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Highway Network and Fire Occurrence in Amazonian Indigenous Lands

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Abstract: The construction and expansion of highways aiming to improve the integration of the most isolated regions in Brazil facilitated the access to many inhabited areas in the Amazon biome, but had as a consequence assisted the degradation of many of these regions. Over the last two decades, we have observed in this biome a gradual diversification and intensification of land uses through vegetation loss and an increase in fire associated with deforestation and an increase in grazing areas. We used data from several active fires products derived from 14 different satellites, available on the Brazilian National Institute for Space Research (INPE). We evaluated the influence of highway infrastructure on fire occurrence inside and around Indigenous Lands (IL) located in the Brazilian Amazon biome, from 2008 to 2021. We classified 332 ILs into "cut by highways", "without highways", and "with highways in a 10 km buffer". We performed: (a) the descriptive statistics of the fire occurrence by state, by season, and by type of land use and land cover (LULC) affected by fire; (b) the spatial distribution of the active fire density; and (c) a simple linear regression model between the fire occurrence and the IL area. Our results showed that in total, 16–46% of the fires occurred within the IL in most of the states, while the 10 km buffer was the region most affected by fire. We confirmed that in the last three years there was a significant increase in the number of active fires, representing anomalies in fire occurrence across the studied period. We discussed the result implications and the role of the highway network in environmental degradation inside and around the ILs located in the Brazilian Amazon.

Keywords: active fires; highways; Amazon biome; land use land cover

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1. Introduction

Currently, the transformations of land cover derived from anthropic activities in the Amazon biome have put the entire international community on alert. One of the main concerns is the fire occurrence in this biome, which is generally associated with deforestation and the effects of climate change, in particular the increase in the length of the dry season [1]. In this sense, forest fires and deforestation are the main threats to the Amazon Forest [2,3].

The drivers of fire occurrences are varied, including natural [4] and anthropic causes, but are mainly the use of fire for land clearance and pasture management [5–8] or other agricultural practices [9,10]. Moreover, fire occurrences can be maximized in drier periods when the above-ground biomass is less moist, so becoming more flammable, and extreme drought events exacerbate the impact of forest fires in the Amazon [1,2]. Studies predict that extreme drought events will become more frequent due to climate change [2,11], posing a risk of an increase in their occurrence.

Currently, most fires in the Amazon are associated with two factors: land-use changes (conversion of forest to pasture or illegal logging) and extreme drought events [2,12]. While land use is shaped and diversified from the opening of highways (municipal, state and federal), the deforested areas are generally concentrated in regions closer to highways [13–15], as the proximity or access to the highway infrastructure facilitates the logistics of deforestation and timber outflow [15]. In this way, the influence of transportation infrastructure that favors displacement in the region and contributes to the flow of local production also facilitates illegal logging activities.

The distance from highways and the presence of urban centers are the most important factors that contribute to the increased probability of deforestation, since in order to create these highways and cities, it was necessary to take down trees and/or change the forest landscape [16]. According to Laurance et al. [17], in regions along the tropics, major highways open up areas of forest resource extraction, allowing access to more remote areas. In the case of the Amazon, deforestation mainly occurs in the near vicinity of major highways [15]. In addition, improvements in transportation infrastructure intensified deforestation along their routes and in areas most closely linked to their buffer area [18].

Highways have been facilitating the selective extraction of timber of commercial interest [19], and this dynamic is also seen in protected areas, where forest remnants can no longer be identified outside of them. Inside these protected areas, the focus is on timber smugglers [20], because Indigenous Lands (ILs) are recognized as areas that inhibit deforestation [21,22] and are strategic spots for the maintenance of biodiversity and providing ecosystem services, such as carbon storage and balance in the hydrological cycle [23].

Despite the importance of these environmental assets, several studies have revealed significant changes in areas of ILs in recent years [23–26]. Thus, according to Santos et al. [3], the number of active fires that occurred outside the ILs can explain the variation in the number detected within them instead of outside. In other words, fire occurrence outside the ILs has a direct influence on the number of active fires that occurred inside these protected areas. Consequently, the presence of the ILs, in turn, has contributed to the protection of other protected areas in the Amazon, such National Parks, Natural Reserves, Environmental Protected Areas, etc. [27].

Most forest degradation by fire in the Brazilian Amazon occurs when fires get out of control in areas of anthropic use or degraded areas and spread from pasture to forest [2]. This dynamic was observed by Santos [28], who noticed that some ILs are encircled by a "fire belt", represented by a higher density of active fires in their surroundings. Given these findings, our objective was to study the influence of terrestrial transportation infrastructure on fire occurrences within and in the immediate surroundings (10 km buffer) of ILs in the Amazon biome in Brazil, during the period from 2008 to 2021. Previous works suggested that highways have an influence on fires occurrence; however, this assertion has not been sufficiently explored in the Amazon Forest Indigenous Lands. Thus, we hypothesized that the federal and state highways located in the Amazon biome facilitate the fire occurrence within the ILs. We used an approach based on the use of remote sensing products over time to perform spatial analysis to test this hypothesis.

2. Materials and Methods

2.1. Study Area

We selected 332 indigenous lands (ILs), which are located entirely within the Amazon biome in Brazil. This biome extends across the Brazilian states of Acre (AC), Amazonas (AM), Amapá (AP), Pará (PA), Rondônia (RO), Roraima (RR), and parts of the states of Mato Grosso (MT), Tocantins (TO), and Maranhão (MA) (Figure 1). The ILs are protected areas created by the government of Brazil through Law No. 6001/73-Statute of the Indian, Decree No. 1775/96, which aims to guarantee the rights of indigenous peoples, forests, and services [29].

