Spatial epidemiology applied to the identification of landscape corridors and dispersion of yellow fever in the state of Minas Gerais, southeastern Brazil: Case study

Epidemiologia espacial aplicada à identificação de corredores da paisagem e dispersão da febre amarela no estado de Minas Gerais, sudeste do Brasil: Estudo de caso

Epidemiología espacial aplicada a la identificación de corredores paisajísticos y dispersión de fiebre amarilla en el estado de Minas Gerais, sureste de Brasil: Estudio de caso

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ABSTRACT

This study aims to identify landscape corridors best able to support Yellow Fever (YF) virus spread and risk areas based on the disease transmission process. Spatial approaches tools were used, such as the land use and land cover to define buffers, kernel estimation to identify areas with greater intensity of ecological corridors, and the Moran Local Bivariate Index of human cases, epizootics of Non-Human Primates (NHP), and the number of corridor areas. Reported 975 Human cases of YF and 2,424 NHP epizootics, but only 576 were confirmed. A high number of epizootics and corridors were observed in quadrant Q1 in the years 2016, 2017 and 2018, with 19, 16 and 24 municipalities respectively. The approach allowed the identification of the principal risk in corridors with a larger area, where groups of NHP can move more frequently, leading to crossings between different groups and providing populations with greater genetic diversity. In this situation, virus spread would be less likely to cause YF in many NHPs, acting as a regulator of virus circulation.

Keywords: Spatial analysis; Health surveillance; Sylvatic arbovirus.

RESUMO

Este estudo visa identificar os corredores de paisagem capazes de suportar a propagação do vírus da febre amarela (FA) e as áreas de risco com base no processo de transmissão da doença. Foram utilizadas ferramentas de abordagens espaciais, como o uso e cobertura da terra para definir *buffers*, estimativa de kernel para identificar áreas com maior intensidade de corredores ecológicos e o *Moran Local Bivariate Index* de casos humanos, epizootias de primatas não humanos (NHP), e o número de áreas de corredor. Foram registrados 975 casos humanos de FA e 2.424 epizootias de NHP, mas apenas 576 foram confirmados. Observou-se elevado número de epizootias e corredores, no quadrante Q1 nos anos de 2016, 2017 e 2018, com 19, 16 e 24 municípios respectivamente. A abordagem permitiu identificar o risco principal em corredores com maior área, onde grupos de PNH podem se movimentar com maior frequência, levando o cruzamento entre diferentes grupos e proporcionando populações com maior diversidade genética. Nessa situação, a disseminação do vírus teria menos probabilidade de causar FA em muitos PNHs, atuando como um regulador da circulação do vírus.

Palavras-Chaves: Análise espacial; vigilância de Saúde; Arbovírus silvestres.

RESUMEN

Este estudio tiene como objetivo identificar corredores paisajísticos capaces de soportar la propagación del virus de la fiebre amarilla (FA) y áreas de riesgo en función del proceso de transmisión de la enfermedad. Se utilizaron herramientas de enfoques espaciales, tales como uso de suelo y cobertura de suelo para definir zonas de amortiguamiento, estimación kernel para identificar áreas con mayor intensidad de corredores ecológicos y el Índice Local Bivariado de Moran de casos humanos, epizootias de primates no humanos (NHP), y el número de áreas de corredor. Hubo 975 casos humanos de epizootias de YF y 2424 NHP, pero solo se confirmaron 576. En el cuadrante Q1 se observó un alto número de epizootias y corredores en los años 2016, 2017 y 2018, con 19, 16 y 24 municipios respectivamente. El enfoque permitió identificar el principal riesgo en corredores de mayor área, donde los grupos de PNH pueden moverse con mayor frecuencia, lo que lleva al cruce entre diferentes grupos y proporciona poblaciones con mayor diversidad genética. En esta situación, sería menos probable que la propagación del virus causara FA en muchas HPN, actuando como un regulador de la circulación del virus.

Palabras clave: Análisis espacial; Vigilancia de la salud; Arbovirus salvajes.

1. Introduction

YF transmission between non-human primates (NHP) and wild vectors precedes human cases of YF. Therefore, the information about NHP deaths is an early warning to trigger control actions (COSTA et al., 2011). In this context, YF surveillance should incorporate the monitoring of NHP epizootics, mosquito vectors, and human cases, enabling increased sensitivity for the earlier detection of viral circulation (ROMANO et al., 2011).

Yellow Fever (YF) transmission can occur in two cycles, wild and urban. In the wild, non-human primates (NHP) are amplifying hosts for the virus. In the urban cycle, man is the only host with epidemiological importance.

