

Title: Impact of deforestation-related fires on air quality and indigenous health in the Brazilian Legal Amazon

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Abstract

Objective: Analyze the effects of exposure to particulate matter (PM_{2.5}) from deforestation-related fires on the hospitalization rate of indigenous people for respiratory diseases. **Methods:** An ecological time-series study was conducted to investigate the relationship between deforestation, forest fires and the health of the indigenous population of the Brazilian Legal Amazon. The respiratory problems evaluated are associated with short and long-term exposure to particulate matter (PM_{2.5}). The methodology was based on the analysis of geo-processing and statistics. **Results:** 81% of the municipalities presented yearly levels of PM_{2.5} above that considered safe by the World Health Organization. Daily levels also exceed recommended levels, especially near deforestation-related fires. The spatial focus of the analysis allowed the identification of links between the phenomena, in addition to mapping of critical regions. **Conclusion:** The study demonstrates that the fight against deforestation and illegally set fires in the Amazon is fundamental as a public health measure, especially during the COVID-19 pandemic.

Keywords fire, indigenous health, respiratory diseases, COVID-19, Amazon.

Introduction

Although little is known about the epidemiological profile of indigenous people, recent broad systematic reviews have shown that these populations are highly vulnerable to respiratory diseases, with a high prevalence of tuberculosis and acute respiratory infections¹. This condition is a result of associated risk factors, such as lack of access to higher quality healthcare, absence of water and sewer infrastructure, low income and large number of people living under the same roof^{2,3}. The effects of atmospheric pollution on human health are well known, as well as its impact on the respiratory system. Studies conducted in the Amazon region have shown a strong association between the particulate matter of forest fires and respiratory diseases for the population in general^{2,4}.

As occurs every year, an increase is expected in the number of deforestation-related fires during the months of August to October across most of the Amazon. The smoke from the fires contains, among other compounds, fine particulate matter, measuring less than 2.5 micrometers in diameter (PM_{2.5}). Particles of this fine particulate matter are easily inhaled and penetrate deeply into the respiratory tract, affecting pulmonary alveoli and bronchioles⁵. According to the World Health Organization (WHO), PM_{2.5} causes a broad range of deleterious effects to the health of the population, predominantly to the respiratory and cardiovascular system. The entire population is vulnerable, but susceptibility to the effects of PM_{2.5} is normally related to age and level of exposure. Although there is little evidence of a safe limit below which there are no

adverse health effects from exposure to PM_{2.5}, the WHO established an annual mean concentration of 10µg/m³ as a safe level for human health⁶.

It is important to highlight that the fire season in the Amazon has coincided with the COVID-19 pandemic in 2020. COVID-19 is an acute respiratory disease caused by SARS-CoV-2. In other words, the combined effect of the fires and the pandemic from the new coronavirus tends to increase the demand for health services associated with respiratory problems. Worsening the current scenario is the fact that part of the biomass felled in 2019 was not burned in that year^{7,8}. In addition, the temperature of the Atlantic Ocean in 2020 is above its historical mean, which tends to cause droughts in the southeastern Amazon, primarily in the state of Acre and adjacent regions⁹. In other words, there is a lot of combustible material (felled biomass), climactic conditions (intense above-average period of drought) and a backdrop of impunity regarding environmental infractions that create expectations of a season of intense fires in 2020 if appropriate command and control measures are not taken⁸. The exposure to smoke from the fires in the Amazon tends to further weaken the respiratory system of the population, which is still struggling to face COVID-19.

Given that deforestation is responsible for over 80% of the occurrences of fires in recently deforested areas¹⁰ and that these fires are responsible for 80% of the increase in particulate matter in the atmosphere¹¹, the increase in detections of deforestation in the Legal Amazon in the middle of the COVID-19 pandemic is of extreme concern. It is against this backdrop that the present study investigates the relationship between deforestation, fires and the health of the indigenous population in the Brazilian Legal Amazon, specifically, the occurrence of respiratory problems associated with short and

long-term exposure to particulate matter (PM_{2.5}). The methodology was based on the analysis of geo-processing and statistics, with a view to identifying links between the phenomena. The aim of the study was to map the critical regions, which deserve attention from researchers and decision-makers.

