FIRE EFFECTS ON WATER AND CARBON FLUXES IN AMAZONIA

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ABSTRACT

The ongoing deforestation process in Amazonia has led to intensified forest fires in the region, after more than a decade of effective forest conservation policy. This study aims to investigate the recovery of two mature sub-montane ombrophile Amazonian forests affected by fire in terms of energy, water and carbon fluxes utilizing remote sensing (MODIS) and climate reanalysis data (GLDAS). These two forest plots, mainly composed of Manilkara spp. (Maçaranduba), Protium spp. (Breu) (~30 m), Bertholletia excelsa (Castanheira) and Dinizia excelsa Ducke (Angelim-Pedra) (~50 m), were subject to fire on the same day, September 12, 2010. The fire significantly increased land surface temperature (0.8 °C) and air temperature (1.2 °C) in the forests over a three year interval. However, the forests showed an ability to recover their original states in terms of coupling between the carbon and water cycles comparing the three-year periods before and after the fires.

Keywords — Amazon, deforestation, fire, water, carbon.

1. INTRODUCTION

Understanding the influence of fire on the carbon and water cycling over terrestrial ecosystems is needed for climate change adaptation and mitigation [1],[2],[3],[4],[5]. The Amazon region has the largest rainforest in the world; however, the anthropogenic pressure and associated land cover changes have led to large-scale forest losses and fires [6],[7], which have recently intensified, particularly in Brazil, after more than a decade of effective forest conservation policy [8]. In 2020, the deforestation in the Brazilian Amazon has reached its greatest rate in the decade (11,088 km^2), which represents an increase of 47% and 9.5% compared to 2018 and 2019, respectively.

Typically, the deforestation and agricultural conversion processes employ fire for final clearing and land preparation. Thus, fire is part of the deforestation process, especially in the "Arc of Deforestation", which concentrates the majority of burned areas in the Brazilian Amazon [9]. Fires associated with the deforestation process are increasing in the Brazilian Amazon, where fire ignitions in September 2019 were 50% higher than those in the 2018, in spite of similar climate conditions, as a result of policies favoring Amazon forest conversion to agriculture [8],[10],[11].

The consequences of Amazon deforestation and related fires are profound, though they are yet to be fully understood. Amazon deforestation and fires cause decreases in biodiversity, reduction in forest resilience to climate change, impacts on land-use and land-cover (LULC) dynamics, changes in hydrological dynamics, enhancement of drought impacts, and risks of savannization [2],[12],[13],[14]. As stated in several recent studies, forest fires are occurring throughout the Amazon region at an unprecedented rate, affecting biogeochemical cycles and ecosystem structure [8],[15]. The fires can also cause changes in the local and regional climate, and specifically in surface energy fluxes [16], as recent research in the Amazon has shown that aerosols can be responsible for changing the amount of solar radiation available at the surface and the partitioning between direct and diffuse radiation [17]. Alterations of surface energy fluxes are essential to predicting impacts on local-through-global scale atmospheric patterns and processes, which feedback on vegetation change [18].

Remote sensing data provide high spatial and temporal coverage of the land surface [20]. The use of orbital sensors to estimate water and carbon fluxes between the surface and atmosphere is performed using models that consider information obtained directly from the satellite images as inputs, such as reflectance and land surface temperature (LST). Currently, some of the most important global products based on satellite observations are derived from MODIS Terra and Aqua sensors. Examples of products derived from

MODIS are related to surface albedo, LST, vegetation indices, land-cover and other variables. More specifically, regarding water and carbon fluxes, we highlight the evapotranspiration (ET) (MOD16) [20], and gross primary productivity (GPP) (MOD17) [21] products.

Analysis of the time course of fire impacts on LST, air temperature (T_{air}), daily net radiation (Rn_{24h}), ET, and GPP is required for accurate assessment of changes in the forest-atmosphere interactions. Moreover, measurements must also account for natural variations associated with vegetation phenology, and generally direct and indirect effects of annual and seasonal time scales of environmental variation including in temperature, rainfall, aerosols, incoming solar radiation, and water and carbon fluxes [13],[17],[22],[23]. These properties can help better understand fire impacts and develop more accurate predictions for recovery from this disturbance.

This study aims to investigate the recovery of two mature Amazonian forests affected by fire in September 2010 in terms of radiation, water and carbon fluxes utilizing remote sensing and climate reanalysis data. The study period comprises 6 years: three years prior to the fire occurrence (September 2007-August 2010) and three years post fire (October 2010-September 2013). We utilized data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the Terra satellite and Global Land Data Assimilation System (GLDAS) reanalysis products.

