Two decades of fires in the Brazilian Amazon and the differences in patterns between open and forest vegetation

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Abstract

This study investigated the pattern distribution of fires in the Brazilian Amazon and their relationship with deforested areas from 2003 to 2022. The primary objective was to analyze fire spots' spatial and temporal variation. First, we examine whether open vegetation (non-forest areas) in the Amazon exhibit a higher density of fire spots than forested areas. Second, we analyze how the density of fire spots in deforested areas varies with the time elapsed since deforestation. Using recent fire monitoring data and satellite imagery, the study employed statistical techniques to reveal significant patterns and trends. Our findings indicate that fire spot density is associated with deforestation in forested lands; however, this relationship does not hold for non-forest ecosystems. Fire spots are more frequent in years with higher deforestation rates, exhibiting similar trends in both forested and non-forested areas. Nevertheless, fire spot density is generally higher in originally forested lands subjected to anthropogenic activities compared to non-forest areas experiencing similar disturbances. In contrast, fires are more common in non-forest ecosystems with minimal or no disturbance compared to forested areas. Additionally, we observe variations in fire spot density over time in deforested areas, with higher densities occurring in the year the forest was cleared. In non-forest vegetation, the frequency of fires is similar in natural and anthropized areas, but both are lower compared to areas where vegetation has been recently suppressed. This study enhances our understanding of the environmental impacts of deforestation and provides valuable insights for formulating management and conservation policies in the Amazon.

1. Introduction

Forests, woodlands, savannas, grasslands, shrublands, tundra, deserts, and wetlands are at risk of burning around the world daily (Hardesty et al., 2005). In Brazil, the potential impacts of fire and interpretation of fire patterns change depending on the affected ecosystem or biome. For instance, Cerrado, Pantanal, and Pampa are fire-dependent, as fire can be an important element in maintaining the predominant herbaceous vegetation (Fidelis et al., 2022; Damasceno-Junior et al., 2021). In the Amazon biome, there are enclaves of open vegetation, such as savannahs, Campinas, and other phytophysiognomies that are also dependent on fire, which in this article are called non-forest areas (NF). Conversely, Amazonian and Atlantic rainforests are fire-sensitive, as their biological characteristics are adversely affected by fire events (Carvalho et al., 2023; Lapola et al., 2023). The Caatinga is considered fire-independent due to the lack of continuous flammable fuel and low incidence of lightning (Pivello et al., 2021).

In the Amazon, fire patterns changed since the 1970s, and their occurrence has increased due to anthropic activities coupled with climate changes (Alencar et al., 2015; Aragão et al., 2016). Anthropic fires in Amazon have reached record levels in the last 20 years (Pivello et al., 2021), being, on average, almost twice as high as in Cerrado in that period (with the area of the Amazon being nearly double that of the Cerrado) (Silveira et al., 2020). Most fires in Brazil occur in the transition between Amazon and Cerrado (Alves and Alvarado, 2019) in the region with the highest concentration of vegetation loss in the Amazon, known as the "arc of deforestation" (Messias et al., 2021).

Fire activity has been highly and positively correlated to deforestation (Cano-Crespo et al., 2021). Fire is used as a tool in the deforestation process (Silveira et al., 2020) and as a management practice for different crops (Cano-Crespo et al., 2015). Gatti et al. (2023) reported that fire emissions rose by 8% in 2019 and 4% in 2020 compared to the average emissions from 2010 to 2018. These increases coincide with significant forest loss in the Amazon during those years (10,129 km² in 2019 and 10,851 km² in 2020) (INPE, 2024).

In this context, it is relevant to analyze spatio-temporal changes in patterns of fire spots and their relationship with deforested areas. This study presents the main distribution patterns of fires in the Brazilian Amazon over the last two decades. Here, we aim to test two assumptions: 1) Amazonian non-forest (NF) areas (fire-dependent) present a higher density of fires-spots than Amazonian forested areas (fire-sensitive); 2) the amount and density of fire spots in deforested areas may vary depending on the time since the deforestation event.