In the 2000s, Brazil experienced an increase in Yellow Fever (YF) cases (BRASIL, 2015). Recently, between 2016 and 2017, the state of Minas Gerais, Southeast Brazil, emerged with a record of 475 new human cases (BRASIL 2018).

We highlighted that the disease is seasonal in Brazil, frequently occurring between December and April (ROMANO et al., 2011; VASCONCELOS, 2010). According to Barcellos et al. (2009), there is an association between infectious disease occurrence and environmental and climate factors. Besides, the existence of forest fragments, their size, and their quantity can influence various ecological processes, alter the stability of ecological interactions, and provide opportunities for organisms to coexist in a host-parasite system (OKLANDER; KOWALEWSKI; CORACH, 2010). The YF virus needs, for its maintenance, forested environments with the capacity to host species of wild vectors and their NHP hosts (MORENO; BARATA, 2011).

Scientific evidence points out that healthy forests with high biodiversity would hinder the proliferation of viruses. The impact of biodiversity on the emergence and transmission of infectious diseases, like Lyme Disease, has already been widely addressed (KEESING et al., 2010). A preserved environment may not be able to eliminate outbreaks but can reduce their intensity for several reasons, among them the more extraordinary genetic biodiversity. In small fragments of forests, without landscape corridors for connection, NHP populations live with mating with their close relatives, resulting in less genetic diversity (OKLANDER; KOWALEWSKI; CORACH, 2010; KELLER, 2002). In this situation, when a virus reaches a population of NHP without genetic diversity, it quickly spreads (HEDRICK; KIM; PARKER, 2001; ZUNINO et al., 2007). The variation in the size of forest fragments and communication between them can influence the spread of the disease. Understanding and anticipating this spread can be crucial in disease surveillance and control (BOULOS e GATTI, 2018; WILK-DA-SILVA et al, 2023).

Landscape corridors join forest fragments and/or conservation units separated by human interference, such as roads, agriculture, and timber activities. These corridors allow the movement of animals, the dispersion of seeds, and increased vegetation cover. They also reduce the effects of ecosystem fragmentation, providing gene flow between species of fauna and flora. This transit allows the recolonization of degraded areas, reconciling biodiversity conservation and environmental development in the region (MMA, 2007; SEOANE et al., 2010; KEESING et al., 2010).

The application of spatial epidemiology approaches (AUCHINCLOSS et al., 2012; DE SOUSA et al., 2020; ELLIOTT E WARTENBERG, 2004; FERREIRA; CHIARAVALLOTI-NETO; MONDINI, 2016) to the analysis of the YF epidemic (human cases, epizootics) allows a better understanding of the extent and trend of its geographical distribution. The results may assist in the organization of health services and guidance on surveillance and control measures, including delimiting areas for intensified vaccination. In this context, this study aims to identify landscape corridors more capable of supporting the spread of the YF virus, applying a spatial analysis method to define risk areas based on the disease transmission process.

2. Materials and Methods

2.1. Study Design and data

This is an ecological study based on a spatial approach, developed in the state of Minas Gerais, southeastern Brazil. Minas Gerais is the fourth largest Brazilian state considering territorial area (586,522,111 km²) and has approximately 21 million inhabitants. The last Census (2022) surveyed 2,315,560 people with a demographic density of 6,988.18 inhabitants per square kilometer (https://cidades.ibge.gov.br/brasil/mg/belo-horizonte/panorama).

This case study will test the proposed methodology that should be validated in the future, considering the local fact or probability of human infection.

Confirmed human cases and NHP epizootic diseases, confirmed or undetermined, according to the municipality records, were provided by the Health Surveillance Secretariat of the Ministry of Health from 2016 to 2018.

The municipalities and mesoregions shapefiles were downloaded from the IBGE website (www.igbe.gov.br). Mesoregion is a subdivision of Brazilian states that brings together several municipalities with economic and social similarities in a geographical area. Satellite images classified by land use and land cover (Thematic Maps of Land Use and Land Cover - MTUCO) were obtained on the MapBiomas website (https://mapbiomas.org/). We used MTUCO from 2012 to 2018, which has a spatial resolution of 30 meters, an accuracy of 85-90% in the Atlantic Forest biome, and 70-75% in the Cerrado (MAPBIOMAS, 2019).

2.2 Theoretical model study

The theoretical model idealized to determine risk areas for YF incorporates new technologies and techniques in the scope of spatial epidemiology (**Figure 1**). It aims to detect trends in the disease's viral spread and spatial distribution based on elements involved in the disease transmission process.

