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Spatiotemporal relationship between agriculture, livestock, deforestation, and visceral leishmaniasis in Brazilian legal Amazon

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Visceral leishmaniasis (VL) is an urgent public health concern in Brazil. We evaluated the spatiotemporal distribution of VL to better understand the effects of economic activities related to agriculture, livestock, and deforestation on its incidence in the Brazilian Legal Amazon (BLA). The data on newly confirmed cases of VL in Brazilian municipalities from 2007 to 2020 were extracted from the Brazilian Notifiable Diseases Information System (SINAN) and analyzed. The data on agricultural production (planted area in hectares) and livestock (total number of cattle) were obtained from the Brazilian Institute of Geography and Statistics (IBGE), whereas deforestation data (in hectares) were obtained from the Amazon Deforestation Estimation Project (PRODES). SatScan and the local indicators of spatial association (LISA) were used to identify the spatial and temporal patterns of VL and its relationships with economic and environmental variables. The cumulative incidence rate was found to be 4.5 cases per 100,000 inhabitants. Based on the LISA results, areas with a high incidence of VL and deforestation were identified in the states of Roraima, Pará, and Maranhão. Strengthening deforestation monitoring programs and environmental enforcement actions can help implement public policies to control illegal deforestation and mitigate the socio-environmental vulnerability in the BLA. Therefore, areas identified in this study should be prioritized for controlling VL.

Keywords Epidemiology, Information systems, Neglected diseases, Statistical models

The ecosystems of the Amazon significantly contribute to the dynamics and control of zoonotic diseases and vector-borne infections, such as visceral leishmaniasis (VL), primarily because they play a pivotal role in preventing the collapse of global biodiversity and reducing the adverse effects of climate change throughout the world[1]. The Brazilian Legal Amazon (BLA) is a political-administrative region covering approximately 5 million km^2 (about 58.9% of Brazil's territory). Additionally, the Amazon rainforest is part of the Amazon Basin, the largest river system in the world[2], making it the theme of discussion at all major global conferences on the economy, biodiversity loss, and climate change.

The BLA is a vulnerable territory inhabited by the poorest populations from the countryside, forest, and water, such as riverside dwellers, settlers, quilombolas (afro-descendant communities), and indigenous people, among others. These populations are largely involved in mining and agricultural activities in the municipalities of the BLA. This region is an occupational model characterized by a rapid but unsustainable "boom-bust"

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economic growth pattern. The first few years of economic activity show rapid and ephemeral growth in income and employment, followed by a social, economic, and environmental collapse[3]. In this context, neglected and socially determined diseases, such as VL, are one of the major risks to the vulnerable population of this region.

Neglected tropical diseases are highly prevalent in low-income countries and are more concentrated in extremely poor populations living in precarious housing conditions that are devoid of basic preventive healthcare services[4,5]. VL is a neglected disease[6–8], with high mortality rates[7] that largely affect low-income populations[6]. Thus, it is a major public health concern worldwide[7,8]. The epidemiology of VL has changed in the last few years due to complex interactions among environmental, socioeconomic, demographic, and immunological factors[7,9,10]. It was previously considered a rural endemic disease in Brazil; however, in recent decades, most cases have been reported in large cities and the surrounding urban areas[7,9,11].

The Amazon region has a hot and humid equatorial climate, with rain occurring mainly between December and April[12]. The rainy season promotes the growth and dissemination of infectious disease vectors such as those responsible for VL[13]. Moreover, deforestation is associated with the emergence of viral, bacterial, and parasitic infections as it, along with other factors, affects the maintenance of pathogens in their natural hosts, alters the dynamics of vectors, and consequently, increases the contact between humans and pathogens[2].

In recent years, the rapid disappearance of Amazon rainforests has allowed the advancement of agriculture and livestock farming, thereby presenting high risks of irreversible changes in biodiversity and ecosystems[14]. Annual deforestation rates have increased significantly throughout the BLA in recent years. The Annual Deforestation Report (RAD 2022) by MapBiomas[15] stated that the deforested area in Brazil increased to 22.3% in 2022. In four years (from 2019 to 2022), more than 303,000 deforestation events were reported to affect 6.6 million hectares of land; in particular, the Amazon and Cerrado biomes accounted for 70.4% of the alerts and 90.1% of the deforested area in 2022[15]. Although the Cerrado accounts for only 8.3% of the total number of alerts, the total deforested area represents almost a third of the natural vegetation suppressed in the country (32.1%). The largest increase in areas occurred in the Amazon (an increase of 190,433 ha) and Cerrado (an increase of 156,871 ha)[15]. Moreover, the presence of squatters and farmers in these territories has resulted in several conflicts and violence against indigenous people[16].

Considering the importance of the BLA and the vulnerability of the population in this region to infectious diseases transmitted by vectors, particularly those related to increases in agricultural and livestock activities and deforestation, we studied the spatiotemporal effects of economic activities, such as livestock and agriculture, on deforestation and the incidence of VL in this region. As the environment and population in the Amazon region are threatened by several challenges, including rapid urbanization, loss of biodiversity, an increasing and dynamic human population, high inequality, and risk of disasters and extreme events due to ongoing climate change, this epidemiological assessment aimed to identify high-risk areas that are more vulnerable to deforestation and leishmaniasis and therefore provide relevant information that can guide the development of monitoring strategies and the formulation of disease control plans.