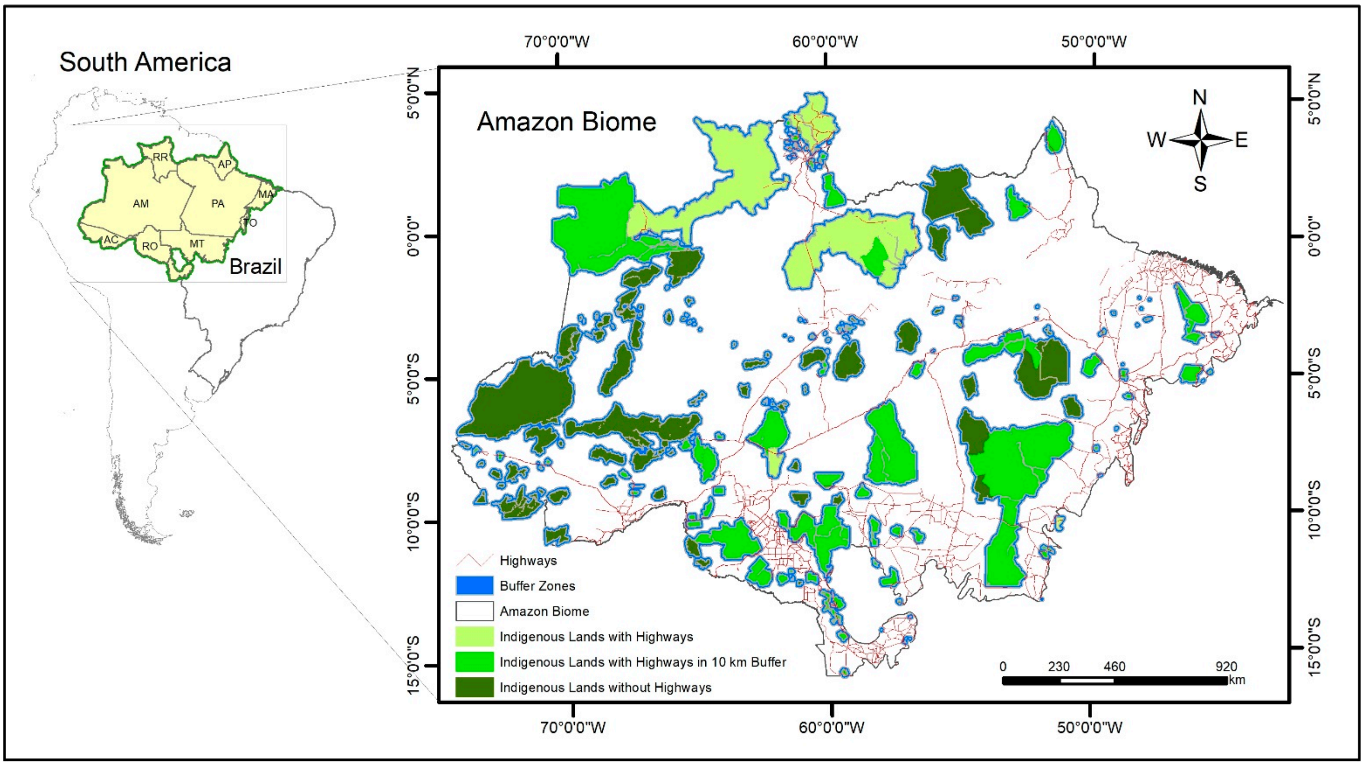

Figure 1. Location of the Indigenous Lands (IL) of the Brazilian Amazon biome, classified according to the highway presence: IL with highways, IL without highways, and IL with highways in a 10 km buffer. Source: Prepared by the authors.

In addition, the surrounding area of 10 km from the limits of the Indigenous Lands was delimited. The 10 km surrounding area (called buffer zones) suffers the greater influence from the economic activities external to the Indigenous Lands [30]. In this sense, several studies have pointed to the fact that non-indigenous anthropic actions that occur outside the ILs can contribute to deforestation within these areas [22,25]. Moreover, according to Rorato et al. [25] and Rorato et al. [26], the threats related to forest loss (deforestation, forest degradation, and fires) are more intense in the buffer zones of the ILs than inside them, showing that the ILs have effectively promoted environmental preservation.

2.2. Data Source

The data of the active fires within the Brazilian Amazon were acquired from the INPE (http://queimadas.dgi.inpe.br/queimadas/bdqueimadas/ (accessed on 1 February 2022)). These data comprise the period from 2008 until 2021. The active fires were detected operationally in Latin America on images from 14 different satellites, using three types of optical sensors with data updated every 3 h. These satellites detected thermal radiation emitted by fire: electromagnetic waves with peak wavelengths of 3.7 to 4.1 μm [31], indicating the geographical coordinates of fire events.

In addition to the active fires data, we used vector files of the federal and state highways, provided by the National Department of Transportation Infrastructure (DNIT) [32], and the limits of the Indigenous Lands provided by the National Indian Foundation (FUNAI) [33]. Here, it is relevant to notice that the highway network in Brazil is classified as federal, municipal, or state highways. The administration of the federal road network occurs through DNIT, a federal agency linked to the Ministry of Infrastructure. State highways are managed by state highway departments or infrastructure secretariats, linked to the state governments. Municipal highways are managed by local governments in each municipality. Generally, the state road network connects cities to each other and to the state capital, while federal highways almost always cross more than one state, and municipal highways connect villages and rural areas to cities (seats of municipalities). In all classifications, there are paved and unpaved roads. Especially in the northern region of Brazil, where the Amazon biome is located, there is no distinction between highways by width or length, as almost all are two-lane rural roads with paved and unpaved transects.

Land use and land cover (LULC) data for the years 2008 to 2021 were acquired from the MapBiomas Project [34], the largest LULC dataset from Brazil, by using the Toolkit plugin through the Google Earth Engine (GEE) platform in order to analyze the fire occurrences by type of LULC. The MapBiomas data are the result of automatic classification processes applied from TM (Lansat 5 for the years 1985–2011) and OLI (Landsat 8 for the years 2013–2020) sensor images, with a spatial resolution of 30 m [35].

2.3. Methods

The ILs were classified in three categories: ILs that are crossed by highways (12 ILs); ILs that have highways within the 10 km buffer (169 ILs); and the isolated IL Lands without highways inside or in their surroundings (151). We then performed the spatial clipping of the active fires for the three classes, as well as the fires within the 10 km buffer for all the considered ILs. We performed various analyses using descriptive statistical and spatial analysis, which are described further below.

2.3.1. Analysis for Basic Descriptive Statistics

For the descriptive analysis, we used a method to verify the outliers based on the Interquantile Range (IQR) in order to identify the points of abrupt changes (outliers) in the time series of active fires (cumulative total of annual active fires), separating the data according to the category of the presence of highways in the ILs: with highways within the ILs; without highways; and with highways in a 10 km buffer. The advantage of this method is that it evaluates the dispersion of the data considering its interval, in this case, the years. In addition, we used histogram analysis for the evaluation of the distribution of active fires by season to establish the seasonality of the fire occurrences throughout the year, dividing each year into four periods: January–March (rainy period), April–June (transition between the rainy period and dry period), July–September (dry period) and October–December (transition between the dry and rainy period). The occurrence of active fires by state was also analyzed using histograms, in order to understand its distribution by state. In these two analyses, the data were analyzed by separating the active fires of the three different ILs categories and the buffer (annual accumulation of fires within the buffers of the three previously mentioned categories).

Finally, for each active fire, we extracted the information about LULC derived from the Mapbiomas product to analyze the occurrence of fires by land cover type. The ILs were classified according to their size into 500 km^2 intervals, with values ranging from 0.14 km^2 to 96,828.73 km^2. Based on this classification, we analyzed the distribution of active fires by IL area class and by LULC, including the following MAPBIOMAS categories: Agriculture and Pasture (pixels classified as Agriculture, Soybean, Sugar cane, Other temporary crops, Other perennial crops, Pasture or Mosaic of Agriculture and Pasture); Forest Formation; Savanna/Grassland formation (pixels classified as Savanna Formation or Grassland); Wetlands; and Non-vegetated areas (pixels classed as urban areas, mining or other non-vegetated areas). Thus, we plotted the active fires by IL area class, showing for each class the count of active fires by LULC separated into the ILs with highways, without highways, and highways in a 10 km buffer.

2.3.2. Spatial Analysis of Active Fires

The spatial analysis of the active fires was performed through the Kernel density method [36]. According to Rudke et al. [37] and Silva et al. [38], this procedure consists of an exploratory interpolation technique that generates a density surface for visual identification purposes. Moreover, according to the authors, Kernel estimation depends on two parameters: radius of influence (τ) and Kernel estimation function (k).