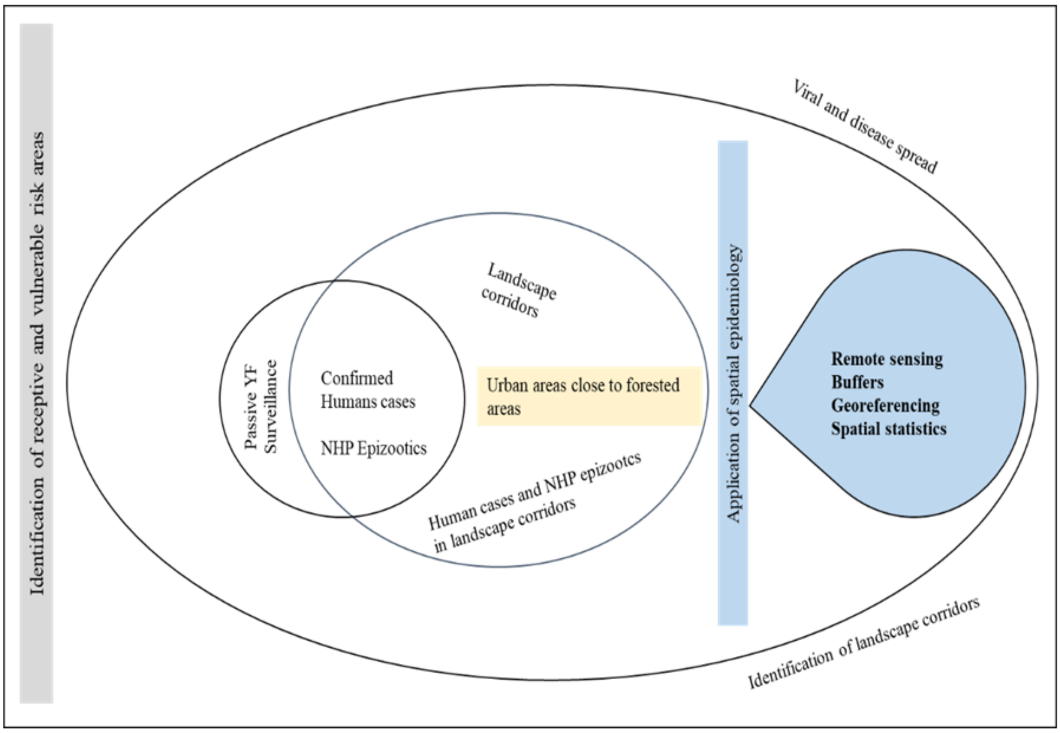


Figura 1. Theoretical methodological model for determining risk areas for Yellow Fever.

2.3. Data processing

The attributes of MTUCO were reclassified, to reduce the number of original classes, through the pixel values (supplementary 1). The reclassification of the annual images from MapBiomas generated eight (8) categories to highlight the land use/cover: (a) wild forests, (b) savannas, (c) natural formations and (d) planted forest, (e) agriculture, (f) non-vegetated areas, (g) urban infrastructure and (h) water. In this step, we use the R software.

The Buffers generation consider the following steps. Conversion of pixels from the Urban Infrastructure and Forest Formation class, from the matrix format to the vector format (a). Calculation of the Urban Infrastructure buffers, using 1km distance (b). Cutting and joining the Forest Formation layer using the buffers from the previous step (c). Thus, an area of interest of 1 km was generated around the Urban Infrastructure areas, in which Forest Formation regions were included. The buffers were calculated for each year of the study, but will only be presented for the year 2018.

As the original data are referenced to municipalities, there is no geographic location. Therefore, human cases and NHP epizootic, confirmed or undetermined, were randomly georeferenced within the buffers. We assume that probable sites of infection with human cases of YF occurred in urban centers (Urban Infrastructure), identified in buffers, and close to areas of Forest Formation regions. The random distribution of the geographic coordinates points considered the years 2016, 2017, and 2018. For human cases by municipalities, random points were generated into the buffer areas outside the forests (a), and only in the municipalities where the human cases were higher than zero (b). Similarly, for confirmed and/or undetermined epizootics, points were created into the buffer areas. But, within the forests (c), and only in the municipalities where there was at least one human case (d). In the municipalities with confirmed and/or undetermined epizootics, but human cases are equal to zero, was used the centroid of the municipality's area as the geographic coordinates point.