Methodology

Conceptual framework

Agriculture and livestock activities have tremendously expanded in Brazil in recent decades and frequently at the expense of customary landowners, traditional livelihoods, biodiversity, health, and quality of life. Although this advancement harms the environment and society, it is often justified as land transformation for developing underprivileged regions[17]. In this study, we determined the spatiotemporal relationships among agricultural and livestock production, deforestation, and health in the BLA. We specifically analyzed the relationship between variables that we grouped into the following dimensions: (i) economy, represented by agricultural and livestock production; (ii) environment, represented by deforestation; and (iii) health, represented by cases of VL.

The conceptual framework we developed considered that most deforestation events in the BLA are driven by an increase in agricultural and livestock production, compounded by poor institutional capacity, unclear land tenure, and restricted law enforcement[18]. Additionally, relatively high levels of deforestation contribute to the emergence of viral, bacterial, and parasitic infections,, which, along with other mechanisms, affect the maintenance of pathogens in their natural hosts, alter the dynamics and population of vectors, and increase the contact of humans with pathogens[2,19] (Fig. 1).

Study area

The term BLA was established by the Brazilian government to plan and promote the socioeconomic development of the states in the Amazon region, which have similar economic, political, and social challenges[20]. The BLA is a political-administrative region that covers approximately 59% of the Brazilian territory (Fig. 2), including the entire area of the Amazon biome, along with parts of the Cerrado and Pantanal biomes, encompassing 5.15 million km^2 of the total (7.59 million km^2) Pan-Amazon region[14]. It includes the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Mato Grosso, Tocantins, and part of Maranhão[16]. This area contains millions of species that have unique biological interactions and are responsible for global climate and hydrological regulation[21]. Moreover, it is inhabited by indigenous populations with rich cultures and unique traditions[22]. The population of the BLA has increased from around 8,200,000 million in 1972 to 29,313,409 in 2020, constituting approximately 13% of the Brazilian population[23].

Data

Visceral leishmaniasis is present on the national compulsory notification list of diseases and is frequently discussed in public health events in Brazil[24]. Information on confirmed cases of VL from 2007 to 2020 was obtained using the Notifiable Diseases Information System (SINAN). The SINAN databases were provided by the Brazilian Ministry of Health, and no personal information was present in these databases. The final database

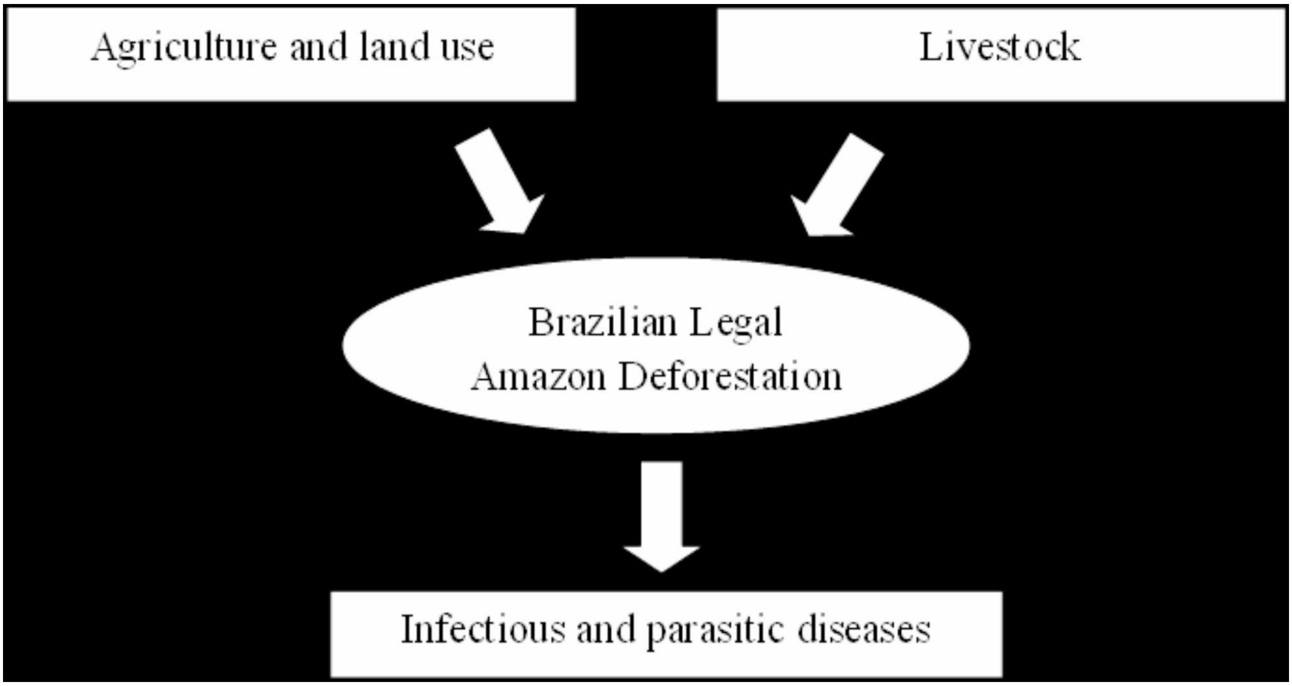

Fig. 1. Conceptual framework of the relationship between economic activities and deforestation and their effects on the incidence of infectious and parasitic diseases in the BLA.

was constructed by grouping the original data into a harmonized and unified database, including only new cases of VL.

