RESEARCH ARTICLE

Persistent fire effect on forest dynamics and species composition of an old-growth tropical forest

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Abstract

Aim of study: To assess structure, recruitment and mortality rates of tree species over almost three decades, 14 years before and 15 years after a forest fire.

Materials and methods: All trees ≥ 5 cm in DBH were identified and measured in 12 permanent plots (50 m x 50 m), in 1983, 1987, 1989, 1995, 2008, and 2012 of a dense ombrophilous forest in Eastern Amazon, Brazil. The analyses were carried out including all sampled species and their ecological groups: shade-tolerant, light-demanding, and pioneer species. Treatments were compared through a Linear Mixed Effect Model.

Main results: The 15-year post-fire period is not enough for the old-growth tropical forest to recover its pre-fire conditions of recruitment and mortality rates. The post-fire recruitment and mortality rates increased, mainly the recruitment of pioneer species (p-value < 0.05).

Research highlights: In a period of 15 years after the occurrence of a surface fire, the old-growth tropical forest still has high recruitment rates of shade-tolerant and light-demanding species and high incidence of pioneer species, confirming the persistent fire effects on forest dynamics and species composition in this ecosystem.

Keywords: pioneer tree species; species dynamics; forest resilience; Tapajós National Forest; Amazonian forests

Abbreviations used: DBH (diameter at 1.3 m from the ground); D (density); G (basal area); EG (ecological group); ST (shade-tolerant); LD (light-demanding); Pi (pioneer); Ni (non-identified ecological group); MR (mortality rates); RR (recruitment rates); LMM (Linear Mixed Effect Model).

Introduction

High humidity and rainfall are climate features of the tropical forests that prevent natural fires. However, the increase of economic activities that require land use shifts from forests to crops and pastures have resulted in greater vulnerability of natural ecosystems to fires (Fernandes *et al.*, 2011). In the Amazon, anthropogenic fires have become increasingly recurrent, which represents a potential threat to the biome's rich biodiversity (Barlow *et al.*, 2016).

In this century, the Amazon will probably face increases in average temperatures, as well as more frequent and spread drought events (Betts *et al.*, 2016). The unsustainable tropical timber exploitation, the persistent use of fire in agriculture, and the establishment of large-scale infrastructure projects (Berenguer *et al.*, 2014) will probably turn primary tropical forests in the Brazilian Amazon in relics. Studies on the post-fire regeneration and resilience of these old-growth forests become essential to understand their dynamics and long-term responses (d'Oliveira *et al.*, 2011). Indeed, the knowledge of forest dynamics,

succession, and biological diversity make management, conservation, and restoration actions of these environments more efficient.

After disturbances, recruitment rates of tree species tend to vary according to the disturbance severity (Amaral *et al.*, 2019), where mortality is highest in the first years after the fire - 1 to 3 years (Barlow *et al.*, 2003; Vasconcelos *et al.*, 2013) and normally concentrated in smaller trees - 10-30 cm in diameter (Cochrane & Schulze, 1999; Barlow & Peres, 2004) belonging to species with high densities of individuals (Slik *et al.*, 2002). Disturbances also promote pioneer and light-demanding species that rapidly colonize and establish themselves in altered forests (Monteiro *et al.*, 2004; Amaral *et al.*, 2019).

Depending on the disturbance severity, such events can promote changes in floristic composition (Barlow & Peres, 2008) and structure of the forests. So, in terms of fires, what is the impact of such disturbance over a fire sensitive tropical forest? How long does it take for an old-growth tropical forest to recover its original tree species composition after a fire?

This study tackled the effects of fire on recruitment and mortality rates of tree species, considering the ecological groups of tree species, with data obtained from permanent plots established in a tropical forest, defined as Dense Ombrophilous Forest. Plots were monitored during 29 years (1983-2012), 14 years before and 15 years after a forest fire, in the Tapajós National Forest, Eastern Amazon, Brazil.

The objective of this study was to answer these questions by testing the following hypotheses: (a) a 15-year post-fire period is not enough for the forest to recover its pre-fire tree species composition; and (b) pioneer and light-demanding species have faster dynamics (increased recruitment and mortality rates) in the post-fire period.