It is essential to highlight that we used the buffer with an artifact to define a risk area that was close to the forest, but that had an urban nucleus, even though the expansion of the circulation of the virus is associated with the occurrence of the wild cycle of the disease, with no evidence of its urbanization, as referred to by the Brazilian Ministry of Health (https://www.gov.br/saude/pt-br/assuntos/saude-de-a-a-z/f/febre-amarela).

Using satellite images from 2016, 2017, and 2018, we classified landscape corridors based on the adaptation of the methodology proposed by Vogt et al. (2007). According to Vogt et al. (2007) methodology, we use only the core, edge, patch, and corridor classes. We used the following steps to classify the runners: (1) creation of a binary image, where the values of the pixels corresponding to the Forest Formation reclassifying to the value 1, and the rest of the image reclassifying to the value 0; (2) calculation of core, edge and patch images using dilation and erosion morphological filters with a 5x5 pixel square mask; (3) classification of the corridors, through Geographic Object-Based Image Analysis (GEOBIA). Steps 1 and 2 were performed using R Core Team (2023), R: A

Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria (https://www.R-project.org/>). To optimize the processing time and computational cost, the image of the state of Minas Gerais was cut out in 21 quadrants. Step 3 was performed in the eCognition software, where a semi-automatic process tree was created. The process tree consists of (a) segmentation of the core, edge, and patch images; (b) classification of images in core, edge, and patch; (c) classification of patches that connect two or more colors/edges as corridors; and (d) exporting the corridors to the vector format as polygons.

After that, for each corridor, the area was calculated in km2. Then, we calculated the number and average of km2 of landscape corridors within or crossing each municipality. This step was developed using operations between layers in the ArcGis 10 software.

2.4 Data analysis

The distribution of human cases and NHP epizootics of YF were initially analyzed every four months, to characterize seasonality, and by municipalities.

The borders of the mesoregions were superimposed on maps of municipalities for better organization and discussion of results.

We applied the following criteria in defining the areas of risk based on the disease transmission process: (a) land use and land cover maps; (b) construction of the urban core buffers, (c) random drawing of cases in the buffer area outside the forests; and epizootics in the buffer areas within the forests and (d) identification of ecological corridors more capable of supporting the YF virus spread.

We calculated the local bivariate Moran index to test the spatial autocorrelation of human cases and epizootics confirmed with the number and average of the areas of the landscape corridors, also considering the municipalities. We used the Queen neighborhood matrix. We performed the Moran Local indices using a script routine in R software (https://gist.github.com/rafapereirabr/5348193abf779625f5e8c5090776a228), after adapting the data to the Gaussian distribution. We produced thematic maps by four months, kernel, and MoranMap using the QGIS 3.4.9-Madeira software.

The Kernel estimate was calculated based on the corridors' centroids to identify the locations of the highest intensity of landscape corridors. This analysis used a radius of 2 km and a quartic function.

The project meets all the ethical precepts contained in Resolution 466/12 of the Guidelines and Regulatory Norms for Research Involving Human Beings. It is noteworthy that the analyzed spatial scale guaranteed the non-identification of human cases of YF.

3. Results

3.1 Descriptive statistics

Between 2016 and 2018, the state of Minas Gerais, Brazil, confirmed 975 YF cases in humans, 52.5% in 2018. The municipality of Ladainha had the highest number of cases in 2016 and 2017, 7 and 46, respectively. In 2018, it was observed that ten municipalities had more than ten confirmed cases of the disease. Juiz de Fora and Mariana municipalities registered higher numbers, 40 and 39 cases, respectively (Table 1). Most (approximately 90%) of human cases occurred in the first four months of the study, mainly in January and February, the summer season.

During the study period, 2,424 NHP epizootic diseases were recorded, but only 576 were confirmed for YF. These records occurred in 190 municipalities (22.3%) of the 853 existing. However, the most confirmed diseases were registered in 2017 (372; 64.6%). Montes Claros, Belo Horizonte, Juiz de Fora, and Uberlândia were the municipalities with the highest number of epizootics in the period (**Table 1**).

We observe that few municipalities had epizootics and human cases in the same year (Table 1). However, in this analysis, we consider only the top 10 municipalities in the notification, not all municipalities with notification.

Table 1: Top ten municipalities and their respective mesoregions according to the number of cases of yellow fever in humans and epizootics of non-human primates, Minas Gerais, Brazil, between 2016 and 2018.