2. Materials and methods

Fire spots between 2003 and 2022 were obtained from Queimadas Program (https://terrabrasilis.dpi.inpe.br/queimadas/), developed by the National Institute for Space Research (INPE). The spots were detected through the reference satellite

AQUA_M-T (MODIS, with passages in the early afternoon). Annual deforestation data sets (from 2002 to 2022) and the forest/non-forest limits were accessed from the the Brazilian Amazon Rainforest Monitoring Program by Satellite (PRODES)/INPE (Almeida et al., 2022), available on TerraBrasilis Plataform (https://terrabrasilis.dpi.inpe.br/).

First, we computed the number of fire spots for each year between 2003 and 2022 in areas naturally constituted by non-forest and forest vegetation. Spots overlapping the water mask were discarded from the analysis. Given the difference in size of forest/non-forest areas in Amazon (3,827,380 km² and 279,492,08 km², respectively), these values were transformed into density (number of fire spots per km^2).

Next, fire spots over areas originally covered by forests were further typified according to four types of land cover at the analyzed time: 1) forest removed in the same year of the fire spots detection; 2) forest removed in the year before the detection of the spots; 3) anthropic areas, i.e. areas in which forest removal happened at least three years before the year being analyzed, 4) primary forests. The density of fire spots was calculated for the four types of land cover.

For non-forest vegetation areas, PRODES mapping was conducted every two years until 2018. Each mapped year included data on NF vegetation removal from that year and the previous year. For the analysis of fire spots in non-forest vegetation, we considered three types of land cover: 1) fire spots from the mapped year in areas of recent vegetation removal (same or previous year); 2) in anthropic areas, i.e. areas in which vegetation removal happened at least three years before the year being analyzed; and 3) in natural non-forest vegetation. We also calculated the densities of fire spots for the three types of land cover.

Fire spots are detected using images with spatial resolution up to 1km$\times$1km. Here, a given fire spot was accounted for a class if the center of the pixel intersects with the polygon delimiting the area of that class. This means fire spots near the border between features ($\sim$500m) may be misplaced. As only density values were calculated, this artifact does not compromise the analysis.

Examples of burned areas in Landsat satellite images, used by PRODES in the mapping, were also employed, along with photos from fieldwork conducted in Roraima in March 2023. The band composition used was short-wavelength infrared (R) / near-infrared (G) / red (B). A spectrum-temporal Normalized Difference Vegetation Index (NDVI) was generated using the Google Earth Engine platform to show the reduction of biomass when deforestation occurs due to progressive degradation caused by fire.

Welch’s ANOVA was used to determine whether there were significant differences in fire spot densities between the groups: primary forests, anthropized areas, and recently cleared lands. This method is robust to heteroscedasticity and does not assume equal variances among the groups (Delacre et al., 2019). Welch’s ANOVA was performed using the *oneway.test* function in R (R Core Team, 2023), specifying the *var.equal* argument as *FALSE*. This approach allowed us to determine whether there were significant differences in fire spot densities between primary forests, anthropized areas, and recently cleared lands. For post hoc comparisons following a significant Welch’s ANOVA result, we employed the Games-Howell test, which is suitable for situations with unequal variances and sample sizes. The post hoc analysis was conducted using the *gamesHowellTest* function from the *PMCMRplus* package in R (Pohlert, 2023). This approach provided detailed insights into which specific group pairs differed significantly.

To compare fire spot densities over time between two land covers, we employed a paired t-test with unequal variance. This statistical test is suitable for comparing two related samples to determine if their means differ significantly (Ross and Willson, 2017). The paired t-test was performed using the *t.test* function in R, with the paired argument set to *TRUE*. This approach allowed us to assess the mean difference in fire spot densities between the two areas for each year, accounting for the paired nature of the data.

Additionally, we used Spearman’s rank correlation to examine the relationship between deforestation rates and fire spot densities. Unlike Pearson’s correlation, Spearman’s correlation does not assume a linear relationship or homoscedasticity, making it more robust for our non-parametric data (Zuur et al., 2007). The correlation analysis was conducted using the *cor.test* function in R, specifying the method as “spearman”. This test provided insights into the strength and direction of the association between deforestation and fire spot densities, enabling us to understand the underlying patterns more clearly.