The radius of influence (which is the bandwidth) was calculated using the spatial variant of Silverman's [39] rule of practice, which is robust to spatial outliers. The calculation of the bandwidth considers: (1) the mean center of the input points; (2) the distance from the mean center; (3) the median of these distances (D_m); and (4) the Standard Distance (SD). It is shown by Equation (1) where n is the number of points analyzed.

This is example 1 of an equation:

$$\tau = 0.9 \times \min\,(SD\ \sqrt{}(1/\ln(2) \times D_m)) \times n^{-0.2} \tag{1}$$

where n is the number of analyzed points.

The kernel density calculation is based on the kernel quartic function (Equation (2)) described in Silverman [39]:

$$k(h) = 3/\pi\,(1 - h^2)^2 \tag{2}$$

where h is the distance between a point and its neighbor [37].

We used the Spatial Analyst tool of the ArcGIS software (v10.6.1, ESRI, Redlands, CA, USA) which projects a circular neighborhood around each active fire (20 km) for each month during the studied period. The density was applied for each year in the period from 2008 to 2021, and also for the sum of all active fires along this period.

Finally, for the description of the results we grouped the Kernel density into five classes: Very Low (0–0.14); Low (0.15–0.46); Moderate (0.47–1.04); High (1.05–2.20); and Very High (2.21–4.35).

2.3.3. Active Fire Regression Analysis

We performed the regression analysis between the active fires data and the IL area for each IL category (with highways, without highways, and with highways in a 10 km buffer). For this analysis, we removed the indigenous lands bigger than 2500 km^2, in order to avoid the outliers (including all IL into the 3rd quartile). We calculated the mean yearly active fires for each IL, and then plotted them against the IL area. For each IL category, we performed linear regressions to analyze the correlation between fire occurrence and the IL size and compare if this relationship is affected by the highway presence.

3. Results

The results presented in this study provided substantial information about fire and its relationship to the highway network in the Amazon. In general, our results showed a heterogeneous scenario of the threats of active fire under the influence of highways and affecting ILs and their buffers in the Amazon biome in Brazil. From the analysis of basic descriptive statistics, we observed that in all three IL categories (Figure 2) the last three years showed a significant increase in fire activity.

Considering the inter-annual variation in fire occurrence among states, we observed that at the beginning of the evaluated period (which ran from 2008 to 2011) the occurrence of fires in the 3 categories of ILs and the buffers was relatively low (Figure 2). From 2012 there was an increase in fires, observing a second increase in the fire occurrence from 2019 in all categories (Figure 2). The peak of fire occurrence was in 2019 for the ILs with highways and 2020 for the ILs without highways or with highways in the 10 km buffer. Despite the findings described, we observed that the ILs with highways around 10 km have shown greater inter-annual variation for the analyzed period (Figure 2).

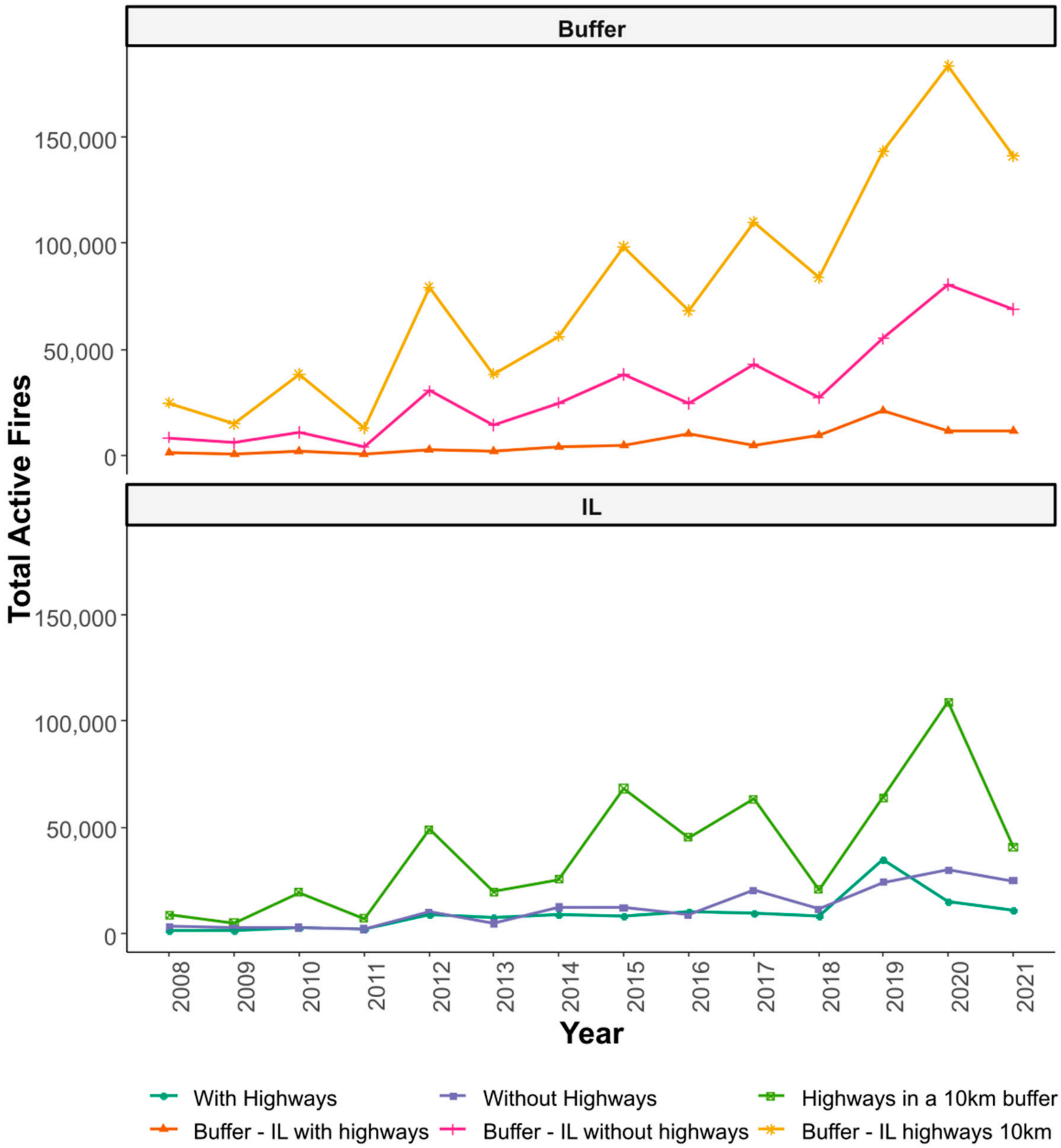

Figure 2. Interannual variation in active fires in the Indigenous Lands (IL) of the Brazilian Amazon biome, classified according to the highway presence: IL with highways, IL without highways and IL with highways in a 10 km buffer, in the Brazilian Amazon biome.