Municipalities / Mesoregion			
2016			
Epizootics of non-human primates		**Human cases**	
Frei Gaspar/Vale do Mucuri	3	Ipanema/Vale do Rio Doce	2
Aimorés/ Vale do Rio Doce	4	Poté/Vale do Mucuri	2
Mirabela/Norte de Minas	6	São Sebastião do Maranhão/Vale do Rio Doce	2
Itueta/ Vale do Rio Doce	4	Teófilo Otoni/Vale do Mucuri	2
Ladainha/Vale do Mucuri	**4**	**Ladainha/Vale do Mucuri**	**7**
Simonésia/Zona da Mata	5	Malacacheta/Vale do Mucuri	3
Imbé de Minas/Vale do Rio Doce	**4**	**Imbé de Minas/Vale do Rio Doce**	**4**
São José do Jacuri/Vale do Rio Doce	6	Itambacuri/Vale do Rio Doce	4
Coração de Jesus/Norte de Minas	9	Piedade de Caratinga/Vale do Mucuri	4
Caratinga/Vale do Rio Doce	11	Ubaporanga/Vale do Rio Doce	2
2017			
Epizootics of non-human primates		**Human cases**	
Leopoldina/Zona da Mata	12	Frei Gaspar/Vale do Mucuri	13
São Romão/Norte de Minas	12	Itambacuri/Vale do Rio Doce	13
São Roque de Minas/Oeste de Minas	12	Ipanema/Vale do Rio Doce	16
Teófilo Otoni/Vale do Mucuri	**23**	**Teófilo Otoni/Vale do Mucuri**	**16**
Nova Lima/Metropolitana	18	Lajinha/Zona da Mata	17
Uberaba/Triângulo Mineiro	17	Setubinha/Vale do Mucuri	18
Manhuaçu/Zona da Mata	30	Poté/Vale do Mucuri	24
Uberlândia/Triângulo Mineiro	48	Caratinga/Vale do Rio Doce	31
Belo Horizonte/Metropolitana	59	Novo Cruzeiro/Jequitinhonha	34
Montes Claros/Norte de Minas	91	Ladainha/Vale do Mucuri	46
2018			
Epizootics of non-human primates		**Human cases**	
Montes Claros/Norte de Minas	14	São Thomé das Letras/Sul e Sudoeste	12
Uberaba/Triângulo Mineiro	14	Sabará/Metropolitana	13
Uberlândia/Triângulo Mineiro	14	Itabirito/Metropolitana	14
Nova Lima/Metropolitana	**18**	**Nova Lima/Metropolitana**	**33**
Matias Barbosa/Zona da Mata	19	Caeté/Metropolitana	16
Barbacena/Campos das Vertentes	21	Santa Bárbara//Metropolitana	16
Brumadinho/Metropolitana	24	Barão de Cocais/Metropolitana	24
Itabirito Itabirito/Metropolitana	24	Ouro Preto/Metropolitana	15
Belo Horizonte/Metropolitana	39	Mariana/Metropolitana	39
Juiz de fora/ Zona da Mata	**86**	**Juiz de fora/Zona da Mata**	**40**

In the first and second quarters of 2016, epizootic diseases were concentrated in the northern region of Minas Gerais, an area with no human cases. In the third quarter, the epizootics were concentrated in the Vale do Mucuri and Vale do Rio Doce mesoregions, where human cases occurred in 2016 and, with higher incidence, in the first quarter of 2017. In this quarter, we observed epizootics in all mesoregions of the state. In the second quarter of 2017, animal diseases were concentrated in the Metropolitan and Campo das Vertentes mesoregions. In the third quarter, the epizootics still occurred in these mesoregions. However, there was more remarkable persistence in the mesoregions Oeste de Minas, Triângulo Mineiro, Sul e Sudoeste de Minas, and Zona de Mata. In 2017, there were also fewer human cases in the mesoregions of Zona da Mata and Metropolitana (**Figure 2**).

In 2018, human cases of YF occurred, mainly in the municipalities belonging to the metropolitan and Zona da Mata mesoregions. In these areas, NHP epizootics were concentrated in the first four months. However, we had epizootics in all mesoregions; we noted less occurrence in the South and Southwest mesoregions, where two municipalities had a higher number of epizootics. Throughout the period, we found that many municipalities in Minas Gerais had epizootics without the occurrence of human cases (**Figure 2**).