The variables used in the analysis were grouped into the following dimensions: (i) economy, represented by agricultural (planted area in hectares)[25] and livestock production (total number of bovine herds), obtained from the Brazilian Institute of Geography and Statistics (IBGE)[26]; (ii) environment, represented by an increase in deforestation (in hectares), obtained from the Amazon Deforestation Estimate Project[27] (PRODES); and (iii) health, represented by confirmed cases of VL obtained from SINAN[28].

Data analysis

The spatiotemporal analysis was performed using SatScan™ version 9.4.4 (Kulldorff, Boston, MA, USA) and LISA models to identify geographic and temporal patterns of VL and its relationship with economic and environmental variables in the BLA. All analyses were performed using the GeoDa software (version 1.10. Arizona State University/Center for Geospatial Analysis and Computation, n.d., 2000).

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Spatiotemporal analysis

Space-time scan cluster analysis was performed using the SaTScan™ 9.4.4[29] software scanning statistics. Spatiotemporal clusters for deforestation and VL were obtained using the following information: population, number of cases, expected cases, annual cases, observed/expected cases, and location. The software provided data on the (1) number of cases, (2) year of infection, (3) population average of three years constituting the three years studied, and (4) geocode of each municipality. All data were entered for the entire period. The Poisson model constructed is as follows:

$$L\left(z,p\left(z\right),q\left(z\right)\right)=\frac{expexp\left[-p\left(z\right)n_z-q\left(z\right)\left(M-n_z\right)\right]}{C!}P\left(z\right)Cz\,q\left(z\right)C-cz\prod\nolimits_i Ci,$$

Here, z represents a candidate cluster, p(z) represents the probability of the phenomenon under study occurring within the circle, q(z) represents the probability of the phenomenon occurring outside of it, C represents the total number of cases in the entire study region, and M represents the total population. The exponential function is represented by exp, where cz and ci $(i, z = 1,2, \ldots, k)$ are the number of cases in circle z and circle i, respectively, and is the number of individuals at risk in circle z[30].

The discrete Poisson model was used[29] to identify spatiotemporal clusters and conduct scan statistics. The settings used were as follows: study period from 2007 to 2020, no geographic overlap of clusters, clusters of maximum size equal to 50% of the exposed population, circular sets, 999 repetitions, and time accuracy standardized at one year[28,31]. This model considers the space and time in which cases occurred[29,31,32]. A null distribution obtained by Monte Carlo simulations was used to conduct a significance test of the identified clusters. Different areas were compared using a program that presents the relative risk (RR) and likelihood ratio