There are notable differences between the years analyzed, by seasons (Figure 3) and by Brazilian states located in the Amazon region (Figure 4). On the one hand, we observed that in the dry season (July–September) the greatest occurrences of active fires for the ILs without highways and those with highways in the buffer. On the other hand, the highest concentrations of active fires on ILs with highways have occurred during the rainy season (January–March). The same pattern was observed for the buffer areas in each category, indicating the influence of the fire occurrence outside the IL into these protected areas.

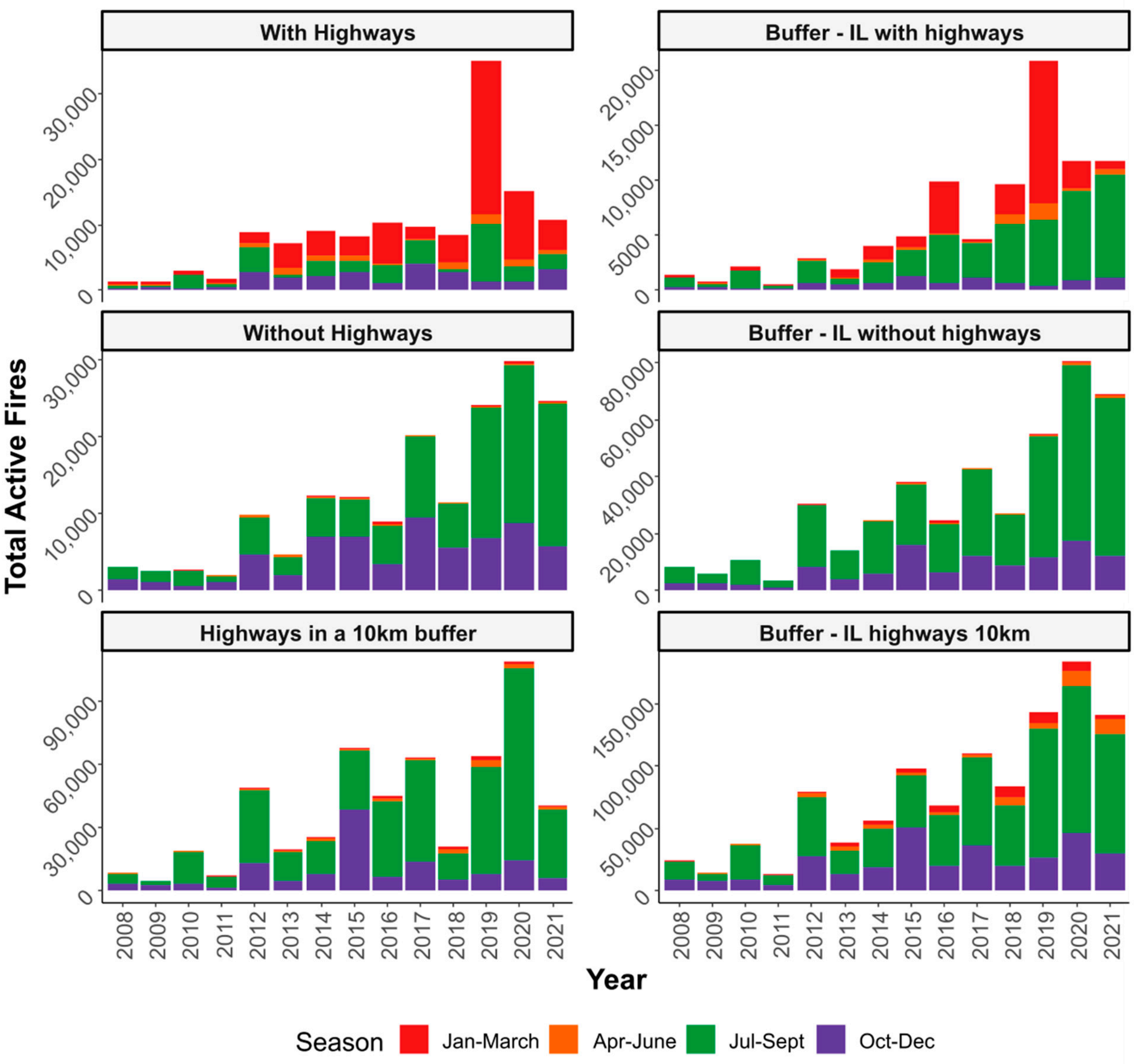

Figure 3. Active fires by season in the Brazilian Amazon Indigenous Lands classified according to the highway presence: IL with highways, IL without highways, and IL with highways in a 10 km buffer.

We found a total of 2,460,644 active fires between 2008 and 2021 along the Brazilian Amazon Indigenous Lands and its buffer zones. In terms of the fire occurrence by state (Figure 4), we observed a difference in the pattern between the IL with highways and the ILs without highways or with highways within the 10 km buffer (Figure 4). In total, the state of Pará stood out with the occurrence of 742,742 cumulative fires over the 14 years studied, of which only 253,813 (34.2%) occurred inside the ILs, followed by Mato Grosso (with 570,657 fires, of which 260,850 occurred inside the ILs, ~45.7%) and Rondônia (with 348,785 fires, of which 53,418 occurred inside the IL, ~15.3%). The states with the lowest accumulated active fires were Tocantins (with 747 fires, 67 of which were inside the IL, <0.01%), Amapá (20,857 fires, 15,219 of which were inside the IL, ~72.9%), and Acre (59,820 total fires, 9406 of which were inside the IL, ~15.7%).