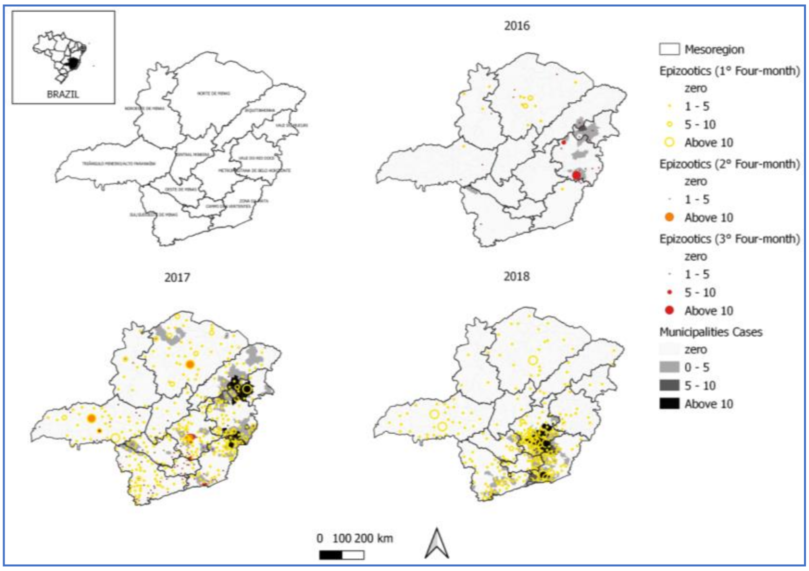


Figure 2. Thematic map of human cases of YF and epizootics of NHP about the quarter of the year, and municipalities, considering the mesoregions of the State of Minas Gerais, Brazil, between 2016 and 2018.

3.2 Spatial statistics

Figure 3 illustrates the methodology of the landscape classification corridors and buffers. This figure considered the georeferencing of the random points of human cases and NHP epizootics inside the buffers.

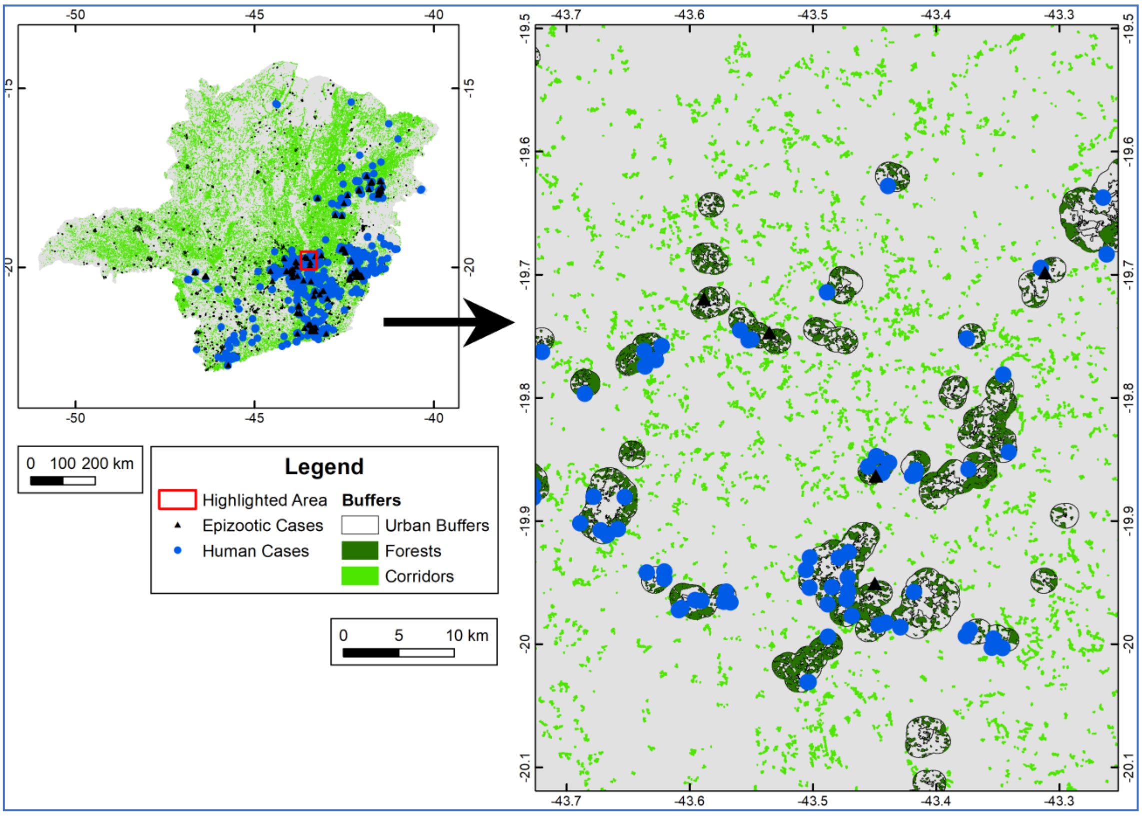
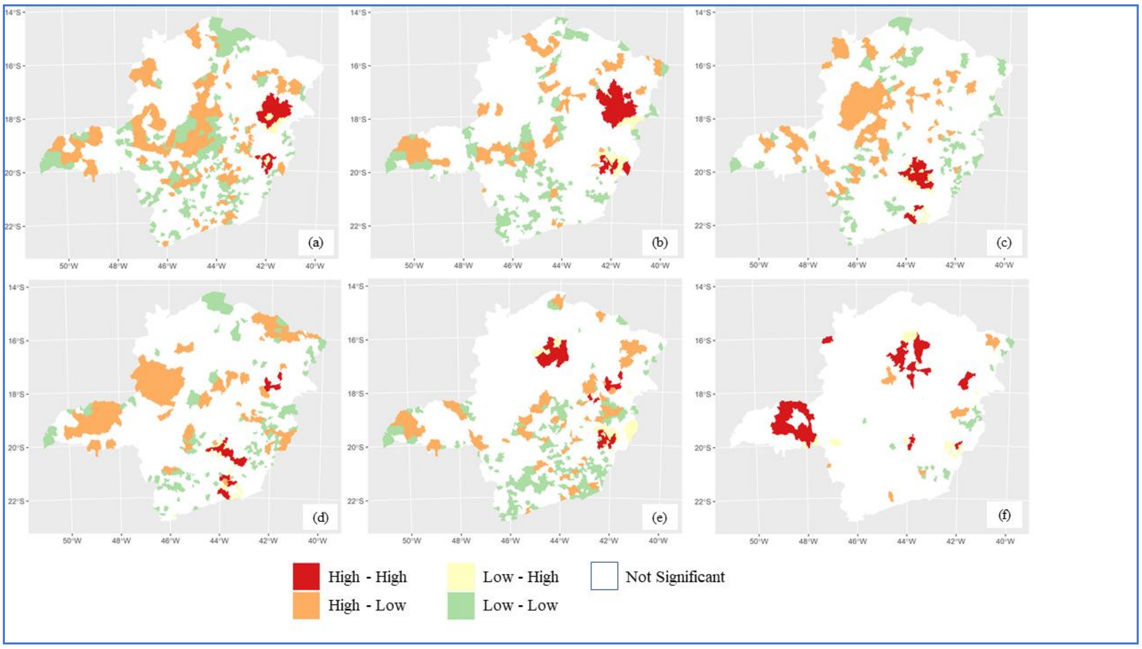