Methods

Although the relationships between deforestation, fire, concentration of PM_{2.5} and indigenous health are complex, we sought to evaluate hospitalization trends for indigenous people with long and short-term respiratory problems. In the present study, the long-term analysis considered the historical annual series of 2010 to 2019. The short-term analysis considered the monthly variation of environmental and health variables for the year 2019.

Concentration data for PM_{2.5} in Amazon municipalities were obtained from the Integrated Health-Related Environmental Information System (SISAM). In this system, data for PM_{2.5} are estimated based on the CAMS-Nrealtime model and are provided twice daily—at midnight and noon. All municipalities within the confines of the Brazilian Legal Amazon were considered, for a total of 760 municipalities. PM_{2.5} data were compiled into monthly and annual means.

Health data regarding hospitalizations for respiratory diseases were obtained from the Hospital Information System of the Unified Health System (SIH/SUS). The morbidities evaluated were: asthma, pneumonia, influenza, acute bronchitis, acute bronchiolitis and other acute infections of the upper respiratory tract. Information on the number of hospitalizations of indigenous people for these morbidities by month and residence were obtained for the age brackets of 0 to 4 years and 50 and over. The hospitalizations were

selected based on the residence of the patient to ensure better representation of the exposure of the population to concentrations of PM_{2.5}. The monthly hospitalization rates per 1,000 inhabitants were analyzed for both age brackets.

To obtain population data, information from the Health Information System for Indigenous Peoples (SIASI) was used to calculate the number of indigenous people treated by the Special Secretariat of Indigenous Health (SESAI) living on indigenous land in different stages of official administrative demarcation and/or in rural areas. Although these data do not cover indigenous people living in cities, it is estimated that they represent at least 74% of all indigenous people in the Amazon, and, therefore, were considered a representative sample of the indigenous people of the region. According to data from SIASI/SESAI, the indigenous population of the Brazilian Legal Amazon was 464,000 in 2019, of which 69,798 people were aged 0-4 years and 45,132 aged 50 and over.

The demographic data, originally grouped by villages, were analyzed and compiled according to municipality. These data cover 221 municipalities of the Legal Amazon, of which 94% contain indigenous lands. Information from SIASI/SESAI was obtained in January 2020 through a freedom of information request. It is assumed, for the sake of analysis, that the cases recorded as indigenous in the SIH/SUS correspond to the hospitalizations of indigenous people from the Indigenous Health Care Subsystem (SASI/SUS).

Data about the deforested area (km²) and number of hotspots by municipality were obtained from PRODES/INPE and BD Queimadas/INPE, respectively. The environmental variables regarding the year 2019 (deforestation, hotspots and PM_{2.5}

concentrations) were spatialized in a geographic database and submitted to a cluster analysis to identify the municipalities with statistically similar characteristics and outliers. The result of this analysis classified municipalities as:

- HH: high-high (tight clustering of high values);
- LL: low-low (tight clustering of low values);
- HL: high-low (outlier of high values that do not cluster, since they are found amidst low values);
- LH: low-high (outlier of low values that do not cluster, since they are found amidst high values);
- Insignificant: do not fit into clusters, since they present various levels just as the values of the adjacent municipalities.

For 2019, monthly data for $PM_{2.5}$, hotspots and hospitalizations were evaluated by grouping them by Amazon region and by state (Rondônia, Mato Grosso and Pará). On a state level, an analysis was conducted on the relationship between environmental variables and health considering the direction and magnitude of the associations between the variables according to a Pearson correlation matrix. Next, a linear regression analysis was used to evaluate the variables that presented significant correlation. The level of significance adopted was 5%.

Results

The analysis of the historical series from 2010 to 2019 shows a strong correlation between the number of hotspots and the mean concentration of $PM_{2.5}$ for the months August to October (Pearson correlation coefficient = 0.91), indicating that the fires of this period are the main source of $PM_{2.5}$ in the Amazon. The peak in the number of

hotspots and PM_{2.5} in the year 2010 is also evident, during a period of extreme drought in the Amazon associated with a high rate of deforestation (7,000 km²). At the end of the historical series, in the year 2019, a fall in PM_{2.5} was observed despite the high number of hotspots and increase in deforestation (10,129 km²).