2. MATERIAL AND METHODS

The study area is located in the municipality of Cumaru do Norte, state of Para (PA), Brazil, in the eastern part of the Amazon basin. The Kayapo Badjonkore indigenous lands are located in the western part of Cumaru do Norte, acting as "shields" against deforestation in the region. For this reason, in the western part there is a predominance of mature tropical forests. In the eastern part there is a predominance of different land-cover types, such as secondary succession forest, pasture and soybean. This is related to the strong agricultural expansion in the state of Tocantins (TO) and in the region along the Araguaia river (which separates the states of TO and PA) [24],[25]. It is important to highlight that Cumaru do Norte is located within the "Arc of Fire", a region that encompasses the states of PA, TO, Mato Grosso (MT) and Maranhao (MA) that is so named because it has the highest annual fire ignitions in the Amazon over the pass two decades [26],[27].

Two forest plots were used in this study. The plots were identified from the study developed by Lima et al. [28], where the authors mapped burned areas in the state of PA, Brazil, in 2010. The method for determining the burned area is based on shade fraction images derived from a linear spectral mixture model applied to bands 1, 2 and 6 of the MODIS daily surface reflectance product (MOD09GA) [29]. Plot 1 (8.69° S, 8.82° S and 51.31° W, 51.44° W) has an approximate area of 122.1 km^2, while plot 2 (8.56° S, 8.61° S and 51.29° W, 51.48° W) has an approximate area of 100.5 km^2. Both plots were subject to fire on the same day, on September 12, 2010.

Remote sensing data were obtained from the MODIS sensor aboard the Terra satellite. We used the following products: MOD09A1, MOD11A2, MOD16A2 and MOD17A2 (Version 5). MO09A1 provided surface reflectance in an 8-day composition at 500 m resolution; MOD11A2 provided land surface temperature (LST) in an 8-day composite at 1 km resolution; and MOD16A2 and M0D17A2 provided evapotranspiration (ET) and gross primary productivity (GPP), respectively, in a monthly composite at 1 km resolution. The data corresponded to the h12v09 tile and were obtained over a 6-year period (2007-2013).

3. RESULTS

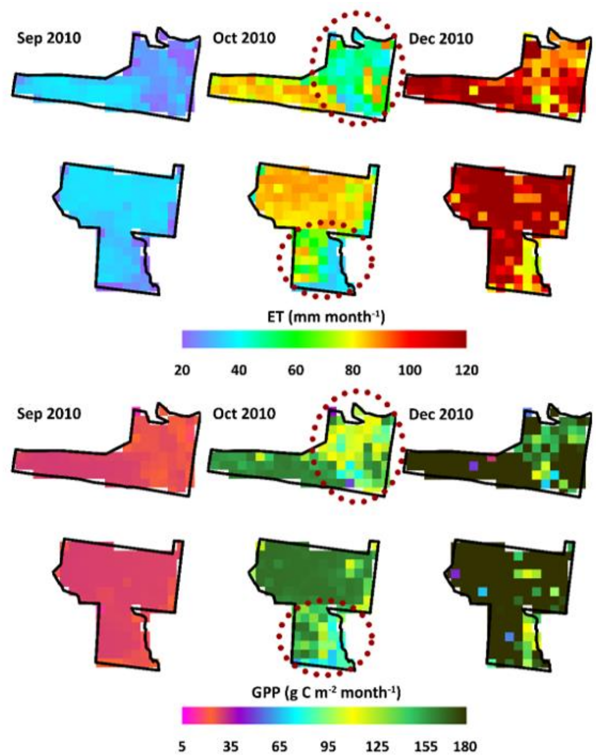

Figure 1. Spatial distribution of evapotranspiration (ET) (mm $month^{-1}$) and gross primary productivity (GPP) (g C m^{-2} $month^{-1}$) in the month of the fire (September 2010), one month after the fire (October 2010), and three months after the fire (December 2010).

Figure 1 illustrates the different variables for the month of the fire (September 2010), one month after the fire (October 2010) and three months after the fire (December 2010). Analyzing the spatial pattern of the different variables, we observe that the Southern part of plot 1 and the eastern part of plot 2 were the most affected areas by the fire (red dashed circles over the October images in Figure 1). The areas most affected by the fire showed lower values of ET and GPP.