3. Results and discussions

3.1 Fire in forest vs non-forest areas

Between 2003 and 2022, 4,639,773 fire spots were detected in the Brazilian territory. From these, 53.13% occurred in the Amazon. The highest amount of fire spots in the last twenty years in Amazon was detected between 2003 and 2007 — matching the period with natural vegetation loss rates higher than 10.000 km² in the region (Figure 1).

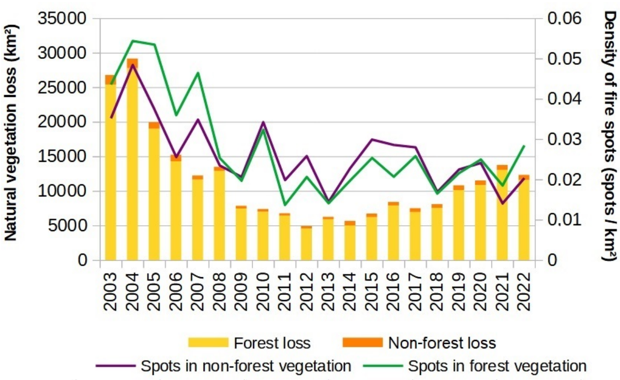

Figure 1. Density of fire spots in areas originally constituted by forest and non-forest vegetation and rates of forest loss.

Figure 1 shows the density of fire spots detected in Amazonian areas originally constituted by forest and non-forest vegetation. Deforestation and fire spots in forested lands showed a significant correlation (rho = 0.63, S = 486, p-value = 0.003) at 5% significance level, whereas the relationship between NF loss and NF fire spots was not significant (rho = 0.32, S = 903.39, p-value = 0.168). This discrepancy may be explained by the fact that fires can occur in NF areas that have not necessarily experienced suppression, such as those used for pasture management in natural vegetation (Costa et al., 2011; Gonçalves et al., 2019) or not classified as suppression by PRODES (see Almeida et al., 2022). Between 2003 and 2008, when natural vegetation loss reached levels higher than 10,000 km² per year in the Amazon, the density of fire spots in forest areas surpassed the one measured in non-forest areas. From 2009 to 2018, a period with natural vegetation losses lower than 7,500 km² per year, the density of fire spots in non-forest areas was higher than in forest areas. In 2020-2022, when the losses exceeded 10,000 km² again, the density of fire spots in forests surpassed those in non-forest areas once more.

Despite the higher spot density in forests in years of high forest losses, fire spots in forest and non-forest areas followed a similar trend considering their total areas: on average 0.028 fire spots.km^{-1}.yr^{-1} in forest areas and 0.026 fire spots.km^{-1}.yr^{-1} in non-forest areas, not differing statistically (paired t test; t = -1.173, df = 19, p-value = 0.255) and showing a strong correlation (rho = 0.84; S = 210, p-value $\leq$ 2.2e-16).

The density of fire spots varied across the types of land cover. When analyzing the density of fire spots stratified by areas of natural vegetation (both forest and non-forest vegetation), anthropic areas, and recently cleared areas (within the same year or the year before), we observed a higher concentration of fire spots in areas where vegetation loss had occurred more recently, particularly in forested regions (see the letters in Figure 2 for statistical differences). The lowest fire density was found in forest natural vegetation, which was statistically lower than that found in natural NF areas (on average 0.013 and 0.022 fire spots.km^{-1}.yr^{-1}, respectively). Despite the significance, the difference is relatively small, as one can see in Figure 2. A possible reason for the difference is the natural occurrence of lightning fires in savannas (Pivello et al., 2021) and the management of native pastures with fire by ranchers and indigenous populations (Gonçalves et al., 2019; Barbosa and Fearnside, 2005).

Grasses are dominant in non-forest areas, and present several adaptations and synergies with fire (Barbosa et al., 2007). Tropical forests are not easy to burn naturally, and their plants have no adaptations to tolerate fire events (Pivello et al., 2021; Brando et al., 2012; Barlow and Peres, 2008). As such, fire spots should be more frequent in areas of non-forest, where they can occur naturally. Our results show that this assumption is only valid for areas covered by their natural vegetation and cannot be generalized to anthropized areas.