To understand the context of this apparent contradiction and the relationship between hotspots and PM_{2.5} in the year 2019, we must remember the “day of fire,” which occurred on August 10, which led to inspection and enforcement activities supported by the Armed Forces (Decree 9.985/19, of August 23) and the prohibition of fires in Brazil for 60 days (Decree 9.992/19, of August 28). These activities may have contributed to reducing the number of hotspots in the month of October, when the number of hotspots fell to its lowest level since 1998. As a consequence, there was a significant decrease in the mean PM_{2.5} for the period considered (Aug/Sept/Oct). However, it should be noted that no effective control measures were taken to prevent the high rates of deforestation that year. In 2020, the same scenario repeats itself: absence of effective measures to control deforestation or the adoption of actions to fight fires. This time, the decree published on July 16, 2020 (Decree 10.424) prohibited fires throughout Brazil for 120 days.

The rate of hospitalization for 2019 was the highest of the historical series for the indigenous population aged 50 years and over and the second highest for children under five years of age. It is very likely that the acute exposure to high concentrations of PM_{2.5} associated with the “day of fire” explains this increase in the number of hospitalizations in this year in relation to the other years in the historical series.

The hospitalizations due to respiratory problems of indigenous people aged 50 and over during the dry season (August to October) present a mean of 1.32 ± 0.31 per thousand inhabitants for the period 2010 to 2019. The hospitalization of indigenous children under the age of five present a mean of 5.54 ± 1.34 per thousand inhabitants for the same period. The cluster analysis of the annual deforestation data, the sum total of the number of hotspots in the months of August, September and October (dry season) and the mean annual concentration of PM_{2.5} identified the groups of municipalities with the highest values for these variables for the year 2019. The result of the cluster analysis is presented in Figure 1, which shows that the region formed by southern Amazonas, southwestern Pará, northwestern Mato Grosso and northern Rondônia concentrate the municipalities with the highest values for deforestation, fires and mean annual concentration of PM_{2.5} (HHCluster).

81% of the municipalities (616) evaluated presented an mean annual concentration of PM_{2.5} above the limit considered safe by the WHO ($\text{PM}_{2.5} > 10 \mu\text{g}/\text{m}^3$). The municipalities with a concentration of PM_{2.5} in line with WHO guidelines are located in northeastern Amazon, including all municipalities in Amapá, and a few municipalities in the southeast of Tocantins and Mato Grosso (Figure 2). The highest concentrations of PM_{2.5} are found in the state of Rondônia, central-north of Mato Grosso, southwestern Pará, southeastern Amazonas, Manaus and Roraima region (Figure 2).

The highest concentrations of PM_{2.5} in the Brazilian Legal Amazon coincide with the period of the highest number of fires (peak in August/September) and lowest rainfall (dry season). At the height of the fires (August) the average concentration of PM_{2.5} in the Amazon reached $28 \mu\text{g}/\text{m}^3$. On a municipal level, the highest monthly value of PM_{2.5} occurred in Novo Progresso (PA), which reached a mean concentration of 132

$\mu\text{g}/\text{m}^3$ in the month of August and peak daily concentration of $570 \mu\text{g}/\text{m}^3$ at midnight on August 12.

In 2019, there were 2,556 hospitalizations of indigenous people aged 0-4 years for respiratory problems, of which 533 were between the months of August and October. In the age bracket of 50 years and over, there were 384 hospitalizations, of which 91 occurred between the months of August and October. For the age bracket 0-4 years, the highest rates of hospitalization during the dry season (Aug/Sept/Oct) occurred in the municipalities of Jaru (RO), Vilhena (RO) and Mirante da Serra (RO); western Mato Grosso; east of the Xingu Basin in Pará (Bannach (PA) and Ourilândia do Norte (PA)), Manaus (AM) and Mucajaí (RR) . Among those aged 50 and over, the highest rates of hospitalization during the dry season occurred predominantly in the arc of deforestation (Figure 3).

Monthly rates of hospitalization per thousand indigenous people in the age bracket of 50 and over was highest in the transition from the rainy season to the dry season (May and June). A lower number of hospitalizations occurred in the month of July; however, there was an increase of 25% in hospitalizations in August in relation to the month of July, which coincides with the period of increased number of fires. In the age bracket 0-4 years there was also a peak in hospitalization at the end of the rainy season (April/May); however, there was no increase in the number of hospitalizations during the period of fires.

