°C) and the fertilization effect is non-existent (partially considered). In the case of maximum fertilization effect, there is no biome change even under conditions of precipitation decrease.

[10] The projections of GCMs and RCMs in the Amazon region show that there are no changes in dominant biome when maximum fertilization effect is considered (Figures 2c, 2f, 2i, and 2l) (except in ETA/CCS for Southeast and RegCM3 for Northeast). When the fertilization effect is non-existent, the models show a shift to seasonal forest in northeast (Figure 2d), northwest (Figure 2g), and southwest (Figure 2j) regions (except for RegCM3 in Northeast and GISS-ER in Northwest). For the southeast region (Figure 2a), GISS-ER and HadRM3P project a biome shift to seasonal forest; ECHAM5, RegCM3 and average IPCC models to savanna, and HadCM3 and ETA CCS, to shrubland. When the fertilization effect is partially considered (25%), the HadCM3 and ETA/CCS show a biome shift to savanna in the southeastern region and to seasonal forest in the other areas. GISS-ER maintains a tropical forest in all areas while the average of IPCC models shows a biome shift to savanna in the southeast, to seasonal forest in northeast; and no changes in western regions.

[11] In these calculations, biome changes in Amazonia are related to climate anomalies and fertilization effect considerations. The increase in temperature alone would be enough to change the biome through reduced NPP (the critical threshold depends on the CO2 fertilization effect considered). The decrease of precipitation and increase of dry season length would trigger the shift from tropical forest (evergreen or seasonal) to drier biomes as savannas and caatinga [*Lapola et al.*, 2009], depending on temperature anomaly and level of fertilization effect (except for northwest Amazonia, where the decrease of 50% in precipitation is not sufficient to significantly increase the dry season length).

4. Conclusions

[12] The future of the tropical forest under different climate change scenarios is still an open question. The uncertainties come from divergences in climate projections and current knowledge of tropical forest response to elevated CO_2 concentrations (fertilization effect) and adaptation mechanisms. Furthermore, climate biophysical feedbacks from climate-induced changes in land cover could modify the future vegetation distribution. Therefore, improved understanding on how the complex tropical ecosystems are and will be responding to the atmospheric CO_2 increase is a key question to reduce uncertainties in the projections of future biome changes in Amazonia. Our results indicate that different levels of fertilization effect show different critical thresholds to biome shift.

[13] Precipitation decreases of 30% in the southeast and 40% in the northeast and southwest represent an increase of the dry season length to more than 4 months and shifts to savanna vegetation. In agreement with *Lapola et al.* [2009], we find that this threshold is critical to maintain tropical forests, even in conditions of maximum fertilization effect.

[14] There is a clear dependence between the temperature threshold and the magnitude assumption of the fertilization effect. In the case of no CO_2 fertilization, the critical threshold for biome shift in Amazonia is 2–3°C up to 4–5°C when the fertilization effect is partially considered (25%). The biome that would replace the original vegetation type depends on the precipitation changes.

[15] Our simulations show that eastern Amazonia is the most vulnerable region for biome changes. In conditions of partial fertilization effect, the GCMs and RCMs projections indicate biome shifts into seasonal forest or savanna (except for the GISS-ER model because of its projected increase in precipitation). If the local deforestation effect on eastern and southeastern Amazonian climate [*Sampaio et al.*, 2007] is combined with climate change scenarios, the tropical forest degradation might be accelerated [*Nepstad et al.*, 2008; *Malhi et al.*, 2009; *Nobre and Borma*, 2009]. Furthermore, some studies point out [*Malhi et al.*, 2009; *Nobre and Borma*, 2009] that an environment of increasing anthropogenic fire activity (ignition points due to forest deforestation, fragmentation and logging) exacerbated by a drier and warmer climate [*Hutyra et al.*, 2005; *Cardoso et al.*, 2003] might accelerate the biome shift from seasonal forest to savanna.

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