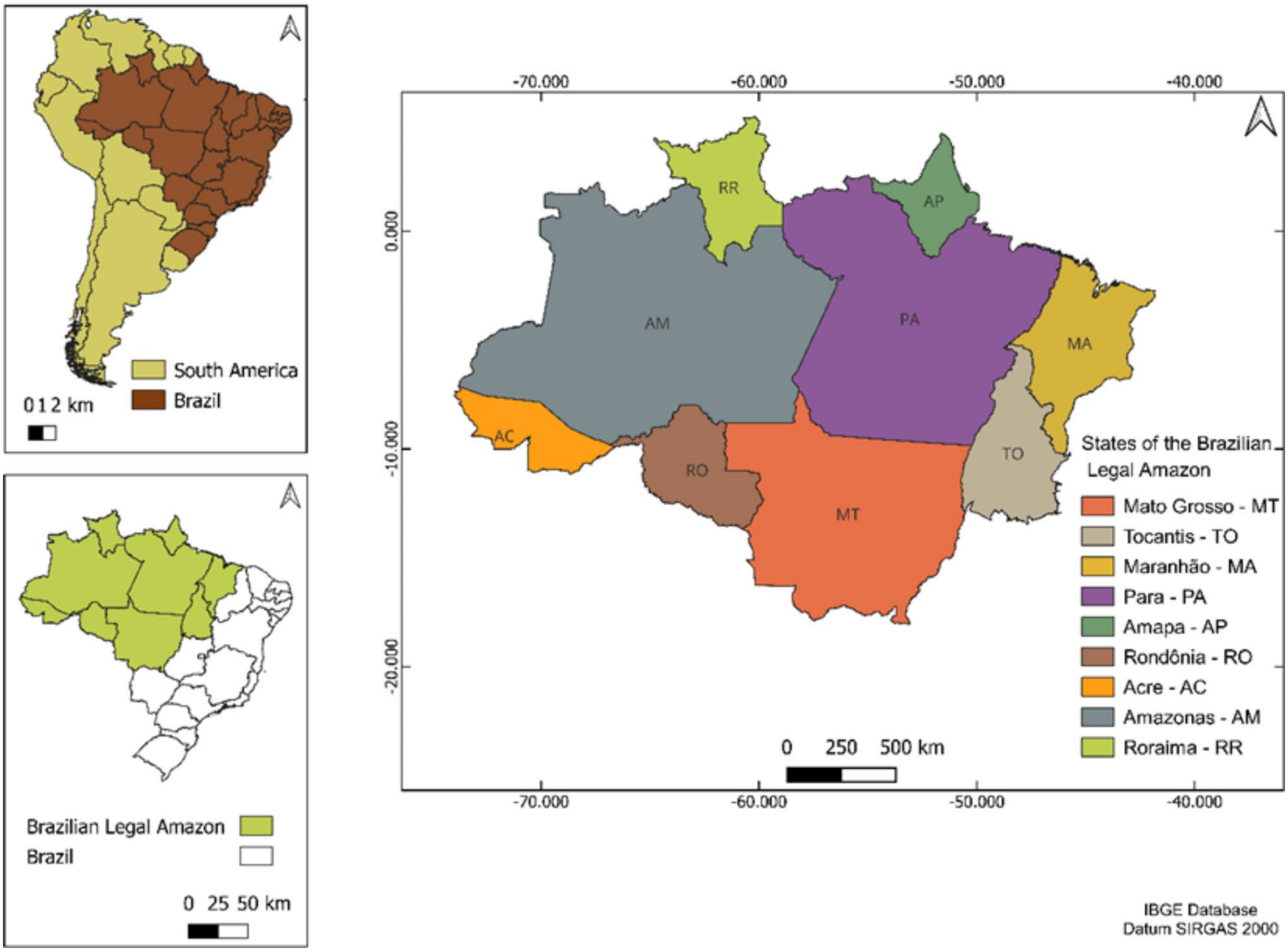

Fig. 2. Spatial location of the BLA in 2023.

of each cluster, which represents the relationship between the risk of injury within the cluster and the risk outside the cluster[29].

Spatial analysis

Bivariate spatial autocorrelation was used to determine whether the observed variable in a specific municipality was surrounded by a certain concentration of values of another variable in neighboring municipalities. Thus, the results for the bivariate LISA index were obtained according to the following analysis criteria: (i) high-high (positive values, positive means) indicating municipalities with high proportions of the variable surrounded by municipalities with high proportions of the other variable under analysis; (ii) low-low (negative values, negative means) indicating municipalities with a low proportion of the variable surrounded by municipalities with a low proportion of the other variable under analysis; (iii) high-low (positive values, negative means) denoting municipalities with a high proportion of the variable, surrounded by municipalities with a low proportion of the other variable under analysis; and (iv) low-high (negative values, positive means) indicating municipalities with a low proportion of the variable surrounded by municipalities with a high proportion of the other variable under analysis. Thus, the first two categories represent concordance areas, whereas the last two represent transition areas[33]. The spatial autocorrelation was considered to be statistically significant at $p \leq 0.05$.

Results

In total, 15,337 cases of VL were reported in the BLA from 2007 to 2020, among which 843 individuals died. The average incidence rate during this period was 4.5 cases per 100,000 inhabitants, and the case-fatality rate was 5.3%. From 2007 to 2020, the state of Tocantins displayed the highest incidence rate (21.3 cases per 100,000 inhabitants), followed by Maranhão (7.2 cases per 100,000 inhabitants) and Pará (4.4 cases per 100,000 inhabitants). From 2007 to 2014, Tocantins had the highest average incidence (26.6 cases per 100,000 inhabitants), followed by Maranhão (5.7 cases per 100,000 inhabitants) and Pará (4.01 cases per 100,000 inhabitants). From 2015 to 2020, Tocantins had the highest average incidence (14.3 cases per 100,000 inhabitants), followed by Maranhão (9.2 cases per 100,000 inhabitants), Roraima (5.4 cases per 100,000 inhabitants), and Pará (4.9 cases per 100,000 inhabitants). Amazonas had the highest case-fatality rate (10%) throughout the study period, followed by Mato Grosso (8.0%), Maranhão (6.09%), Roraima (5. 5%), Tocantins (5.2%), and Pará (4.1%) (Table 1).

States	Cases	Deaths	Incidence Rate (%)	Mortality Rate (%)	Case-fatality Rate (%)
Acre	0	0	0	0	0
Amapá	5	0	0.05	0	0
Amazonas	20	2	0.04	0.00	10.00
Maranhão	5580	340	7.27	0.44	6.09
Mato Grosso	587	47	1.38	0.11	8.01
Pará	4711	195	4.44	0.18	4.14
Rondônia	66	1	0.30	0.00	1.52
Roraima	233	13	3.69	0.21	5.58
Tocantins	4135	215	21.35	1.11	5.20
Total	15,337	813	4.5	0.24	5.3

Table 1. Incidence rate of VL in the States of the BLA from 2007 to 2020.

States	Increase in total deforestation (ha)	Average head of cattle	Average harvested area (ha)
Acre	4.817,60	2.852.713,36	106.979,50
Amapá	523,30	100.637,64	30.286,07
Amazonas	11.035,00	1.373.879,64	142.550,43
Maranhão	6.144,00	7.063.148,21	1.758.115,36
Mato Grosso	21.426,50	29.027.693,50	12.571.875,29
Pará	45.674,40	19.098.330,36	1.376.890,36
Rondônia	14.307,40	12.837.578,36	640.619,07
Roraima	3.393,10	701.073,64	59.159,00
Tocantins	723,90	8.176.002,86	990.159,00
Total	108.045,2	9.025.673,1	1.964.070,5

Table 2. Distribution of agricultural and livestock production and deforestation indicators in the States of the BLA from 2007 to 2020.