On a municipal level, the mean hospitalization rate for the age bracket of 50 and over during the dry season (Aug/Sept/Oct) was 3.65 per thousand, while for the age bracket of 0-4 years this rate was 19.65. Figure 4 shows the locations of the municipalities that

present hospitalizations above (in red) and below the mean (in green) for the period for both age brackets.

The regions with above average hospitalizations during the dry season for the age bracket 50 and over are primarily located in municipalities with Indigenous Lands and the Xingu Basin, western Mato Grosso and Rondônia, and in some municipalities located in the transition zone between the biomes of the Amazon and Cerrado. In the age bracket 0-4 years, the above average hospitalizations are located in western Rondônia and Mato Grosso, Marcelândia (MT) and Nova Xavantina (MT), São Félix do Xingu (PA), Bannach (PA), Novo Progresso (PA), Novo Repartimento (PA), Grajaú (MA), Jenipapo dos Vieiras (MA), Manaus (AM), Mucajaí (RR) and Cruzeiro do Sul (AC) (Figure 4).

The state of Rondônia presented a strong correlation between monthly data for hotspots and concentration of $PM_{2.5}$ (Pearson correlation coefficient = 0.94), and a strong correlation with the rate of hospitalization for respiratory problems of indigenous people aged 50 and over (Pearson correlation coefficient = 0.82). The concentration of $PM_{2.5}$ explained 67.61% of the hospitalizations of indigenous people in this age bracket.

In the state of Mato Grosso, the peak in number of hotspots and concentration of $PM_{2.5}$ occurred in the month of September and there is a strong correlation between these variables (Pearson correlation coefficient = 0.84). Although the hospitalization rate for the 50-and-over age bracket tended to increase starting in the month of July, the peak in particulate matter and the peak in hospitalizations did not coincide. The variation observed in the rate of hospitalization during the period of fires may be related to the daily and intra-municipal variability of the concentration of $PM_{2.5}$ in the state. In any case, the mean rate of hospitalization for this age bracket for the months of August,

September and October (dry season) in the state was 1.55, while for the three previous months this rate was 1.16 (an increase of 33.62% for the dry season in relation to the three preceding months). No relationship was found between the monthly data on hospitalization rate for the age bracket 0-4 years and monthly concentration of PM_{2.5}.

In the state of Pará, there was no significant correlation between the number of hotspots and concentration of PM_{2.5}. There was also no significant correlation between the concentration of PM_{2.5} and hospitalizations in either age bracket. As in the state of Mato Grosso, in Pará, the weak correlation between the environmental and health variables may be related to the large intra-municipal variability of the data on deforestation, hotspots and PM_{2.5}.

Discussion

The present study shows the relationship between deforestation, fires and the health of the indigenous population in the Brazilian Legal Amazon. The forest tends to be burned by human action primarily during the months of August to October throughout most of the Amazon (dry season). With the fires, there is an increase in the concentration of PM_{2.5} in the atmosphere, which results in an increase in hospitalizations for respiratory problems in the region. To our knowledge, this is the first study that analyzes the specific impacts of the fires on the health of the indigenous population.

Although the health data available from the Hospital Information System of the Unified Health System (SIH/SUS) is measured on a monthly basis, which does not allow an evaluation of the influence of daily variation of the concentration of PM_{2.5} on the number of hospitalizations, and that it has not been possible to determine the ability of the indigenous populations to access health services, it was possible to evaluate the

relationship between deforestation, fires and indigenous health on different levels of spatial clustering.

The greatest concentrations of PM_{2.5} were in the state of Rondônia, central-north of Mato Grosso, southwestern Pará, southeastern Amazonas, Manaus and Roraima region. The region formed by southern Amazonas, southwestern Pará, northwestern Mato Grosso and northern Rondônia concentrate the municipalities with the highest values of deforestation (Aug/Sept/Oct), fires and mean annual concentration of PM_{2.5}. This region has already been highlighted in other studies on the effects of fires on health, corroborating the results found^{11,12}.

