FUTURE FIRE PROBABILITY IN THE AMAZON UNDER CLIMATE AND LAND-USE CHANGE

Marisa G. Fonseca[1], Lincoln M. Alves[2], Ana Paula D. Aguiar[2], Graciela Tejada [2], Egidio Arai[1], Liana O. Anderson[3], Yosio E. Shimabukuro[1], Luiz Eduardo O. C. de Aragão[1,4]

[1]National Institute for Space Research (INPE), Av. dos Astronautas 1758, São José dos Campos/SP,12227-010, Brazil - marisa_fonseca@yahoo.com.br, (egidio, yosio, laragao)@dsr.inpe.br; [2]Earth System Science Center (CCST), INPE, Av. dos Astronautas 1758, 12227-010, São José dos Campos/SP, Brazil - (lincoln.alves, ana.aguiar)@inpe.br; [3]National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), Parque Tecnológico de São José dos Campos, Estrada Dr Altino Bondensan, 500, 12247-016, São José dos Campos/SP, Brazil - liana.anderson@cemaden.gov.br; [4]College of Life and Environmental Sciences, University of Exeter, Exeter, UK

ABSTRACT

Climate and land-use changes are expected to influence future fire regime in the Amazon. We combined regional land-use projections and climatic data from the CMIP5 multi-model ensemble to investigate the probability of fire occurrence by the end of the 21st century (2071-2100) in the Brazilian and Bolivian Amazon. Under the RCP 8.5 emission scenario combined with a land-use scenario based on the depletion of natural resources, the area with fire relative probability (FRP) ≥ 0.3 (a threshold chosen based on the literature) increases by 54%. Areas with a negative change in FRP are projected in the South and South-eastern of both Brazilian and Bolivian Amazon, but only 10% of the study area shows a decrease in FRP ≥ 0.3. The projected overall increase in FRP in the Amazon will likely threaten its inhabitants health, livelihood and important ecosystems services, including the regions' biodiversity and carbon stocks.

Key words *— Fire modeling, Hot pixels, Maximum Entropy, Tropical forest.*

1. INTRODUCTION

Climate and land-use changes are expected to influence future fire regimes in the Amazon, which will impact ecosystems processes and police issues such as greenhouse gases emissions, climate policy, biomes distribution, biodiversity conservation, human safety, public health, and land-use management [1–4].

Most previous studies on the future fire activity over the Amazon basin (e.g. [5]) considered the emissions scenarios of the Intergovernmental Panel of Climate Change (IPCC) Special Report on Emissions Scenarios (SRES; [6]) or just climate records [7], and some did not include land-use change effects [8, 9]. In the IPCC Fifth Assessment Report [10], however, the SRES were substituted with the Representative Concentration Pathways (RCP's), a new set of scenarios that include time paths for emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land-use/land-cover changes.

Studies concerning the effects of the RCP's combined with land-use change on fire occurrence in the Amazon are still scarce. Le Page et al. [11] provided an important contribution to this subject. The authors used future land-use distributions from the land harmonization processing developed for the RCPs [12] and climatic data from two RCP scenarios to simulate fire occurrence by the end of the 21st century in the Amazon basin. However, observed historical deforestation rates in Amazon are substantially different from the rates projected in the RCPs, as the latter do not integrate, for instance, regional land management policies, existing or future road building or the establishment and level of protection of conservation areas [13]. Therefore, fine-tuned scenarios may provide a more accurate picture of regional processes and the resulting land-use change than the global estimates.

Here, we combined the regional land-use projections developed by Aguiar et al. [14] and Tejada et al.[15] and the climatic data from the CMIP5 multi-model ensemble [16] to investigate the probability of fire occurrence by the end of the 21st century (2071-2100) in the Brazilian and Bolivian Amazon. The specific questions are: (1) what is the effect of RCP 8.5 combined with a pessimistic land-use scenario, which considers the depletion of natural resources and significant social inequality, on the fire relative probability (FRP) in the Amazon biome within Brazil and Bolivia by the end of the century?; (2) How does this effect vary spatially in the study area? What are the most and least affected regions?