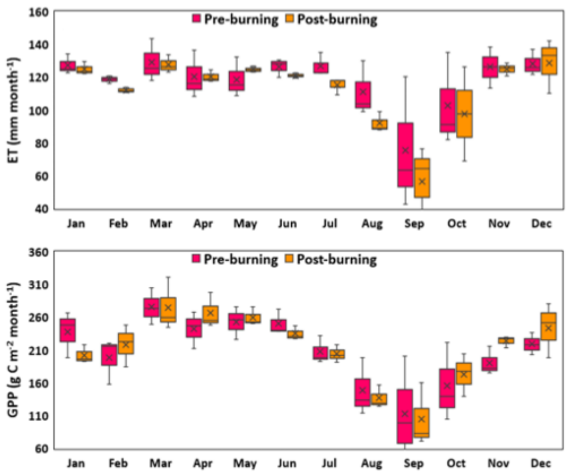

Figure 2. Evapotranspiration (ET) (mm month^{-1}), (f) gross primary productivity (GPP) (g C m^{-2} month^{-1}) for the entire period pre-burning (September 2007-August 2010) and post-burning (October 2010-September 2013), considering the average between plots 1 and 2.

Figure 2 shows that the fire caused an immediate reduction of ~31% in ET (p-value < 0.05), taking into consideration the months of August (99.2 mm month^{-1}) and October (68.9 mm month^{-1}) of 2010. One year after burning, the average ET was ~11% lower in comparison to the three years pre-burning annual average (p-value < 0.05). Comparing the annual average ET two and three years after burning with the annual average three years prior burning, we observe differences of ~6% and ~5%, respectively (p-value < 0.05). The forest plots were able to recover the evaporative fluxes on a yearly rate of 21%. We note that the average ET three years prior and after burning were not significantly different, highlighting the resilience of the forests analyzed in recovering their original water fluxes.

GPP in the month before burning (August 2010) was 133.7 g C m^{-2} month^{-1}, increasing to 138.9 g C m^{-2} month^{-1} in the subsequent month (October 2010), representing a variation of ~4%. One year after burning year, annual average GPP decreased ~6% when comparing to the pre-burning annual average (p-value < 0.05), which could relate to lingering lower canopy layer impacts. Here, we note that the lower canopy layers are usually the most affected areas during burning events in the Amazon forest [30]. The averages two and three years prior and after burning did not differ statistically.

4. DISCUSSION

Understanding how recurrent fire events in the Amazon impact the fluxes of energy, water and carbon is essential to understand how different forest-atmosphere feedbacks may exacerbate the long-term expected warmer and drier conditions in the region [2],[14]. Our findings suggest that the mature forests analyzed were able to recover their original state in terms of water (ET) and carbon fluxes (GPP) within three years. Although we did not specifically analyze the levels of severity within the plots, we hypothesize that the fires occurred in these forests were not likely severe enough to kill the upper parts of the canopy, thus being mainly restricted to its lower parts and/or understory. Also, no significant seasonal differences were found for these fluxes considering the periods prior to burning and post burning. Here, we note that a high severity fire can alter the canopy characteristics more strongly than a low severity fire, which means that distinct disturbance regimes can potentially affect the carbon and water cycling after the fire in forested areas quite differently [31]. Here, we highlight the importance of considering fire severity in future studies, which can provide a better idea of how different degrees of fire severity affect forest recovery processes in terms of structural damages, biomass, and species composition changes [32],[33].

It is important to note that once the forests are burned, they are more likely to be subjected to future fires, and this recurrence may potentially kill and eradicate trees from the landscape [32]. This can also lead to other long-term impacts, such as an increased forest degradation in the region and the risk of savannization in Amazonia, as recently discussed by Stark et al. [14]. Within this context, our approach and, consequently, the results obtained here will help improve the understanding of how forest fires in the Amazon and impact land-atmosphere coupling considering different spatial and temporal scales.

5. CONCLUSIONS

In this study, we assessed the legacy effects following fire on surface energy, water and carbon fluxes in mature Amazonian forests based on high temporal and spatial resolution remote sensing and climate reanalysis data. These datasets allowed us to clearly identify the areas most affected by burning in both forest plots analyzed. The areas most affected by the fire showed lower values of evapotranspiration (ET) and gross primary productivity (GPP). We believe that our findings will help to improve fundamental, process-level understanding of expected legacy effects of forest fires in the Amazon and how they impact land-atmosphere interactions in the region.

8. REFERENCES

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