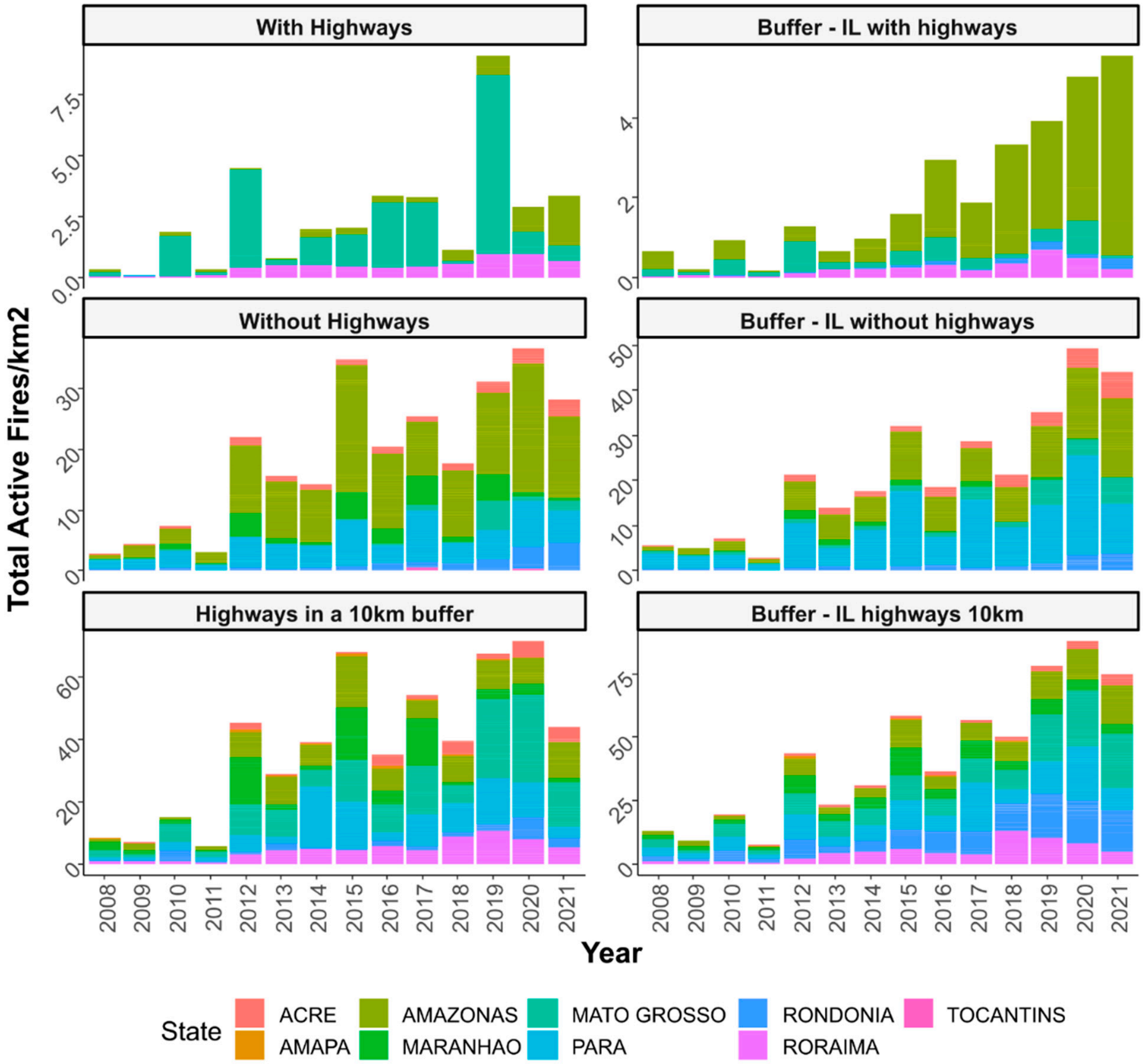

Figure 4. Active fires density by state in the Brazilian Amazon Indigenous Lands classified according to the highway presence: IL with highways, IL without highways, and IL with highways in a 10 km buffer.

The state of Roraima presented the highest number of fires in the ILs with highways, ranging from 772 fires in 2010 to 25,183 fires in 2019 (Figure 4). In contrast, this state showed very low values of fires in the other two categories of ILs and in the buffer. The state of Pará (1374–20,487 fires), followed by Amazonas (348–5253 fires), both presented the highest number of fires in the ILs without highways, while Pará (1548–35,082 fires), followed by Maranhão (530–30,284 fires), stood out as the states with the highest number of fires in the ILs with highways in the 10 km buffer. However, when we standardized the active fires by the IL or buffer area, we observed a change in the pattern of the state with the higher active fire density (number of active fires/km^2), where Mato Grosso showed the highest fire density in the IL with highways and the Amazonas state also was highlighted in the IL without highways and with highways in a 10 km buffer (Figure 4).

Through the Kernel map, we verified that the “Very Low” densities were mapped only for 2011 (Figure 5). Moreover, according to the density map, we observed that the year 2012 has marked the increase in "High" densities. In addition, the year 2012 also showed the spread of densities throughout the Amazon biome, from east to west and from north to south. Previously, the highest densities were concentrated in the westernmost and southernmost regions. There was also an increase in the density of active fires for all years after 2015 (Figure 5). In this time interval, "High" and "Very High" intensities of the density of active fires were predominant. The years 2019, 2020, and 2021 stood out as the years with the highest density of active fires.

In addition to the increases in fire densities for the last three years (Figures 4 and 5), we observed that high densities are concentrated in the south of the Amazon biome, in the northwestern region of the state of Rondônia. Moreover, we noted that high densities were persistent in specific areas in the south, extreme north, and east of the Amazon biome. Analyzing the fire density regarding the distribution and location of federal and state highways (Figure 6), it is possible to observe a strong relationship between the density of active fires and highways, especially in the south, east, and far north of the biome, a region that corresponds to the arc of deforestation of the Amazon biome.

When analyzing the distribution of protected areas in intervals according to their size, we observed a similar pattern of distribution between the ILs without highways (n = 151) and with highways in the 10 km buffer (n = 169) (Supplementary Materials Figure S1). The 88.7% and 66.3%, respectively, of the ILs within these categories were classified within the area class intervals <2500 km^2, with 59.6% and 46.2% of them classified in the 0–500 km^2 interval (Supplementary Material Figure S1).

We observed that the distribution of the frequency of active fires within the different IL area classes varied according to the size of the IL and the type of land cover (Figure 7). Interestingly, we also observed that the interval between 0–500 km^2 (area interval that predominates the largest number of IL) did not concentrate the largest number of active fires, especially in the ILs with highways, where we have 2 ILs that presented one of the lowest numbers of active fires for this category. In this same IL category, the active fires were mainly concentrated in three ILs in the area class of 17,000–17,500 km^2, 6500–7000 km^2, and 5000–5500 km^2, where fires occurred mostly in savanna/grassland formations (Figure 7).

In the other two categories of ILs without highways and with highways in the 10 km buffer, most of the active fires occurred in forest formations, regardless of the size of the IL, with the exception of active fires peak that we found for the ILs without highways in the 30,500–31,000 km^2 interval where a single IL concentrated more than 40,000 accumulated fires (The Indigenous Land Normandia, Pacaraima, Uiramutã, located in Roraima state, in the Guianan savanna Ecoregion), in an area dominated by savanna/grassland vegetation (Figure 7). In this same IL category, we found the second peak of accumulated active fires in the 7500–8000 km^2 interval where we found 3 ILs and most of the active fires occurred in forest formations or agriculture and pasture areas (Figure 7).

In the category of ILs with highways in the 10 km buffer, we found a higher occurrence of active fires in the ILs including those >2500 km^2 (75 ILs), where the forest areas were the most affected LULC, followed by the savanna/grassland formations and agricultural and pasture areas (Figure 7).

We considered only ILs with an area <2500 km^2 (n = 257 units) in the regression analyses. This n corresponds to the 3rd quartile of the distribution of ILs by area as well as the ILs with a low cover of savanna vegetation. This was relevant, since the fires occurrences in the savannas can follow a different dynamic and could be associated with other types of events. The dispersion of data separated by category of IL showed a slightly positive correlation between the size of the IL and the average annual active fires (total correlation 0.3, Figure 8). We observed the highest correlation in ILs with highways, with a correlation of 0.98, while for ILs without highways or with highways in the buffer the correlations were 0.22 and 0.27, respectively.