2. MATERIALS AND METHODS

The study region covers approximately 6,117,741 km^2 and encompasses the Amazon *"sensu latissimo"* limit [17] within Brazil and Bolivia borders, excluding the 0.25° grid-cells with less than 10% of forests in 2005 [14, 15].

We used agriculture, including both crops and pastures, as land-use predictor variable to model fire occurrence. The baseline values were calculated as the mean during 2005 to 2013 [14, 15], based on data from the Brazilian National Institute for Space Reasearch (INPE) and from the Noel Kempff Mercado Museum of Natural History (NKMMNH).

The approach for building and quantifying land-use scenario are described in detail in Aguiar et al. [14] and Tejada et al.[15]. Here, we used the "Fragmentation" scenario, which considers the depletion of natural resources and significant social inequality and is aligned with the IPCC Shared Socioeconomic Pathways (SSP) 3.

The climatic data was obtained from the CMIP5 multi-model ensemble dataset [16]. These are the results of 37 global model runs from several research centres worldwide (https://cmip.llnl.gov/cmip5/availability.html), which are available from the data archives of the Earth System Grid Federation (ESGF) data distribution portal (http://www.earthsystemgrid.org). We considered monthly mean output for September from historical simulations and future changes in climate variables using the RCP 8.5 scenario [10].

The climatic variables mean evaporation, maximum temperature and minimum precipitation were selected based on preliminary jackknife tests. The baseline values were calculated for the period between 2003 and 2015. All climate and land-use variables were resampled to a common 0.25° spatial-resolution grid.

To calibrate the model we used the afternoon hot pixel data detected by the MODIS sensor onboard the AQUA satellite, published online by the Centre for Weather Forecast and Climate Studies (CPTEC) /INPE [18]. The 0.25° grid cells which showed 13 or more hot pixels[19] in any September between 2003 and 2015 were considered to have suitable conditions for fire occurrence. From these grid cells, we randomly sampled 500 to be included as fire occurrence points.

The Maximum Entropy method (MaxEnt) [20, 21] is successfully applied as a tool for modelling species distribution using presence-only data, i.e. when absence records are not available. Satellite-based fire records indicate locations that have been burnt, but it is not possible to determine whether other areas were also suitable to burn at that time, making it appropriate to use a presence-only approach to model fire suitability [22].

The analysis was carried out using the MaxEnt software version 3.4.1 [23]. The software cloglog output was used, which can be interpreted as a normalized suitability surface with values ranging from zero to one, equivalent to a relative probability of fire occurrence. We used bootstrap resampling technique with 50 runs and maximum of 1000 iterations in each run to estimate the outputs mean and standard deviation, setting aside 30% of sample points for model testing. Other parameters were kept as the software default.

The AUC value, which indicates the probability that the model correctly ranks a random presence locality higher than a random background site [21], was used as a measure of model performance. If the AUC value is 0.5, the model is no better than random, while an area with a value close to 1 indicates an accurate model [21]. Models with AUC values above 0.75 are considered potentially useful [24]. Additionally, in order to evaluate the model performance, we used the calibrated model to projected the FRP for January of the baseline period and compared the resulting surface with the actual occurrence of hot pixels.

3. RESULTS

Mean training AUC of the fire model was 0.814 ± 0.009 and mean testing AUC was 0.800 ± 0.013. The comparison of the FRP surfaces modelled for September and simulated for January during the baseline indicates that the model accurately simulates the seasonal spatial variation in fire occurrence in this period (Figure 1). This is confirmed by the observation that the FRP values simulated for January in the grid cells where fire actually occurred during the baseline following the criteria we adopted (marked with black crosses in Figure 1B) was significantly higher than in grid cells where fire did not occur (Figure 2).

Most of the study region shows an increase in FRP by the end of the century under the modelled scenario (Figure 3). During September in the baseline, about 42% of the study region shows FRP $\geq$ 0.3, but this figure is expected to reach 64% in 2071-2100, which represents a 54% increase in the area with FRP $\geq$ 0.3. While over half (54%) of the grid cells show an increase in FRP $\geq$ 0.1, approximately 19% show a decrease of the same magnitude (Figure 3). Accordingly, 34% show 0.3 or larger increase in FRP, while only 10% show a similar decrease. The regions where a decrease in FRP is projected are located in the South and South-eastern of both Brazilian and Bolivian Amazon. The increase in FRP is widespread over the rest of the study area, except for the north-western Brazilian Amazon. Most areas under such increase are currently densely forested, including indigenous territories and protected areas.