A growth of 33.1% was recorded for the total effective cattle herd from 2007 to 2020 in the BLA, increasing from 69,774,161 to 92,843,271. The harvested area increased by 90%, from 12,418,631 hectares to 23,597,667 hectares. The deforested areas in the BLA accounted for more than 108,045 hectares over 14 years. The largest average herd size was found in the states of Mato Grosso (29,027,694), Pará (19,098,330), and Rondônia (12,837,578), which had the largest deforested areas (75.3%) in this region from 2007 to 2020. The states with the largest average harvest areas were Mato Grosso (12,571,875 ha), Maranhão (1,758,115 ha), and Pará (1,376,890 ha) (Table 2).

The results of the bivariate analysis performed using the Moran local indicator (LISA) are presented in Fig. 3. The areas of greater agricultural production and deforestation were mostly distributed in Mato Grosso and the northern and northeastern mesoregions. Municipalities in these mesoregions demonstrated high proportions of agricultural production surrounded by those with high proportions of increased deforestation in 2020. The states of Acre (Vale do Acre mesoregion), Amazonas (south mesoregion), Mato Grosso (north mesoregion), Pará (southwest mesoregion), and Rondônia (Madeira Guaporé mesoregion) were identified as areas of high agricultural and livestock production and deforestation (Fig. 4). Finally, the areas at high risk of deforestation and VL infection were identified and were mostly located in the states of Roraima (north mesoregion), Pará (southeast mesoregion), and Maranhão (east mesoregion) (Fig. 4).

The maps shown in Fig. 4 illustrate the scanning analysis results for deforestation and VL cases in the municipalities of the BLA, thus identifying the risk areas in two different periods. During the first period (from 2007 to 2014), eight high-risk clusters for deforestation were identified, located in Pará (low Amazonas, southwest, northeast, and southeast mesoregions), Maranhão (west and center mesoregions), Rondônia (Madeira Guaporé and east mesoregions), Mato Grosso (west mesoregion), and Amazonas (southern mesoregion). During the second period, from 2015 to 2020, eight high-risk clusters were identified, located in Mato Grosso (north, northeast, and southwest mesoregions), Pará (Marajó, lower Amazonas, and southwest and southeast mesoregions), Maranhão (west and north mesoregions), Rondônia (Madeira Guaporé and east mesoregions), and Amapá (south mesoregion) (Supplementary material 1).

Concerning the incidence of VL, 10 high-risk clusters were identified in Pará (northeast and southwest mesoregions), Maranhão (east mesoregion) and Mato Grosso (southeastern mesoregion) states from 2007 to 2014. From 2015 to 2020, seven high-risk clusters for VL were identified in the BLA, in Pará (northeast and southeast mesoregions), Maranhão (east and south mesoregions), and Roraima (north mesoregion) states (Supplementary material 2). Areas located in Pará, Maranhão, and Roraima were high-risk clusters for deforestation and incidence of VL in the BLA from 2007 to 2020.