Material and methods

Study area

The study was carried out in the Tapajós National Forest, a conservation unit that comprises nearly 527,000 hectares of tropical forest. It is located in the west of Pará state, Brazil (Andrade *et al.*, 2020). The experiment is located in a plateau region (3° 18′ S/ 3° 19′ S, 54° 56′ W/ 54° 57′ W), near km 114 of the BR-163 highway, and represented, up to 1983 (the year the site was selected), a Dense Ombrophilous Forest, also known as *terra firme* forest, typical of the region, characterized by a canopy dominated by large-sized (DBH > 60 cm) and few emergent trees (Carvalho, 2002).

The climate, based on data collected from the weather station of Belterra municipality (the closest station of the study, approximately 30 km in a straight line), is hot and humid, with an average annual temperature of 26 ºC, average relative humidity of 87.3% and average annual rainfall of 1,780 mm (INMET, 2018). The relief is flat to slightly undulated, with an average altitude of 175 m above sea level. The predominant soil type is yellow dystrophic latosol with texture ranging from medium to very clayey (Rodrigues *et al.*, 2001).

Data collection

A total of 12 permanent sample plots of 0.25 hectare each (50 m x 50 m) were randomly installed, in 1983, in 36 hectares of old-growth forest to monitor the dynamics of the floristic composition and structure of an unmanaged natural forest (Fig. S1 [suppl.]). The representativeness and precision of results in relation to the number and dimensions of these plots were tested by Castro *et al.* (2019), who considered them sufficient to generate results with high precision level. Other important studies have been carried out in this area, such as those reported by De Avila *et al.* (2018; 2019) and Andrade *et al.* (2020). All trees with a diameter at 1.3 m from the ground (DBH) ≥ 5 cm were identified, numbered with aluminum tags, and measured in 1983, 1987, 1989, 1995, 2008, and 2012.

Trees were identified in the forest through their vernacular or scientific name by tree spotters and those non-identified had botanical materials collected for further identification in the herbarium IAN of Embrapa Eastern Amazon, in Belém, Pará, Brazil. Successive measurements and other studies previously conducted in the study area (*e.g.*, De Avila *et al.*, 2018) have been important to improve the list of species and reduce mistakes in species identification. Species were classified according to APG IV (2016), and their names were standardized according to the classification of REFLORA (2018).

Sampling data

Data from permanent plots were set up through the Tropical Forest Monitoring (MFT) software, produced by Embrapa Eastern Amazon, and subsequently exported to electronic spreadsheets for analysis. In the first measurement (1983), 3,360 trees belonging to 300 species of 61 botanical families were recorded in the 12 permanent plots – equivalent to 1,120 trees ha^{-1} and a basal area of 29.98 m^2 ha^{-1} (Coefficient of Variation = 18.01%; Relative Sampling Error = 11.44%).

Identification of plots hit by the fire

From December 9th to 13th, 1997, an accidental fire burnt a 1200-m strip of the Tapajós National Forest along

km 114 of the BR-163 highway. The surface fire spread through some of the installed permanent plots of the experiment. After two days of working, Embrapa staff was able to extinguish the fire and avoid larger forest losses (Andrade *et al.*, 2020). In the control area, five of the 12 plots were burnt (Fig. S1 [suppl.]). The fire did not affect the survival of large trees and has been considered, in other studies carried out in the same experimental area, as a surface fire (Andrade *et al.*, 2019; 2020).

Data analysis

Forest structure was analyzed using tree density (D) in numbers of individuals ha^{-1}, basal area (G) in m² ha^{-1}, and the distribution of trees and basal area in diameter classes, considering a 10 cm interval between each DBH class. Small DBH interval classes were used to detect the maximum details in dynamics, considering tree size, according to Carvalho (2002).

Inventoried species were classified in ecological groups (EG) divided in shade-tolerant (ST), light-demanding (LD), and pioneer (Pi) species. Species with no ecological groups defined due to lack or inconsistency of information were assigned as "Ni" (non-identified ecological group). The criteria used to allocate species in ecological groups were based on field observations and literature review.