Figure 3. Thematic map of confirmed human cases of YF and epizootics of NHP, confirmed/indeterminate georeferenced within buffers, and landscape corridors in 2018. State of Minas Gerais, Brazil, 2016-2018.

The visual analysis of the comparison of the distribution of epizootics in NHP, human cases, and the intensity of the occurrence of landscape corridors in the municipalities (kernel estimate) shows that most human cases and NHP epizootics were concentrated in the areas of greatest intensity of landscape corridors. For better visualization of the cases and epizootics that were concentrated in the areas with the highest intensity of corridors, a clipping of an area of the study region was highlighted, reinforcing the importance of corridors in transmission, even though some cases fell in areas of low intensity, but within the 1km buffer proposed in this study (**Figure 4**).

The results show variation in the municipalities with the highest number of human cases and landscape corridors during the study period. In 2017, this scenario occurred in the Vale do Mucuri and Rio Doce mesoregions. In 2018 in the Zona da Mata and Metropolitana. Regarding the number of municipalities with the highest records of human cases and the largest number of landscape corridors in the Q1 quadrant (high-high), there were 12 in 2016, 20 in 2017, and 19 in 2018. Approximately 55% (11) of 2016 municipalities remained in the Q1 quadrant in 2017 but did not remain in 2018. In 2018, other municipalities were identified in the Q1 quadrant. Regarding a high number of epizootics and corridors, we observed 19, 16, and 24 municipalities in the Q1 quadrant in 2016, 2017, and 2018, respectively. Of the 19 in 2016, 4 remained in 2017 (Itaipé, Malacacheta, Poté, Setubinha) and 2018 (Itaipé, Nova Lima, Poté, Sabará) (**Figure 5**).