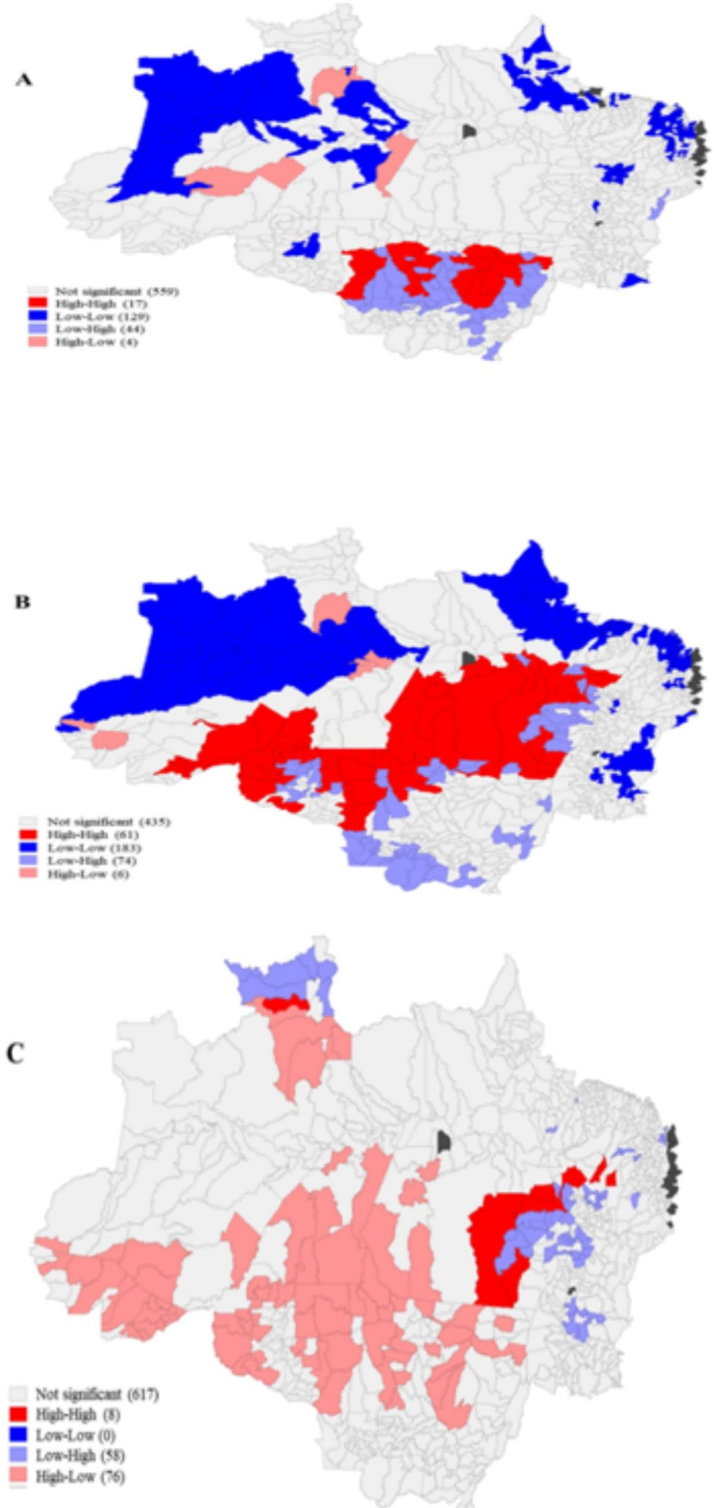

Fig. 3. Cluster map, scatter graph, and bivariate Moran indicator for (**A**) agricultural production × deforestation, (**B**) livestock production × deforestation, and (**C**) deforestation × visceral leishmaniasis × in 2020.

Discussion

The Amazon rainforest has received attention from researchers worldwide, especially because of the effects of climate change and the ongoing biodiversity crisis[34]. Economic activities can threaten the environmental stability of the municipalities in the BLA[35]. The relationship between global food markets and the Amazon forest highlights the overexploitation of natural resources and their effects on biodiversity[36]. Our study revealed

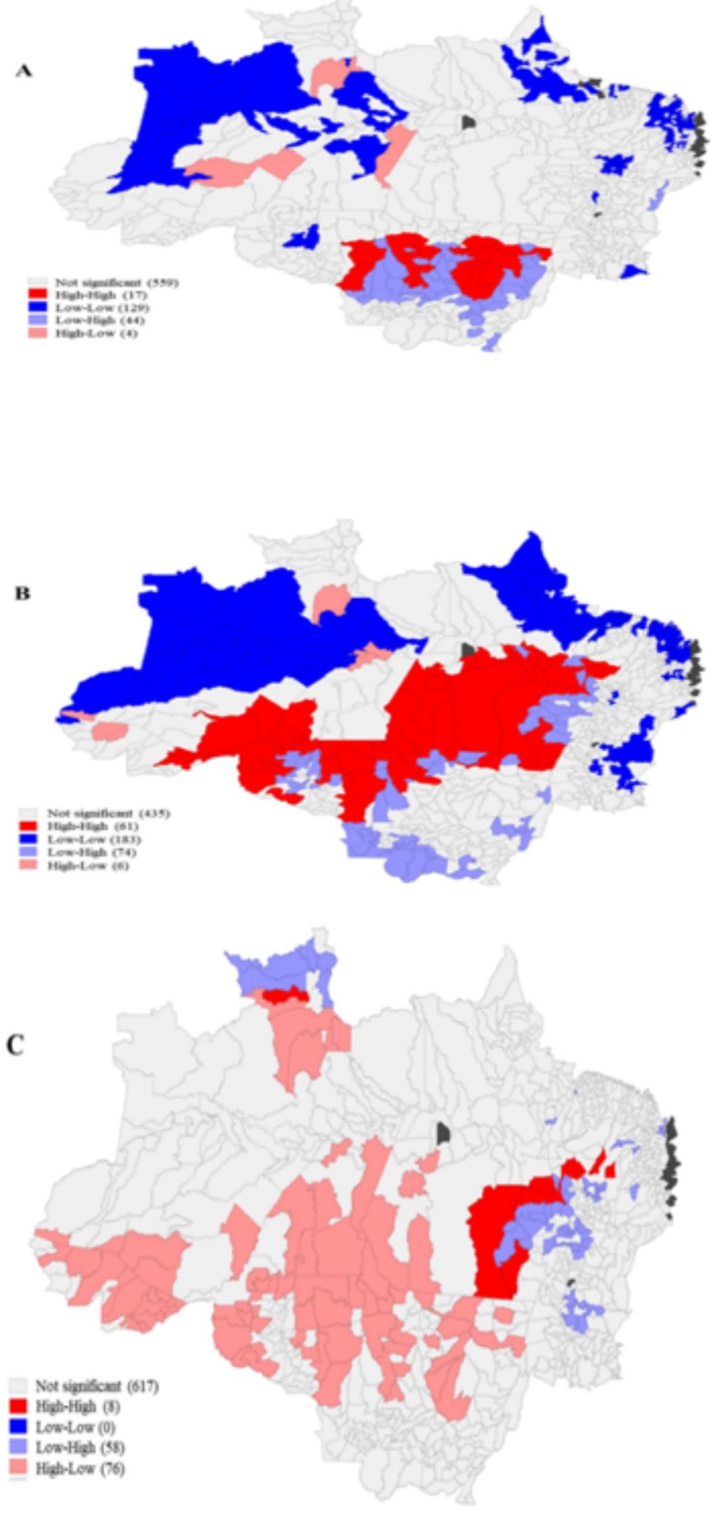

Fig. 4. Clusters with space-time trends for deforestation (**A**) and VL (**B**) in the BLA, Brazil (2007–2020).

the complexity of the spatiotemporal dynamics of VL and provided insights into the relationships between this disease and economic and environmental determinants, as measured by agricultural production and deforestation in a large region with unique environmental characteristics around the world.