4. DISCUSSION

The model was calibrated for September, the current peak of fire activity it the region, when fire is widespread in Bolivian Amazon and along the so-called deforestation arc in Brazil. Still, it correctly simulated the spatial pattern of fire occurrence in the study region in January, when fire activity is usually lower and concentrates in the north and north-eastern Brazilian Amazon [18]. The AUC values also indicate satisfactory model performance.

A decrease in FRP is projected for the deforestation arc in the Brazilian Amazon, as well as in a region of Bolivia where intense deforestation is expected under the modelled land-use scenario [15]. This can the related to the advance of the deforestation in already depleted landscapes, leading to a reduction of the biomass available to burn. The lower change in FRP in the north-western Brazilian Amazon is probably related to the relatively low change in precipitation and evaporation (data not shown) combined with sparse land use and therefore scarcity of ignition sources in this region.

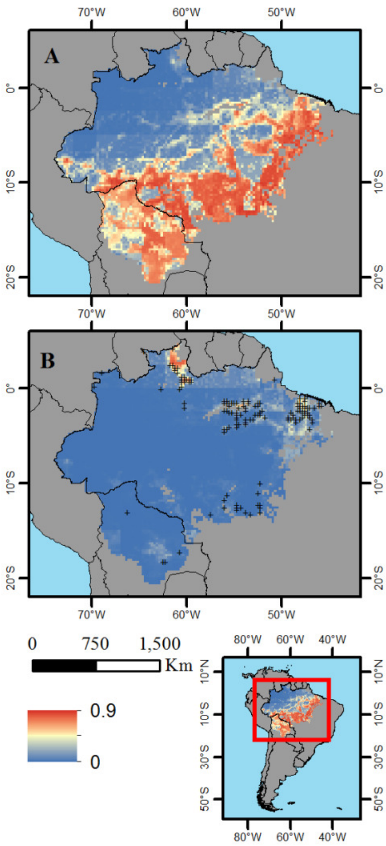

Figure 1: Fire relative probability (FRP) surfaces in the Brazilian and Bolivian Amazon simulated for (A) September and (B) January of the baseline period (2003 - 2015). Black crosses indicate grid cells where 13 or more MODIS hot pixels were detected in at least one month (January) during this period.

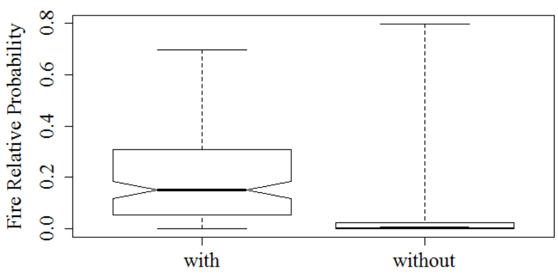

Figure 2: Distribution of Fire relative probability (FRP) values in grid cells where fire actually occurred in January during the baseline following the adopted criteria (see Methods section) ("with") and in grid cells where fire did not occur ("without"). The lower and the upper limits of the box represent the first and third quartiles, respectively, the horizontal line within the box represents the median and the vertical bars the data range.

On the other hand, the intense increase in FRP in the northern, central and western Brazilian Amazon under the modelled scenario is expected to affect currently protected areas, including the inhabited ones, and indigenous