Rondônia, Pará and Mato Grosso also stand out for the number of municipalities with above average hospitalizations for the dry season in both age brackets analyzed. Silva *et al.* (2013)¹³ also concluded that the emissions of particulate matter originating in the Legal Amazon are related to the prevalence of hospitalizations for respiratory diseases in sensitive population groups in the state of Mato Grosso. In Silva *et al.* (2009)¹⁴, the authors observed a reduction in the rate of hospitalization and the number of hotspots in Rondônia for the period 2001-2010. The decrease in the occurrence of hotspots was, above all, the result of a set of government measures. The authors highlight that the hotspots should be used only as an indirect variable in a study that considers the correlation between atmospheric pollution and respiratory diseases¹⁴. This position reinforces the need for analysis of concentrations of PM_{2.5} at ground level, as used in the present study.

It is important to highlight that the adverse effects of the concentration of PM_{2.5} occur both in the short and long term. In addition to measures to reduce mean annual

concentrations of PM_{2.5} to the level recommended by the WHO, it is important to avoid peaks in concentration of PM_{2.5} over 24 hours. In the specific case of the Amazon, compliance with levels recommended by the WHO must be associated with control measures and punishment for deforestation and illegal fires. In addition, expanded healthcare access and infrastructure and social assistance are needed for indigenous people, especially in the critical municipalities identified.

Particulate matter can penetrate deeply into the lung, which can trigger an inflammatory process, and the smaller the particle, the worse the effect on human health. In addition, the longer the exposure, the greater the risk to health. In the case of indigenous children, repeated exposure to high concentrations of particulate matter can lead to pulmonary insufficiency, which is discovered only years later. The study showed high rates of hospitalization in both age brackets studied in the region known as the arc of deforestation. This finding is in agreement with Cardoso *et al.* (2009)¹⁵, who observed higher rates of hospitalization for asthma in children in the arc of deforestation, especially in the states of Rondônia and Maranhão.

Respiratory infections are among the main causes of hospitalization and deaths of indigenous children under the age of 5 in Brazil^{1,2}. Respiratory diseases are the main cause of hospitalization for the indigenous population in Brazil, except for hospitalizations for pregnancy, childbirth and post-partum. A detailed study conducted with a population of the Xavante ethnic group identified that children under 5 represent 50% of the total hospitalizations of the group, and most of these hospitalizations (45%) are the result of respiratory tract diseases². If the prevalence of respiratory diseases in indigenous populations is the result of associated factors, the high concentrations of

particulate matter act to significantly increase the vulnerability of the age groups most sensitive to these morbidities. With the arrival of the fire season in the Amazon in the middle of the COVID-19 pandemic, the study serves as a warning of the high risk that illegal forest fires pose to the original populations. In addition to the comorbidities, which can aggravate the COVID-19 condition, hospitalizations resulting from the fires could further test hospital capacity, as they are already overloaded by patients infected by the new coronavirus. Indigenous people are at particular risk, since their mortality rate for COVID-19 is 1.5 times the national average.

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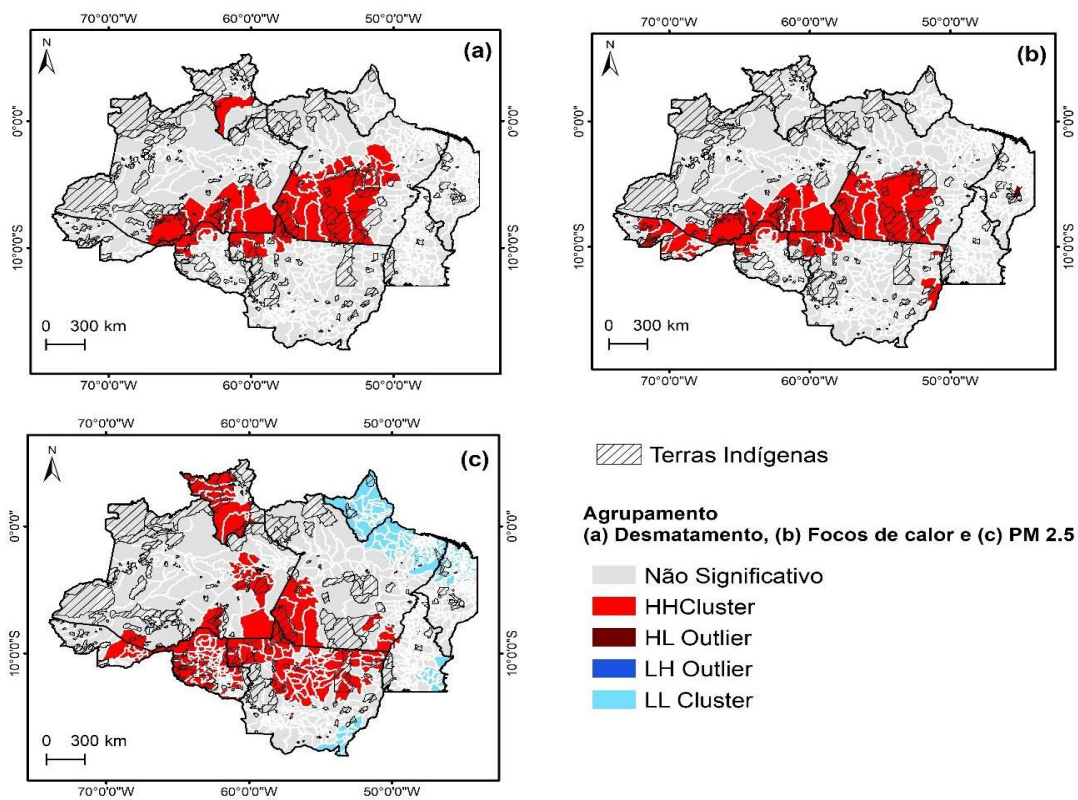