We found that VL is an important public health concern in the BLA, considering that high morbidity and case- fatality rates were observed from 2007 to 2020. We also found that livestock and agricultural production had heterogeneous effects on deforestation and cases of VL in BLA municipalities. The spatial and spatiotemporal models revealed areas of deforestation and disease control strategies, including the increase in risk in new areas in the final few years of the study, in the state of Roraima.

These results are especially relevant to social determinants, such as poverty, and the lack of basic sanitation, among other factors, which are commonly present in the municipalities in the BLA, due to the association between the incidence and spatial distribution of VL and other neglected and vector-transmitted diseases[37]. These conditions occur unequally among the different regions of Brazil, as well as, among different states and municipalities of the BLA. Furthermore, Brazil has failed to reduce the case- fatality of the disease during the last few decades due to challenges primarily related to the spread of the vector and unequal access to diagnosis and treatment in different regions[38]. Therefore, the planning and implementation of public policies should consider problems such as social inequality, poor infrastructure and social services, and a lack of programs supporting the prevention and control of VL and other neglected tropical diseases[7,38]. The identification of higher-risk areas for deforestation and VL can also highlight socio-environmental vulnerability areas, which can be extremely valuable for health agencies to analyze the behavior of different health problems and direct efforts and resources for more effective surveillance and control measures, in addition to predicting risks in time.

Tocantins had one of the highest incidence rates and mortality rates during the study period, while the highest case- fatality rates were observed in Amazonas and Mato Grosso. Over the past decade, the incidence rates in the northern region surpassed those in the northeastern region, which until 2015 had the highest incidence rates in Brazil[39,40]. Additionally, the Cerrado (Mato Grosso and Tocantins) had the highest incidence rates between 2017 and 2020, and this trend might be related to the loss of native vegetation observed in recent years in this biome. A significant relationship was also found between dengue and the loss of native vegetation in the Cerrado biome between 2001 and 2019[41].

The environmental and social configurations of the BLA increase its vulnerability to VL transmission[5,7,42], especially considering the growth of economic activities in the region[5], which threatens its environmental stability. Currently, Brazil has the largest cattle herd in the world, with 218 million heads[43]. In 2022, meat exports increased by 26% in volume compared with those in the previous year. By 2030, meat exports are expected to reach 2.34 million tons, representing a 30.5% increase in exports[44]. Brazil is the fourth largest grain producer and the second largest grain exporter in the world. Brazil is also the largest producer and exporter of soybeans, accounting for 50% of the soybean trade in the world. Additionally, the production of coffee and sugar in Brazil has broken global records[45,46]. From 1985 to 2021, Brazil lost 13.1% of its native vegetation, including forests, savannas, and other non-forest formations. Most of this territory was occupied by agriculture and livestock activities, which now account for one-third of the land used in Brazil. This process of converting native vegetation into crop and pasture areas was more intense in certain regions, with an emphasis in recent years on MATOPIBA, an area with a predominance of the Cerrado between the states of Maranhão, Tocantins, Piauí, and Bahia, as well as AMACRO, in the BLA, between the states of Acre, Amazonas, and Rondônia. The MATOPIBA region accounted for 56.2% of the native vegetation loss in the Cerrado over the last 20 years. In AMACRO, the loss of forest increased considerably during the last decade, representing 22% of lost forest cover in the Amazon compared to 11% in 2000–2010[47].

Codeço et al.[5] analyzed the dominant technological trajectory of each municipality in the Amazon biome and its association with environmental degradation and vulnerability to neglected tropical diseases. They reported an association between livestock production and higher deforestation rates. They also reported that in parts of the BLA, agricultural and livestock economies have become dominant trajectories, characterized by large-scale production of cattle and grains. As found in this study, the authors also reported that these trajectories are associated with a rapid loss of biodiversity and a high prevalence of neglected tropical diseases[5]. Among all the dominant technological trajectories (TTs) for each municipality in the Amazon biome, TT4 (dominant in Rondônia, Mato Grosso, Maranhão, sul do Pará e Norte de Tocantins), which is associated mainly with beef production, had the highest number of municipalities with VL cases. These municipalities, which are located in areas with non-forest original physiognomy, have homogeneous landscapes produced by the dominance of large clean (managed) pasture areas with small patches of remaining fragmented forests[5].