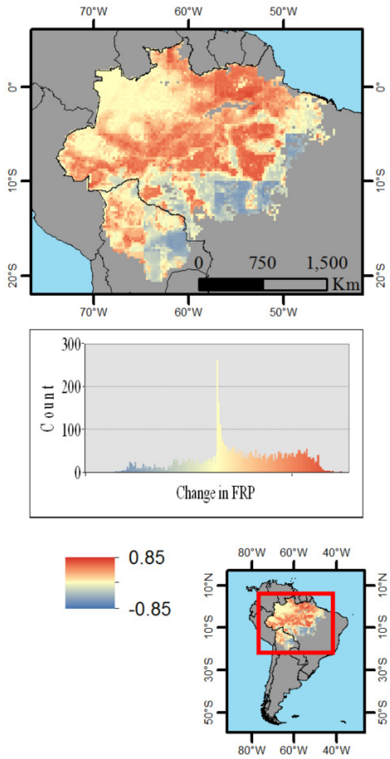

Figure 3. Absolute change in Fire Relative Probability (FRP; future minus baseline) by the end (2071-2100) of the 21st century in the Brazilian and Bolivian Amazon projected considering a pessimistic scenario (Fragmentation land-use and RCP 8.5 scenarios).

territories, threatening its biodiversity as well as traditional populations and their cultural practices through the depletion of the natural resources they depend upon [25]. Furthermore, such increase in FRP is expected to have striking negative impacts on precipitation and the dynamics of atmospheric circulation [26], on human health [27], and on forest structure, carbon stocks and emissions [4, 28].

The spatial pattern of fire increase we found is similar to the one reported under the RCP 8.5 climate and land-use scenarios by Le Page et al.[11], although differences are evident in the Roraima state, in the Brazilian deforestation arc and in Bolivia. Such divergences can be due to the different land-use projections, the climate models included or differences in model parameterization.

We acknowledge that projections of fire probability based on statistical models are conservative given that this modelling approach do not incorporate future self-amplified vegetation-fire-climate feedbacks that could increase ecosystems flammability [29].

5. CONCLUSIONS

We conclude that pessimistic land-use and climate change scenarios combined are expected to increase fire occurrence probability over more than half of the Amazon biome located within Brazil and Bolivia, threatening its inhabitants health, livelihood and important ecosystems services, including the regions' biodiversity and carbon stocks.

Further studies should investigate other scenarios and the relative contribution of land-use and climate variables in each of them, in order to guide efficient mitigation strategies.

6. ACKNOWLEDGEMENTS

This work was supported by CAPES, through a postdoctoral fellowship provided to M.G.Fonseca, by CNPq, through a finantial support to L.E.O.C Aragão and L.O. Anderson (grant numbers 305054/2016-3 and 309247/2016-0), and FAPESP (grant 16/02018-2).

7. REFERENCES

[1] Flannigan, M. D.; Krawchuk, M. A.; De Groot, W. J.; Wotton, B. M.; and Gowman, L. M., "Implications of changing climate for global wildland fire," *International Journal of Wildland Fire*. 2009.

[2] Barlow, J. *et al.*, "Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation," *Nature*, 2016.

[3] Knorr, W.; Arneth, A.; and Jiang, L., "Demographic controls of future global fire risk," *Nat. Clim. Chang.*, 2016.

[4] Aragão, L. E. O. C. *et al.*, "21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions," *Nat. Commun.*, 2018.

[5] Silvestrini, R. A.; Soares-Filho, B. S.; Nepstad, D.; Coe, M.; Rodrigues, H.; and Assunção, R., "Simulating fire regimes in the Amazon in response to climate change and deforestation," *Ecol. Appl.*, vol. 21, no. 5, pp. 1573–90, Jul. 2011.

[6] IPCC, "Emissions Scenarios," 2000.

[7] Devisscher, T.; Anderson, L. O.; Aragão, L. E. O. C.; Galván, L.; and Malhi, Y., "Increased wildfire risk driven by climate and development interactions in the Bolivian Chiquitania, Southern Amazonia," *PLoS One*, vol. 11, no. 9, pp. 1–29, 2016.

[8] Golding, N. and Betts, R., "Fire risk in Amazonia due to climate change in the HadCM3 climate model: Potential interactions with deforestation," *Global Biogeochem. Cycles*, vol. 22, no. 4, pp. 1–10, 2008.

[9] Justino, F. *et al.*, "Greenhouse gas induced changes in the fire risk in Brazil in ECHAM5/MPI-OM coupled climate model," *Clim. Change*, 2011.