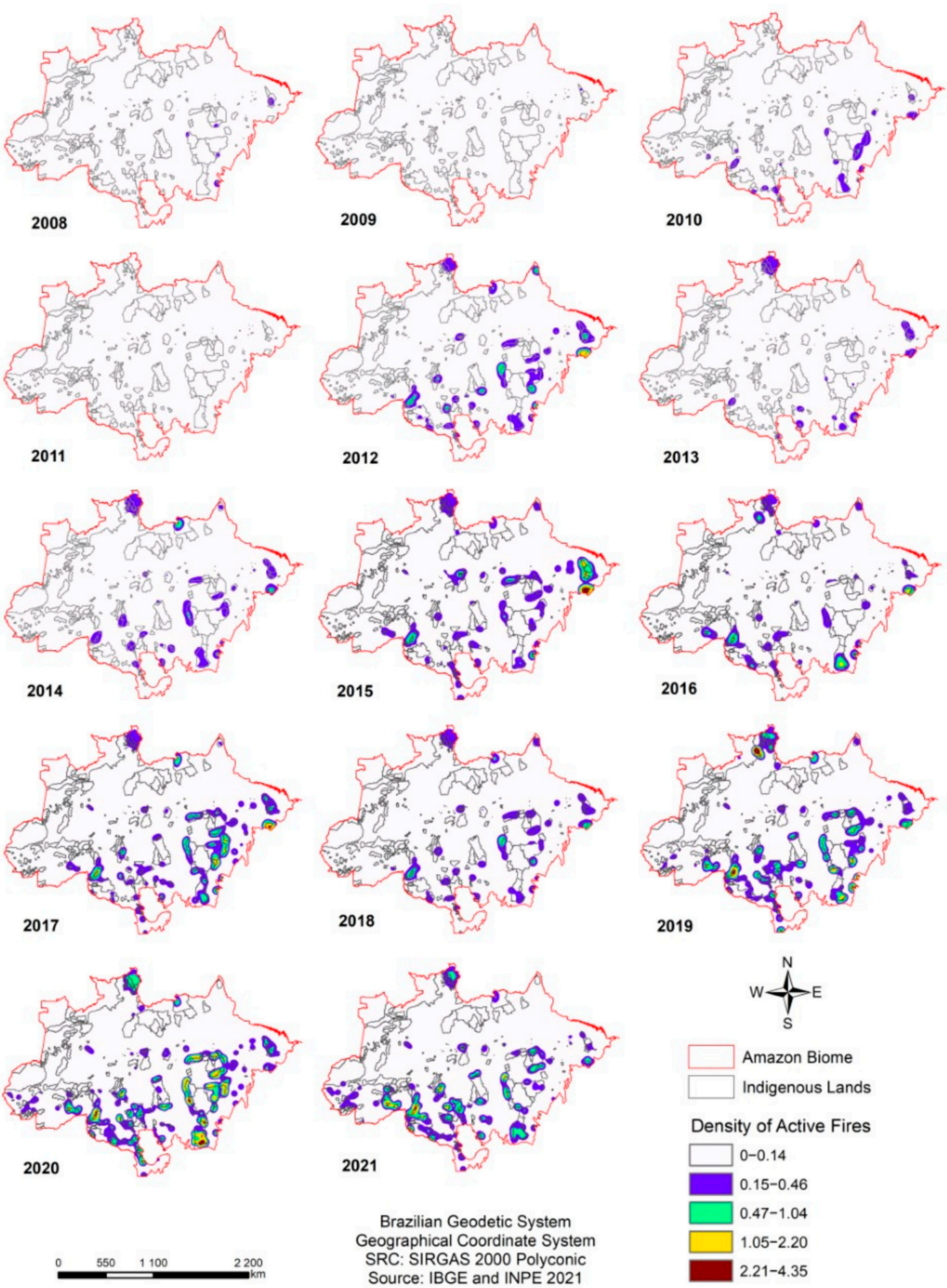

Figure 5. Density of active fires calculated for the years 2008 to 2021 in the Indigenous Lands (IL) and their buffers across the Brazilian Amazon biome.

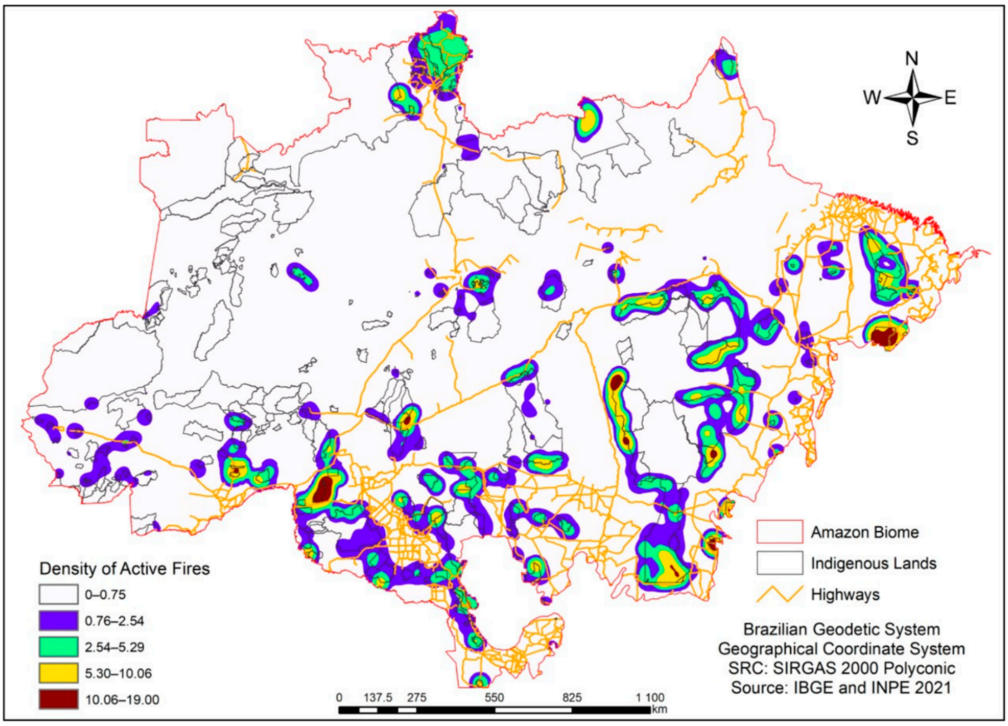

Figure 6. Density of active fires calculated for period 2008–2021 in the Indigenous Lands (IL) and their buffers across the Brazilian Amazon biome.