In our study, the LISA maps revealed that the relationship between agricultural production and deforestation were stronger in 17 municipalities of Mato Grosso, including Brasnorte, Comodoro, Feliz Natal, Gaúcha do Norte, Ipiranga do Norte, Itanhanguá, Juína, Nova Lacerda, Nova Mutum, Nova Ubiratã, Porto dos Gaúchos, Santa Carmem, São José do Rio Claro, Sinop, Vera, and Nova Maringá. These municipalities are located in the Amazon under pressure, a region that covers 29% of the BLA and is characterized by municipalities with extensive forest coverage, which suffer from high deforestation, illegal logging, gold mining, and land grabbing[48]. The relationship between animal production and deforestation was also classified as high-high in 61 municipalities in the states of Acre, Amazonas, Mato Grosso, Pará, and Rondônia, and also in the Amazon under pressure (Fig. 2). The LISA results also revealed areas with a high incidence of VL and deforestation in the states of Roraima, Pará, and Maranhão (Fig. 2). Additionally, the spatiotemporal scanning analyses identified common areas at high risk for VL and deforestation, which were concentrated in the states of Pará and Maranhão, but later shifted to Roraima in the last few years of the study. This finding indicated that VL spread to new areas over time.

These results are especially relevant in the BLA, which is characterized by the fastest and most intense environmental changes caused mainly by the conversion of forests into pastures and planted areas, largely to export beef and soybeans[15]. This is the most prevalent and high-impact transition in the Brazilian Amazon[5,49], which increases the risk related to the sustainability of this social-ecological system due to the widespread application of chemical fertilizers and pesticides, unsustainable withdrawal of groundwater and surface water, air pollution, and degradation of soil quality, which have greatly altered the ecosystems and biodiversity in the region[4]. Thus, the expansion of agricultural land at the expense of natural habitats can increase the abundance of reservoirs and vectors of diseases in humans[5,50]. These changes can increase the predisposition to the emergence of new diseases or the incidence and death caused by endemic diseases[51,52], such as leishmaniasis, malaria, Chagas disease, leptospirosis, and dengue, along with other neglected tropical diseases prevalent in the BLA and associated with socio-environmental factors that increase vulnerability, including poverty, lack of basic sanitation, and poor availability of drinking water[5,16]. These challenges have led to international debates and increased pressure from society for a new development model that integrates economic growth and environmental conservation.

This study provides a better understanding of the effects of economic activities, such as livestock and agriculture, on deforestation and the incidence of VL, under conditions of rapid urbanization, loss of biodiversity, a growing and dynamic population, inequality, demand for social justice, rapid technological changes, poverty, land degradation, and food insecurity, along with risks of pandemics and increasingly intense extreme events due to ongoing climate change in the region. A major challenge involves maintaining the growth of agricultural production and simultaneously reducing the effects of these activities on the ecosystems in question. It is also necessary to reinforce deforestation monitoring programs and environmental inspection actions to successfully implement public policies to control illegal deforestation and mitigate socio-environmental vulnerability in the BLA. These challenges have led to international debates and increased pressure from society to develop a new model that integrates economic growth and environmental conservation.

Studies that use secondary data from surveillance systems have several limitations, mainly related to underreporting bias and incomplete recording of information[53]. Therefore, health surveillance professionals, such as nurses and doctors, should be trained to identify and investigate suspected cases of the disease to ensure early diagnosis and timely treatment, especially in regions where the disease has been introduced recently[54]. Additionally, most surveillance programs for neglected diseases in developing countries such as Brazil suffer from a lack of funding and other challenges, including migration, poorly planned or unplanned urbanization, social inequality, poor access to basic sanitation, climate changes, and deforestation, with effects on control actions[7,37,38]. Despite these limitations, our study highlighted the high risk of VL in this region, mainly in certain areas, and the combined effect of economic activities and deforestation on this risk in a regionalized manner. Epidemiological data on risk need to be analyzed to develop effective population-based prevention strategies and specific control policies for extremely vulnerable populations.

It is essential to highlight that the BLA is a huge, highly heterogeneous, and complex region. Such that other variables not considered could influence the analyzed relationships presented in this study, such as other economic activities (such as mining), climatic variables, urbanization connectivity between regions, the presence or absence of environmental protection areas in municipalities, deforestation monitoring programs, and environmental surveillance. In this context, it is important to highlight that this was an exploratory study, in which we assessed the spatiotemporal relationships between variables and did not evaluate the causal relationships between them, but rather their spatiotemporal associations. This approach could indicate potential causal relationships that need to be further explored in future studies. These future studies could also utilize the results obtained from these models to evaluate smaller geographic areas, particularly those at risk of deforestation and VL, including Maranhão, Pará, and Roraima. Furthermore, new studies might also identify the effects of other economic activities in the BLA, such as mining, and their impact on the incidence of VL and other neglected and socially determined diseases. Therefore, we believe that the proposed method to examine VL could serve as a tool for surveillance, given the increasing need to understand the dynamics of this neglected disease in the BLA and its relationship with economic and environmental factors.

Data availability

All data generated or analyzed during this study are included in this published article.

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Competing interests
The authors declare no competing interests.

Ethical approval
The study was approved by the Ethics Committee of the Faculty of Medicine of the Federal University of Pelotas, CAAE 46019321.6.0000.5317, in accordance with all ethical principles and current legislation for research involving human beings. In this way, the patient data were kept confidential and used only for research purposes.

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