[10] IPCC and Pachauri, R. K., *Climate Change 2014 Synthesis Report*, no. February. 2014.

[11] Le Page, Y. *et al.*, "Synergy between land use and climate change increases future fire risk in Amazon forests," *Earth Syst. Dyn.*, 2017.

[12] Hurtt, G. C. *et al.*, "Harmonization of land-use scenarios for the period 1500-2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands," *Clim. Change*, 2011.

[13] Guimberteau, M. *et al.*, "Impacts of future deforestation and climate change on the hydrology of the Amazon Basin: A multi-model analysis with a new set of land-cover change scenarios," *Hydrol. Earth Syst. Sci.*, 2017.

[14] Aguiar, A. P. D. *et al.*, "Land use change emission scenarios: Anticipating a forest transition process in the Brazilian Amazon," *Glob. Chang. Biol.*, 2016.

[15] Tejada, G. *et al.*, "Deforestation scenarios for the Bolivian lowlands," *Environ. Res.*, 2016.

[16] Taylor, K. E.; Stouffer, R. J.; and Meehl, G. A., "An overview of CMIP5 and the experiment design," *Bulletin of the American Meteorological Society*. 2012.

[17] Eva, H. *et al.*, "A proposal for defining the geographical boundaries of Amazonia," 2005.

[18] INPE, "Programa Queimadas," 2017. [Online]. Available: http://www.inpe.br/queimadas/portal.

[19] Fonseca, M. G.; Aragão, L. E. O. C.; Lima, A.; Shimabukuro, Y. E.; Arai, E.; and Anderson, L. O., "Modelling fire probability in the Brazilian Amazon using the maximum entropy method," pp. 955–969, 2016.

[20] Phillips, S. J.; Dudík, M.; and Schapire, R. E., "A maximum entropy approach to species distribution modeling," *Proceedings, Twenty-First Int. Conf. Mach. Learn. ICML 2004*, pp. 655–662, 2004.

[21] Phillips, S. J.; Anderson, R. P.; and Schapire, R. E., "Maximum entropy modeling of species geographic distributions," vol. 190, pp. 231–259, 2006.

[22] Peters, M. P.; Iverson, L. R.; Matthews, S. N.; and Prasad, A. M., "Wildfire hazard mapping: Exploring site conditions in eastern US wildland-urban interfaces," *Int. J. Wildl. Fire*, vol. 22, no. 5, pp. 567–578, 2013.

[23] Phillips, S. J.; Anderson, R. P.; Dudík, M.; Schapire, R. E.; and Blair, M. E., "Opening the black box: an open-source release of Maxent," *Ecography (Cop.).*, vol. 40, no. 7, pp. 887–893, 2017.

[24] Elith, J., "Quantitative methods for modeling species habitat: comparative performance and an application to Australian plants.," in *Quantitative methods for conservation biology*, Ferson S; Burgman M, Ed. New York: Springer-Verlag, 2002, pp. 39–58.

[25] Schwartzman, S. *et al.*, "The natural and social history of the indigenous lands and protected areas corridor of the Xingu River basin The natural and social history of the indigenous lands and protected areas corridor of the Xingu River basin," *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, vol. 368, pp. 1–12, 2013.

[26] Zhang, Y. *et al.*, "Impact of biomass burning aerosol on the monsoon circulation transition over Amazonia," *Geophys. Res. Lett.*, vol. 36, no. 10, pp. 1–6, 2009.

[27] Smith, L. T.; Aragão, L. E. O. C.; Sabel, C. E.; and Nakaya, T., "Drought impacts on children's respiratory health in the Brazilian Amazon," *Sci. Rep.*, vol. 4, pp. 1–8, 2014.

[28] Anderson, L. O. *et al.*, "Disentangling the contribution of multiple land covers to fire-mediated carbon emissions in Amazonia during the 2010 drought," *Global Biogeochem. Cycles*, 2015.

[29] Krawchuk, M. A.; Moritz, M. A.; Parisien, M. A.; Van Dorn, J.; and Hayhoe, K., "Global pyrogeography: The current and future distribution of wildfire," *PLoS One*, 2009.