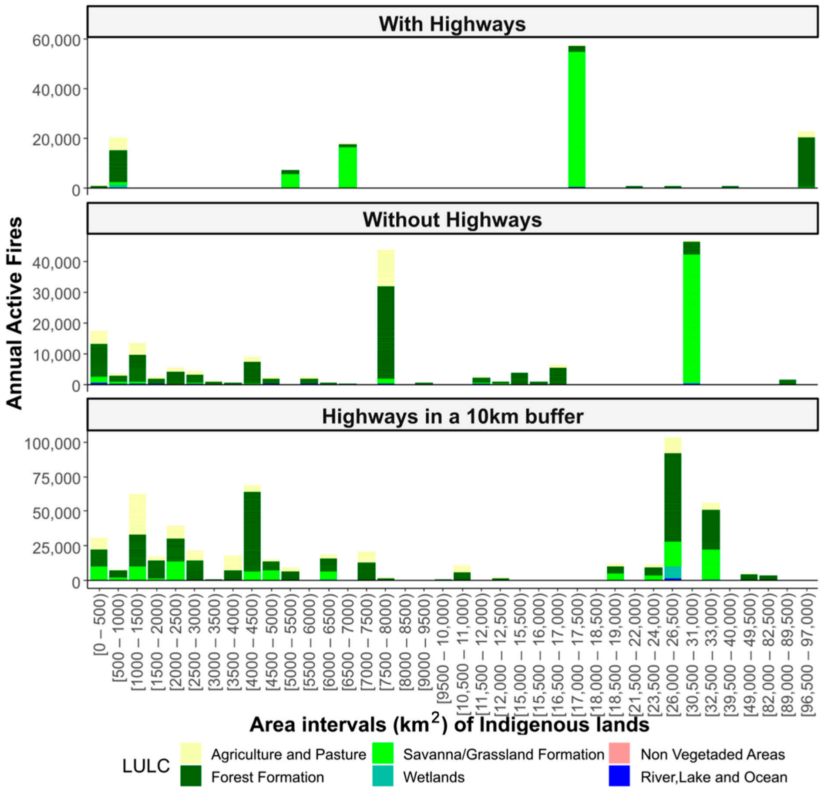

Figure 7. Distribution of accumulated active fires by IL area intervals and according to land use and land cover type in the Indigenous Lands of the Brazilian Amazon biome.

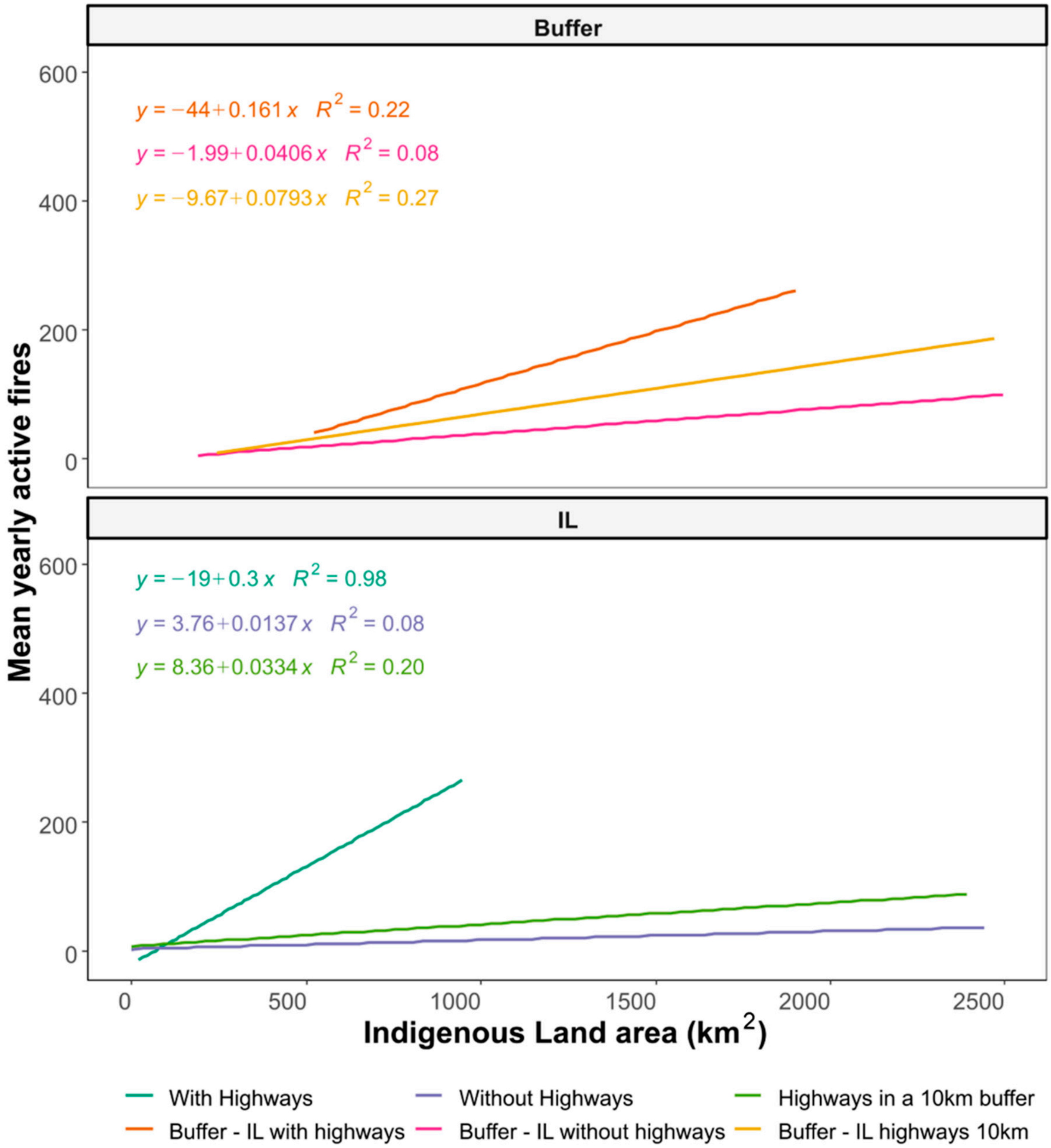

Figure 8. Linear regression analysis between the annual average active fires by the size of indigenous lands for each IL category (with highways, without highways, and highways in a 10 km buffer).

Finally, when analyzing the density of active fires per km^2, and taking into account the areas of the selected categories, we observed that ILs with highways have approximately three times the density of those that do not have highways (Figure 9).