3.2 Fire dynamics in forest areas

Figure 3 shows the temporal trend of the density of fire spots that occurred in different land covers distributed in areas originally constituted by forest vegetation in the Amazon. The highest density of fire spots occurred in deforested areas with relatively recent deforestation events. Density values in areas with forest removal in the year of analysis (on average 0.461 fire spots.km^{-1}.yr^{-1}) were statistically higher (paired t-test: t = 6.789, df = 19, p-value = 1.75e-06) than those in the prior year (on average 0.364 fire spots.km^{-1}.yr^{-1}). Our results are in accordance with the findings of Alves and Alvarado (2019), which demonstrated a spatial correlation between recent deforestation and burn scars. In Amazon, it is a common practice to use fire to clear remaining debris after deforestation and to prevent regrowth, a process known as slash-and-burn (Reis et al., 2021; Aragão et al., 2016; Armenteras et al., 2017). Additionally, ashes from the burns can be used to fertilize the soil (Silveira et al., 2020).

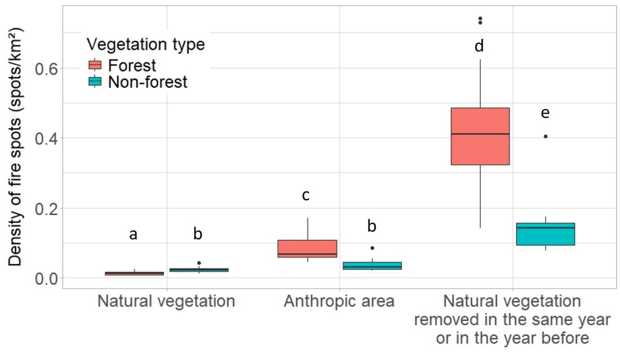

Figure 2. Density of fire spots in natural vegetation areas (primary forests or natural NF vegetation), anthropic areas, and natural vegetation cleared in the same year or the previous year. Different letters above the boxplots indicate statistically significant differences (Welsh's ANOVA test; p-value $\leq$ 0.05).

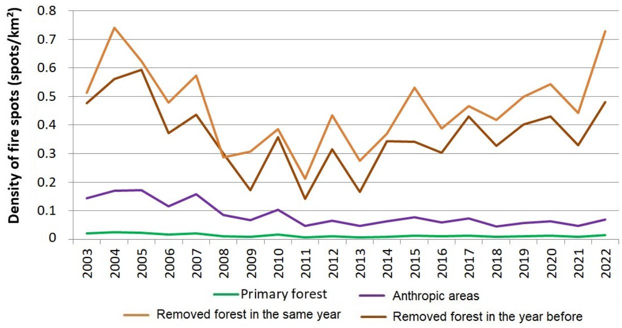

Figure 3. Density of fire spots per type of cover in areas originally covered by forest vegetation.

The density of fire spot values was lower in anthropic areas (on average 0.086 fire spots.km^{-1}.yr^{-1}) compared to recently removed forests. Deforested areas are predominantly used for pastures in the Amazon (TerraClass, 2024), which commonly are managed by fire. Fires are commonly used as a management practice for nutrient mobilization, pest control, and removal of brush and weed accumulation. Additionally, fire is used to remove regenerating vegetation for new crop or pasture implementation (Cano-Crespo et al., 2015; Lima et al., 2012).

Primary forests exhibited the lowest density of fire spots, averaging 0.013 fire spots.km^{-2}.yr^{-1}. Fires are typically rare in continuous forests located towards the center of the biome (Drüke et al., 2019). They mainly occur at forest edges, where ongoing deforestation intensifies edge effects, increasing the susceptibility of these areas to fire (Reis et al., 2021; Silva-Junior et al., 2022; Armenteras et al., 2017). Forest edges have a drier and hotter microclimate, ample fuel availability in the understory, and greater exposure to ignition sources (Silva-Junior et al., 2022).

3.3 Fire dynamics in non-forest areas

Figure 4 illustrates the temporal trend of the density of fire spots per year between 2004 and 2022 in different types of land cover located in areas originally covered by non-forest vegetation in the Amazon. The highest density of fire spots occurred in non-forest cleared in the same year or the year before (Figure 3), averaging 0.15 fire spots.km^{-2}.yr^{-1}.