Figure 1. Result of the cluster analysis with data for annual deforestation (a), number of hotspots in the months of August, September and October (b) and mean annual concentration of PM_{2.5}.

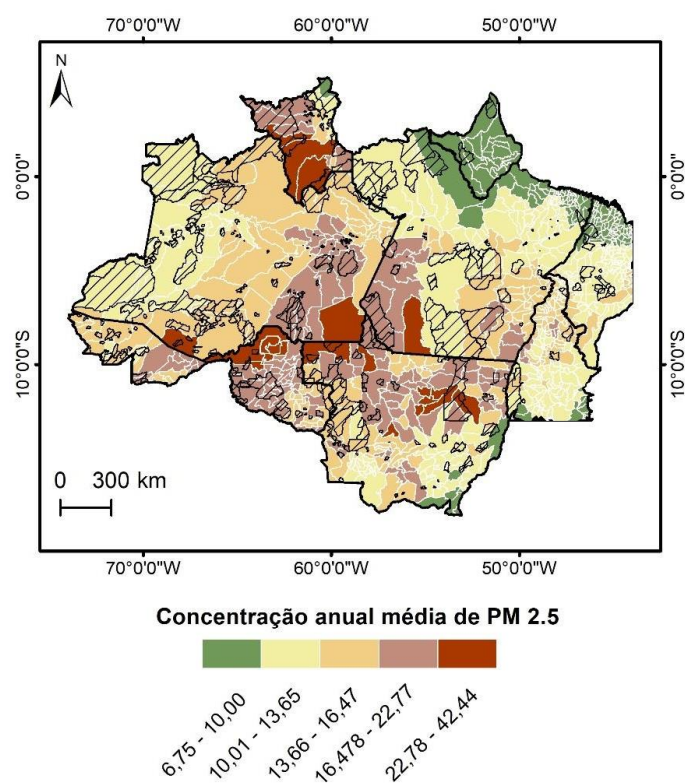


Figure 2. Mean annual concentration of PM_{2.5} in $\mu\text{g}/\text{m}^3$. Indigenous lands denoted by hatch pattern.