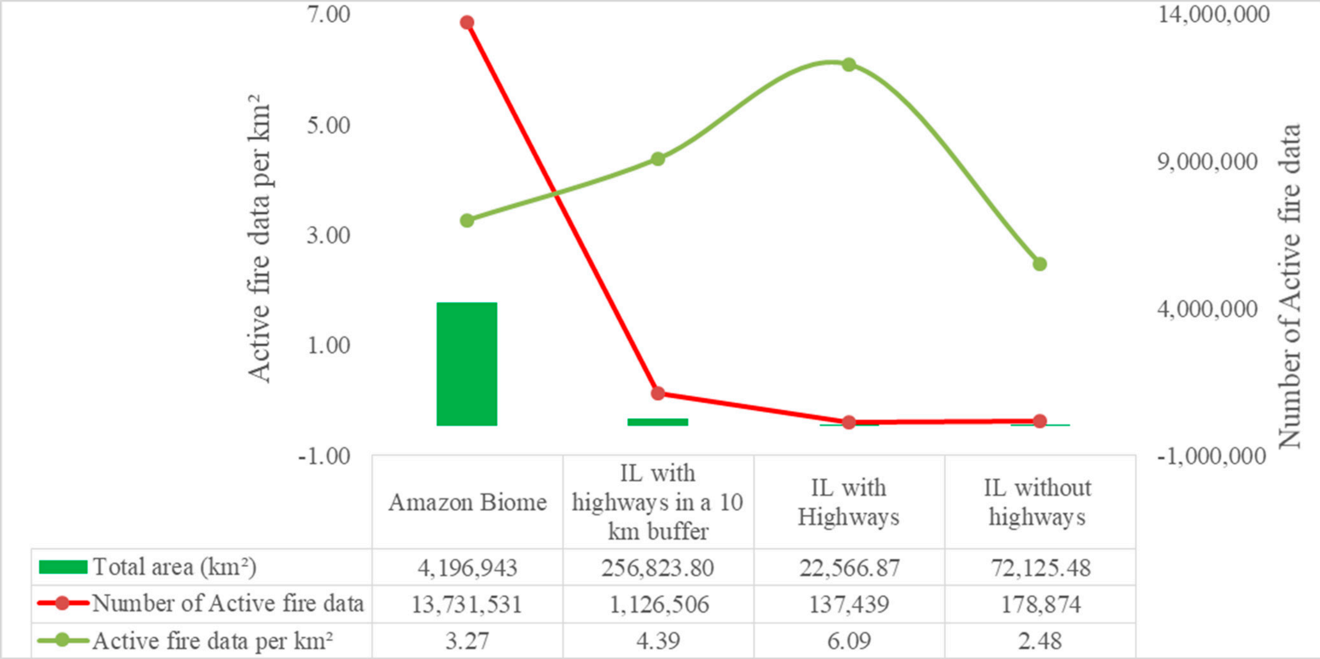

Figure 9. Number of active fires per km^2 classified according to the total area for Amazon biome, IL with highways in a 10 km buffer, IL with Highways, and IL without highways.

4. Discussion

Our work showed spatial and temporal patterns that revealed the influence of highways in the increase of active fires in the Indigenous Lands across the Brazilian Amazon, especially in the last three years. Our results reinforced the argument that deregulation, dismantling of environmental agencies, disregard for indigenous peoples′ rights, and budget cuts for deforestation containment policies [15] in the last three years have contributed to significant environmental transformations in the Brazilian Amazon.

Our results also showed the differences between the ILs categories according to the climatic period. We observed a large number of active fires during the rainy season in the ILs with highways [40]; this pattern was not recurrent throughout the entire Amazon region, but was concentrated in the northern region, in the state of Roraima, as was also observed by Barbosa et al. [41]. According to these authors, the spatial distribution of active fires suggests a pattern where the northern Amazon, specifically Roraima, records more active fires in the wettest period, while the states of Mato Grosso, Acre, Tocantins and Pará have more active fires in the driest period [41].

The occurrence of a higher number of active fires in a specific region of the Amazon, during the rainy season, was explained by several studies [41–44]. Silva Junior et al. [42] corroborate the analysis associating the increase in fires in the rainy periods due to climatic events with the influence of a neutral period (rainfall anomalies) between January and July in 2007, and also with the highest magnitude of trade winds that could favor fire spread. Barbosa et al. [41] also showed the role of other economic phenomena that could buffer the climatic effects on fires (for example the increase in the occupied area by agriculture and cattle ranching activities), driving in particular the abnormally wet periods of the fire regime of the Amazon region. Lima et al. [44] also found that the average number of active fires remained high, not varying, even in periods of extreme drought or periods of greater rainfall, thus attesting to human interference in this type of environmental degradation. Additionally, in the work from Xu et al. [45] they observed that the number of fires increased from 2019 in the absence of drought, suggesting an increased human disturbance in the Amazon.

Our results also showed that the southern region of the biome coincides with the region known as the arc of deforestation [25,26]. According to Rorato et al. [25], the ILs affected by multiple and relatively severe threats are mainly located in the arc of deforestation. This is a region where the highest rates of deforestation are caused mainly by the advance of the agricultural frontier toward the forest [25].

The density analysis of active fires also revealed the role of ILs in the protection of natural resources and the influence of highways in these areas, because highways strongly influence and represent threats to protected areas [23,46]. Santos [47] highlighted the influence of highways on Indigenous Lands in the State of Rondônia, particularly the federal highway BR-421, the implementation of which created lawsuits that requested its interdiction, but it was finally opened in 2014. In general, it was observed that there is no control over the opening of highways in areas of restricted use in the Amazon [47]. For example, new actions for maintenance of federal highway BR 319 were reported such as the Brazilian government′s campaign that promises to favor the occupation of the region, increasing the risk of fire [44].

Our research allowed for the analysis of the most degraded ILs under the influence of the highway network. It was also observed that the highways network inside and outside the perimeter of the Indigenous Lands reveals a differentiated dynamic, confirming the results of Rorato et al. [25], who showed that the threats related to forest loss (deforestation, forest degradation, and fires) are more intense in the buffer zones of the ILs than inside them, showing that ILs effectively promote environmental preservation [48].

The "fire crisis of the year 2019" in the Brazilian Amazon dominated the global news [43]. According to Aragão [49], the "Day of Fire", occurred on August 10th of 2019 when a coordinated series of forest fires in the Amazon region caused, in just one day, produced a 300% increase in active fires. Days later, the smoke reached the city of São Paulo, more than two thousand kilometers away, and turned day into night [49].

Active fires in ILs with an area higher than 2500 km^2 predominated in savanna enclaves within the Amazon biome, as mapped by Alves et al. [50]. Fire is a natural part of savanna dynamics, and this biome is resilient to this action [50,51]; thus, fire in ILs located in savanna environments may have its origins linked to natural factors [28].

We observed the highest correlation (0.98) between the fires and the IL area in the ILs with highways. This confirms the hypothesis about the influence of highways on the fire regimes within the ILs [2,43,52]. For example, in the State of Roraima, fire anomalies were observed mainly in areas where there is a high density of highways, rural settlements, and secondary vegetation cover of recent deforestation [52]. Moreover, the variable "distance to highways" had a positive correlation with fire occurrence in all three years in the area up to 3 km from highways [2]. Our work showed spatially explicit correlation that revealed the potential role of the highway network in the degradation, through active fires, within and around the ILs located in the Amazon biome.

5. Conclusions

The presented results from this study provide substantial information about fire and its relationship with the proximity of the highway network in the Amazon biome in Brazil. That is, the results reveal that the number of active fires occurring within the ILs is influenced by the presence of highways. This was possible through the observation that the ILs with highways around 10 km presented a greater inter-annual variation for the analyzed period.

Another aspect concerns the State of Roraima, which presented the highest number of fires in the ILs with highways, varying from 856 fires in 2010 to 25,879 in 2019. The number of active fires in ILs with areas from 0 to 500 km^2 (range of area that predominates the largest number of lands) did not concentrate the largest number of active fires, especially in the ILs with highways, where there were 2 ILs that showed one of the lowest numbers of active fires for this category. These data suggest that the ILs contribute to the preservation of the Amazon Forest.

Lastly, in the category of ILs with highways in the 10 km buffer, we found a higher occurrence of active fires in the IL, including those >2500 km^2 (75 units), with the forest areas being the most affected, followed by the savanna/grassland formations and agricultural and pasture areas.

In addition, it was also revealed that the dispersion of data separated by IL category showed positive correlations between the size of the IL and the average annual quantity of active fire spots. The highest correlation was found in ILs with highways, showing that highways have a direct influence on the increase in active fires in ILs.

Finally, we saw that the last three years presented significant differences in the analyzed period, showing significant increases in the number of active fires within the studied area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14159167/s1, Figure S1: Distribution of Indigenous Lands of the Brazilian Amazon biome by area intervals.

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