New individuals ≥ 5 cm DBH (the minimum diameter for measurements) were recorded as "recruited", dead or not found trees ≥ 5 cm DBH were recorded as dead, and alive trees inventoried in the first and end measurement of time assessed were recorded as survivor trees for calculating recruitment and mortality rates. Percentage of mortality by species was calculated taking into account the number of dead trees by each species in relation to the total number of dead trees during each period over all 12 permanent plots. The same procedure was used to calculate the percentage of recruitment in each species population.

Mortality rates (MR) through time were calculated according to Condit *et al.* (1999):

$$MR = (\ln n_0 - \ln St)/t$$

where ln = Neperian log; n_0 = population size at the initial of time assessed; St = number of survivor trees at the end of time assessed; t = time interval, between measurements, in years.

Recruitment rates (RR) through time were calculated according to Condit *et al.* (1999):

$$RR = (\ln nt - \ln St)/t$$

where nt = population size at the end of time assessed; St = number of survivor trees at the end of time assessed;

ln = Neperian log; t = time interval, between measurements, in year.

Since different lengths of inventory intervals interfere in the computation of demographic rates (MR and RR), the estimates were standardized using the correction factor of Lewis *et al.* (2004):

$$rcorr = r * t^{0.08}$$

where r = Recruitment rate or Mortality rate uncorrected; t = time interval, between measurements, in year. Lewis *et al.* (2004) proposed this correction factor by using the mean rate of decline, moving the estimate to a standardized interval of one year (De Avila *et al.*, 2017).

The variables G, MR, and RR of plots hit by fire were compared with data from previous measurements and non-burnt plots. Non-burnt plots worked as control (T0), which would be expected for a non-burnt primary forest (Sit & Taylor, 1998). The wildfire is a not planned event in the original experimental design. Because of this, the measurements, ecological groups, and treatments were compared through a Linear Mixed Effect Model (LMM) to account for the unbalanced design (Pinheiro & Bates, 2000). The treatments (T0 and T1), Ecological Groups (ST, LD, Pi, and Ni), and time (measurements – G variable - or periods - MR and RR) were considered as a fixed effect and the measurement units (permanent plots) were inserted as a random effect in the model. In the analyses in which significant differences were detected between independent variables (probability level α = 0.05), the averages were compared by the pairwise post-hoc Sidak test (probability level α = 0.05). Statistical analyzes were performed in the Software IBM SPSS 20, trial version.

Results

Mortality and recruitment rates were higher after fire in the burnt area (Fig. S2A [suppl.] and S2B [suppl.]; see Andrade *et al.* 2019), and recruitment rates of pioneer species increased in the post-fire period, indicating a divergent pattern observed in the non-burnt area ($F_{8.21}$ = 12.30; P < 0.01). In the post-fire period, the population of pioneer species increased in burnt area (Fig. S3 [suppl.]).

During the monitoring period, the basal area recorded for pioneers, in the burnt area, increased significantly (Fig. S2C [suppl.] and S2D [suppl.]; $F_{1764.20}$ = 17.83; *p*-value < 0.05). In 1995 in the non-burnt area, about 1.4% (0.45 m² ha^{-1}) of the basal area was composed by pioneer species, while in the burnt area this percentage was 5.72% (1.67 m² ha^{-1}). After the fire, in the non-burnt area, the pioneer species continued to represent small fractions of the total basal area, 1.14% of the total (0.40 m² ha^{-1}) in 2008 and 1.23% (0.43 m² ha^{-1}) in 2012. However, in the burnt area, pioneer species represented 8.79% (2.70 m² ha^{-1}) and 7.88% (2.42

m² ha⁻¹) of the basal area in 2008 and in 2012, respectively. In both areas, shade-tolerant and light-demanding species together represented approximately 90% of the basal area (Fig. S2C [suppl.] and S2D [suppl.]).

In both areas, *Inga* spp., *Duguetia echinophora*, *Rinorea guianensis* and *Protium apiculatum* presented the highest percentage of mortality during 29 years of monitoring. (Table S1 [suppl.]). Species with highest mortality had also high recruitment of new trees, especially *Rinorea guianensis* and *Protium apiculatum*, which maintained elevated density of trees in both areas, before and after fire. In addition, in the burnt area, 15 years after fire (2012), four pioneer species and three light-demanding appeared among the 10 species with highest recruitment rates, which was not observed before the fire in both areas (Table S2 [suppl.]).