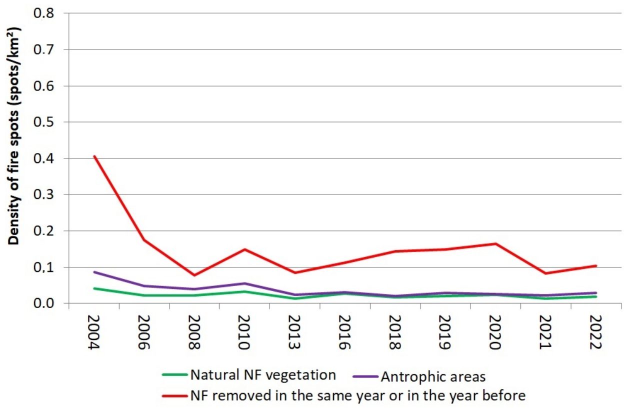

Figure 4. Density of fire spots per type of cover in areas originally covered by non-forest vegetation.

In non-forest areas, the average annual density of fire spots in anthropic areas and natural vegetation has shown similar values (0.037 and 0.029 fire spots.km^{-2}.yr^{-1}, respectively), with no statistically significant difference (Figure 2). However, the occurrence of fire spots in anthropized NF areas was lower compared to those in anthropic areas located originally in forested lands (0.037 and 0.086 fire spots.km^{-2}.yr^{-1}, respectively). This disparity likely stems from the predominant land uses. In savannas, the primary non-forest vegetation type in the Amazon, the leading cause of vegetation loss has been associated with the expansion of soybean cultivation (Messias et al., 2024b), which typically involves less frequent use of fire compared to pasture cultivation.

4. Impacts of fires in the Amazon

Our results demonstrated that fires were more common in areas originally constituted by forest vegetation than in non-forest vegetation in the Amazon. Around 93% of the Brazilian Amazon's vegetation consists of forests (Messias et al., 2021), vulnerable to several impacts by fires (Pivello et al., 2021). The increased likelihood of fires is expected to negatively impact carbon stocks and biological diversity (Lima et al., 2012).

Active fires in pasture and agricultural areas often spread uncontrollably into primary forests, becoming the primary driver of forest degradation by fire (Cano-Crespo et al., 2015; Reis et al., 2021). This issue is exacerbated during periods of severe water deficit, caused by extreme drought events such as El Niño. These conditions reduce the moisture of the forest understory and available fuel, increasing forest flammability (Faria et al., 2017; Reis et al., 2021). As a result, large tracts of primary forest are becoming more flammable and will likely burn more frequently in the coming decades (Brando et al., 2020).

Successive fire incursions into forests lead to a decline in aboveground carbon density, progressive loss of forest biomass, and reduced structural diversity (Rappaport et al., 2018). In the final stage of degradation, this results in complete loss of the forest cover, which corresponds to the landscape pattern mapped as deforestation by PRODES (Almeida et al., 2022). Figure 5 (A, B, C, and D) illustrates an example of such degradation in Mato Grosso. The Normalized Difference Vegetation Index (NDVI) indicates successive biomass losses, especially since 2018, leading to complete canopy loss detected by PRODES in 2022. That year, 928.05 km² of forest loss detected by PRODES was due to progressive forest degradation, accounting for 7.43% of the total.