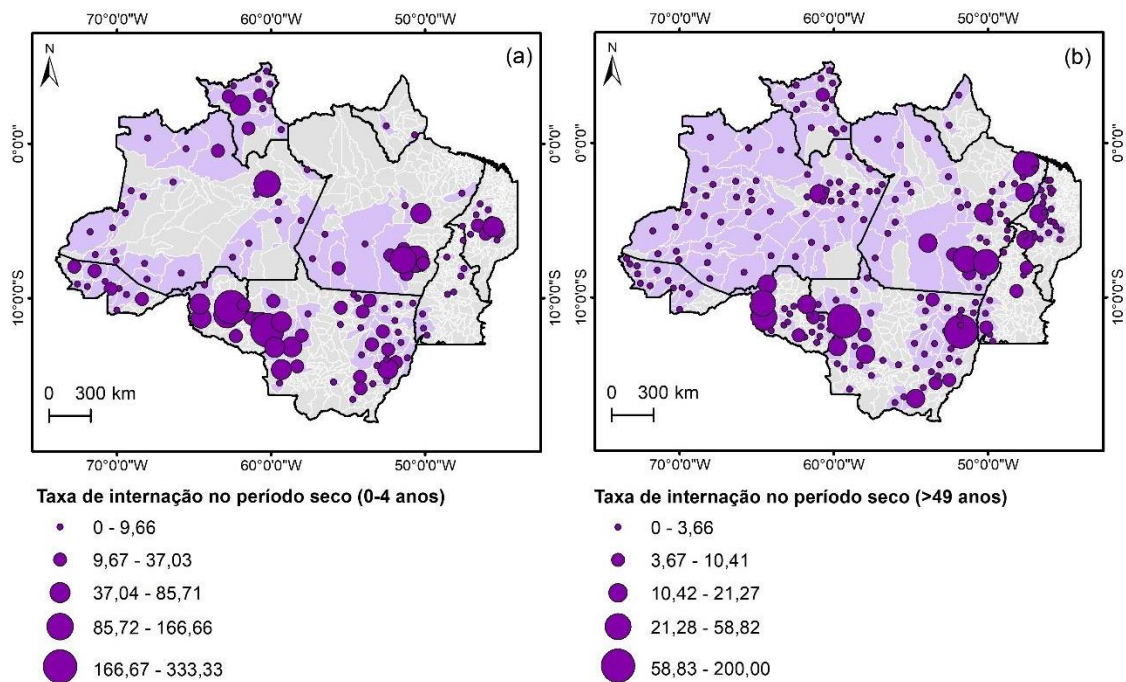


Figure 3. Rate of hospitalization per thousand indigenous people for the age bracket 0-4 years (a) and 50 and over (b) for the year 2019.

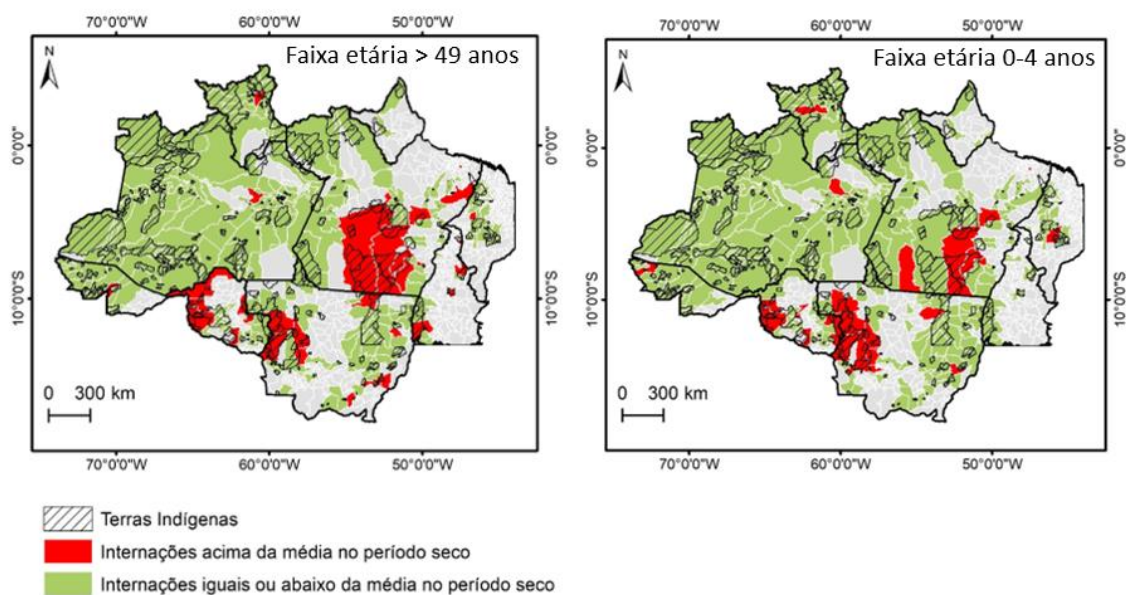


Figure 4. Municipalities with rates of hospitalization above (red) and below (green) the mean for the dry season (Aug/Sept/Oct) in the age bracket 50 and over (left) and the age bracket 0-4 years (right). Municipalities in gray have no information about indigenous populations for the age brackets considered.