Discussion

Our results did indicate small changes in forest structure after fire (increase in the basal area of pioneers and in the percentage of young trees), and helped to understand the effect of surface fires over a primary tropical forest. Recruitment rates, mainly of pioneer species, increased and divergent mortality patterns were found due to fire, especially for shade-tolerant species.

Numata *et al.* (2017) observed a higher presence of shade-tolerant species with low frequency of pioneer species in the dynamics of mortality and recruitment in nonburnt forests of Acre state, Brazil, Western Amazon. In the state of Roraima, Brazil, Northern Amazon, 12 years after a fire, Martins *et al.* (2012) reported that biomass stocks of a dense ombrophilous forest had recovered to pre-fire levels, but differences in floristic composition were still present. The fact the pioneer species were abundant in burnet areas and very scarce in the unburned areas suggest that the density values of pioneer species are an indication of the degree of fire severity (Barlow & Peres, 2004; Amaral *et al.*, 2019).

In Acre, Numata *et al.* (2017) reported that nine years after fire in a natural forest, the basal area and density of trees ≥ 10 cm in DBH attained similar values to those of a non-burnt forest. This suggests that, after fire, the high recruitment of tree species, mainly pioneers with high growth rates, directly impacts the recovery of plant biomass in a short time. Shade-tolerant and light-demanding species had great influence on the dynamics of both areas, mainly because most of the inventoried species belonged to these groups. In tropical forests, however, high numbers of individuals belonging to pioneer species is expected after disturbances (Numata *et al.*, 2017; Amaral *et al.*, 2019). Pioneer species tend to be dominant in the understory of forests severely affected by fire (Cochrane & Schulze, 1999), where most of them are often short-lived (Carvalho, 2002).

The hypothesis that the forest post-fire conditions are favorable to the establishment of both pioneer and light-demanding species was corroborated by the results found in this study. Such species increased their basal area. The increase in abundance of pioneer species in the natural regeneration of the Amazonian forest disturbed by fire, with consequent increase in competition with non-pioneer species, was expected. Such fire effects were like those observed in forests after selective logging, with consequent increase in recruitment rates, mainly of fast-growing pioneer species (Amaral *et al.*, 2019).

Barlow & Peres (2004) and Cochrane & Schulze (1999) also observed that mortality was concentrated mainly in small and medium-size trees of shade-tolerant species. Although old-growth Amazonian forests have high concentration of smaller diameter trees, where the dynamics of mortality and recruitment is more intense (Barlow & Peres, 2004; Cochrane & Schulze, 1999), the death of large trees results in strong effects on the availability of light, water, and nutrients in the forest, enhancing the recruitment of new trees (De Avila *et al.*, 2018).

In this study, the higher post-fire recruitment rates (Fig. S2D [suppl.]) were not associated with gaps due to the death of large trees (DBH > 60 cm) as demonstrated in Andrade *et al.* (2019), but mainly due to the loss of small and medium-size trees. Probably, seedbeds were activated, and regrowth increased after fire, which intensified competition and dynamics among small trees, but we did not measure such variables.

Immediately after fire it is expected that numbers of species and individuals belonging to pioneer species increase due to more intense solar radiation attaining the forest floor. In this study, the post-fire 15-year period was not enough for tree density and basal area of the pioneer species to be reduced to pre-fire levels, but it was enough to stabilize mortality rates. The current level of forest recovery, with high recruitment rates of both shade-tolerant and light-demanding species, confirms that the intensity of the superficial fire was not enough to jeopardize the forest's resilience as well as the restoration of these species populations. The results of this study showed that old-growth tropical forests can be resilient to surface fire, but fire effects can persist for decades in species composition. It is evident, however, that mortality rates and changes in forest are strongly linked to the disturbance severity and frequency (Barlow & Peres, 2004; De Avila et. al. 2018; Amaral *et al.*, 2019; Andrade *et al.* 2020).