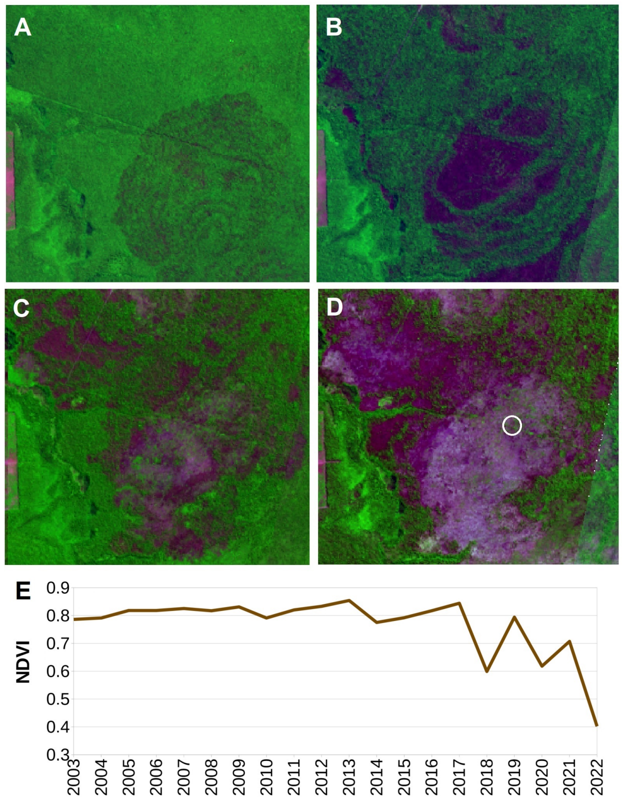

Figure 5. Evolution of degradation, leading to the opening of the forest canopy and resulting in deforestation due to progressive degradation, visualized in Landsat satellite imagery for the years: A) 2014; B) 2018; C) 2020; D) 2022. E) Spectrum-temporal NDVI from the highlighted point in white in the 2022 image.

Between August 2022 and July 2023, 58.22% of burn scars in Amazon non-forest vegetation occurred in savannas, mostly in the Lavrado (state of Roraima), in the northern portion of the Amazon (Messias et al., 2024a). These features are easily detected in satellite images (Figure 6A) (Messias et al., 2024a). Burned area and fire frequency in the savannas of Roraima depend on the vegetation types, and the higher the density of trees and the greater the amount of herbaceous vegetation in high-altitude surfaces, the greater the burned area (Barbosa and Fearnside, 2005). Although some types of natural non-forest vegetation in the Amazon benefit from fires for maintaining biodiversity and ecological processes, the frequency, occurrence period, and extent of fires have been altered by human activities (Alencar et al., 2015; Brando et al., 2020; Aragão et al., 2016). Generally, changes in the fire regime have negative effects on vegetation (Pivello et al., 2021). Figure 6B shows the occurrence of fire in a savanna vegetation area in the Lavrado of Roraima, observed during fieldwork.

In southern Amazonia, forest fire regimes have strongly changed (Brando et al., 2020). Human activities and extreme weather events have led to fires, increasing forest carbon emissions to the atmosphere, even in areas where deforestation has been declining (Brando et al., 2020). In the biome, fire emissions increased by 8% and 4% in 2019 and 2020, respectively, while deforestation rose by 82% and 77% and burned area by

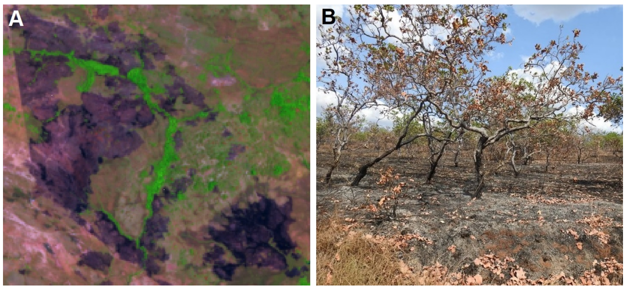

Figure 6. Non-forest vegetation in Roraima. A) Lavrado, burn scars in Landsat image (magenta), 2022; B) Savanna fire occurrence, fieldwork, 2023.

14% and 42%, reducing the capacity of the Amazon to act as a carbon sink (Gatti et al., 2023).

5. Conclusions

Our results indicate that fire spot density is associated with anthropic activities in originally forested lands, but this relationship is not true for non-forest ecosystems. Also, fire spots are more frequent in years with higher natural vegetation suppression rates, exhibiting similar trends in both forested and non-forested areas. However, fire spot density is generally higher in forested lands subjected to anthropogenic activities compared to non-forest areas experiencing similar disturbances. Conversely, in natural areas with minimal or no disturbance, fires are more common in non-forest ecosystems than in forested ones. We also demonstrated variations in the density of fire spots over time for deforested areas based on the age of the deforestation event, being higher in the year the forest was cleared. In non-forest vegetation, the frequency of fires in natural and anthropized areas was similar, but both were lower compared to areas where vegetation had been recently suppressed.

These results highlight the need for fire control actions in different Amazonian scenarios, given the importance of fire spots as a carbon source. The severe forest degradation due to successive fires can also result in the complete loss of the canopy, and its capacity for self-regeneration, as well as the loss of the forest's ecological functions.

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