Conclusions

During the post-fire monitoring period, changes in dynamics (mortality and recruitment rates) occurred. Our results showed increase in recruitment rates, mainly of

pioneer species, and divergent patterns of mortality rates in the burnt area, with higher rates in shade-tolerant species.

The post-fire 15-year period was not enough for tree density and basal area of the pioneer species to be reduced to pre-fire levels, but it was enough to stabilize mortality rates. The current level of forest recovery, with high recruitment rates of shade-tolerant and light-demanding species, confirmed that the intensity of the surface fire was not enough to undermine forest's resilience and the population recovery of the species present in the area before fire.

Acknowledgments

References

Amaral MRM, Lima AJN, Higuchi FG, Santos JS, Higuchi N, 2019. Dynamics of Tropical Forest twenty-five years after experimental logging in Central Amazon Mature Forest. Forests, 10: 89. https://doi.org/10.3390/f10020089

Andrade DFC, Gama JRV, Ruschel AR, Melo LO, De Avila AL, Carvalho JOP, 2019. Post-fire recovery of a dense ombrophylous forest in Amazon. Ans Acad Bras Cienc 91 (2): e20170840. https://doi.org/10.1590/0001-3765201920170840

Andrade DFC, Ruschel AR, Schwartz G, Carvalho JOP, Humphries S, Gama JRV, 2020. Forest resilience to fire in eastern Amazon depends on the intensity of pre-fire disturbance. For Ecol Manag 472: 118258. https://doi.org/10.1016/j.foreco.2020.118258

APG IV. 2016. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG IV. Bot J Linn Soc 181: 1-20. https://doi.org/10.1111/boj.12385

Barlow J, Peres CA, Lagan BO, Haugaasen T, 2003. Large tree mortality and the decline of forest biomass following Amazonian wildfires. Ecol Lett 6, 6-8. Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, Nally RM, Thomson JR, Ferraz SFB, Louzada J, Oliveira VHF et al. 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature 535 (7610): 144-147. https://doi.org/10.1038/nature18326

Barlow J, Peres CA, 2004. Ecological responses to El Niño-induced surface fires in central Brazilian Amazonia: management implications for flammable tropical forests. Philos Trans R Soc Lond B Biol Sci 359: 367-380. https://doi.org/10.1098/rstb.2003.1423

Barlow J, Peres, CA, 2008. Fire-mediated dieback and compositional cascade in an Amazonian forest. Philos Trans R Soc Lond B Biol Sci 363: 1787-1794. https://doi.org/10.1098/rstb.2007.0013

Berenguer E, Ferreira J, Gardner T, Aragão ALEOC, Camargo PB, Cerri, CE, Durigan M, Oliveira-Junior RC, Vieira, ICG, Barlow J et al., 2014. A large-scale field assessment of carbon stocks in human-modified tropical forests. Glob Change Biol 20: 3713-3726. https://doi.org/10.1111/gcb.12627

Betts RA, Malhi Y, Roberts JT, 2016. The future of the Amazon: new perspectives from climate, ecosystem, and social sciences. Philos Trans R Soc Lond B Biol Sci 363: 1729-1735. https://doi.org/10.1098/rstb.2008.0011

Carvalho JOP, 2002. Changes in the floristic composition of a terra firme rain forest in Brazilian Amazonia over an eight-year period in response to logging. Acta Amaz 32: 277-291. https://doi.org/10.1590/1809-43922002322291

Castro TC, Ruschel AR, Carvalho JOP, Ramos EMLS, Gomes JM, 2019. Representatividade e precisão na estimativa da densidade e área basal na Floresta Nacional do Tapajós. Nativa, 7: 312-316. https://doi.org/10.31413/nativa.v7i3.6921

Cochrane MA, Schulze MD, 1999. Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. Biotropica 31: 2-16. https://doi.org/10.1111/j.1744-7429.1999.tb00112.x

Condit R, Ashton PS, Manokaran N, LaFrankie JV, Hubbell SP, Foster RB, 1999. Dynamics of the forest communities at Pasoh and Barro Colorado: comparing two 50-ha plots. Philos Trans R Soc L B Biol Sci 354: 1739-1748. https://doi.org/10.1098/rstb.1999.0517

d'Oliveira MVN, Alvarado EC, Santos JC, Carvalho Jr JA, 2011. Forest natural regeneration and biomass production after slash and burn in a seasonally dry forest in the Southern Brazilian Amazon. For Ecol Manag 261: 1490-1498. https://doi.org/10.1016/j.foreco.2011.01.014

De Avila AL, Schwartz G, Ruschel AR, Lopes JC, Silva JNM, Carvalho JOP, Dorman CF, Mazzei L, Soares MHM, Bauhus J, 2017. Recruitment, growth, and recovery of commercial tree species over 30years following logging and thinning in a tropical rain forest. For Ecol Manag 385: 225-235. https://doi.org/10.1016/j.foreco.2016.11.039

De Avila AL, van der Sande MT, Dormann CF, Peña-Claros, M, Poorter L, Mazzei L, Freitas, LJM, Ruschel,

AR, Silva, JNM, Carvalho, JOP *et al.*, 2018. Disturbance intensity is a stronger driver of biomass recovery than remaining tree community attributes in a managed Amazonian forest. J Appl Ecol 55: 1647-1657. https://doi.org/10.1111/1365-2664.13134

Fernandes K, Baethgen W, Bernardes S, DeFries R, DeWitt DG, Goddard, L, Lavado W, Lee, DE, Padoch C, Pinedo-Vasquez M, Uriarte M, 2011. North Tropical Atlantic influence on western Amazon fire season variability. Geophys Res Lett 38: L12701. https://doi.org/10.1029/2011GL047392

INMET, 2018. Estações convencionais.. Available from: http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesConvencionais

Lewis SL, Phillips, OL, Sheil D, Vinceti B, Baker TR., Brown S, Graham AW, Higuchi N, Hilbert DW, Laurance WF *et al.*, 2004. Tropical forest tree mortality, recruitment and turnover rates: calculation, interpretation and comparison when census intervals vary. J Ecol 92: 929-944. https://doi.org/10.1111/j.0022-0477.2004.00923.x

Martins FSRV, Xaud HAM, Santos JR, Galvão LS, 2012. Effects of fire on above-ground forest biomass in the northern Brazilian Amazon. J Trop Ecol 28: 591-601. https://doi.org/10.1017/S0266467412000636

Numata I, Silva SS, Cochrane MA, d'Oliveira, MVN, 2017. Fire and edge effects in a fragmented tropical forest landscape in the southwestern Amazon. For Ecol Manag 401: 135-146. https://doi.org/10.1016/j.foreco.2017.07.010

Pinheiro JC, Bates DM, 2000. Linear Mixed-Effects Models: Basic Concepts and Examples. In: Mixed-Effects Models in S and S-PLUS. Statistics and Computing; Pinheiro JC, Bates DM (eds). pp: 3-56. Springer, New York, NY. https://doi.org/10.1007/0-387-22747-4_1

REFLORA, 2018. Herbário Virtual. Jardim Botânico do Rio de Janeiro. [cited 2018 November 22] Available from: reflora.jbrj.gov.br/reflora/herbarioVirtual/

Rodrigues TE, Santos PL, Oliveira Junior RC; Valente MA, Silva, JML, Cardoso Junior EQ, 2001. Caracterização e classificação dos solos da área do planalto de Belterra, município de Santarém, PA. Belém, PA: Embrapa Amazônia Oriental, 54pp.

Sit V, Taylor B, 1998. Statistical methods for Adaptive Management Studies. In: Land Management Handbook nº 42; Sit V, Taylor B. (eds). pp: 19-39; Victoria: British Columbia Ministry of Forests Research Program.

Slik JF, Verburg RW, Keßler PJ, 2002. Effects of fire and selective logging on the tree species composition of lowland dipterocarp forest in East Kalimantan, Indonesia. Biodivers Conserv 11: 85-98.

Vasconcelos SS, Fearnside PM, Graça PMLA, Nogueira, EM, Oliveira LC, Figueiredo EO, 2013. Forest fires in southwestern Brazilian Amazonia: Estimates of area and potential carbon emissions. For Ecol Manag 291: 199-208. https://doi.org/10.1016/j.foreco.2012.11.044