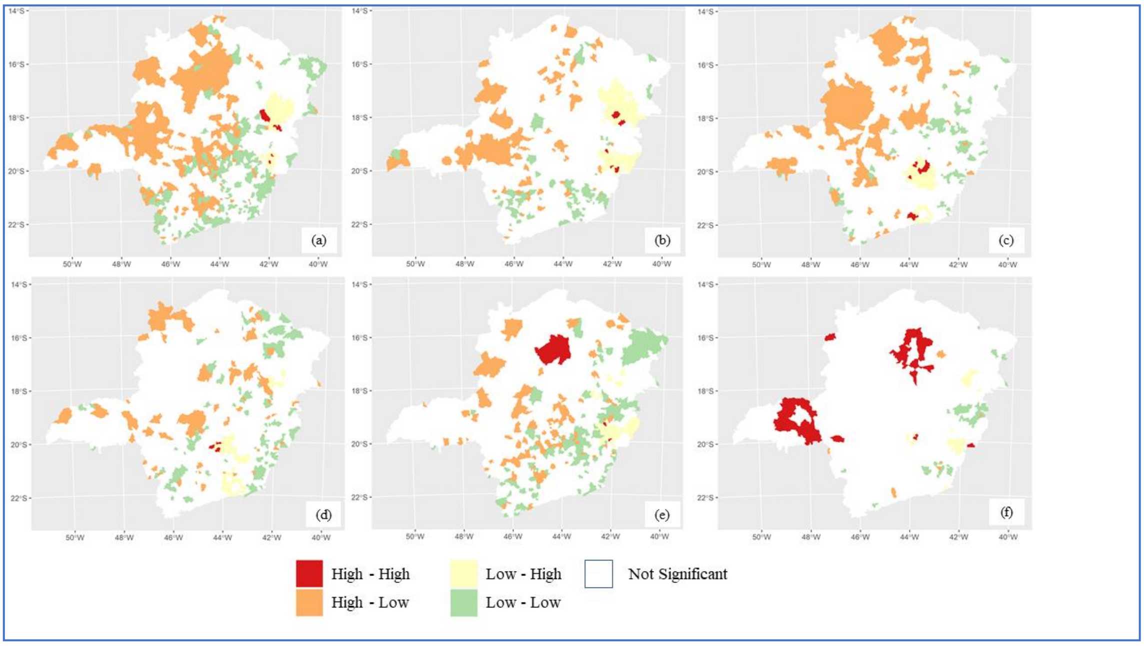


* a-2016; b-2017; c-2018 / ** d-2016; e-2017; f-2018

Figure 5. Map of the bivariate Moran index of the number of landscape corridors with confirmed human cases (a, b, c)* and confirmed / undetermined epizootics (d, e, f)**, according to municipalities in Minas Gerais, Brazil, between 2016 and 2018.

Figure 6 shows the presence of corridors with an elevated average area where there are few municipalities with human cases of YF (a, b, c), but with a coincidence of municipalities with epizootics, that is, high-high pattern, in the northern mesoregion of Minas Gerais in 2017 (e), and in 2018 (f) in the North and also Triangulo Mineiro.

It is relevant to highlight the occurrence of a cluster (High-High) with the same location for the number and size of corridors with epizootic diseases in 2017 (**Figures 5e and 6e**) and 2018 (**Figures 5f and 6f**).



* a-2016; b-2017; c-2018 / ** d-2016; e-2017; f-2018

Figure 6. Map of the bivariate Moran index of the average area of ecological corridors in km2 with confirmed human cases (a, b, c)* and confirmed/undetermined epizootics (d, e, f)**, according to municipalities in Minas Gerais, Brazil, between 2016 and 2018.

4. Discussion

Delimitation of risk areas for the occurrence of wild YF is of paramount importance for the surveillance and monitoring of this disease due to the overlap of areas infested by species of wild or urban vectors (OPS, 2005; RIBEIRO; ANTUNES, 2009).

In this case study, the method used made it possible to find the spatial coincidence of vulnerable areas, such as landscape corridors and FA in the PNH. Furthermore, in these areas, there was an increase in human cases of YF in a later period, associating the increase in the circulation of the virus among humans with the occurrence of the sylvatic cycle of the disease.

Landscape corridors with small areas interconnecting forests may reduce the crossing between groups of non-human primates from different regions. Thus, these small areas can decrease the probability of maintaining genetic variability between animals (OKLANDER; KOWALEWSKI; CORACH, 2010). This scenario increases the likelihood of many NHPs dying during an epidemic (HEDRICK; KIM; PARKER, 2001; ZUNINO et al., 2007).

Instead of small areas, the larger landscape corridors that interconnect forests can help restrain YF. In our results, we observed a few areas of high-high correlation with higher means in Km of landscaped corridors and municipalities with human cases. Through these corridors, groups of non-human primates can move more often. Crosses between different groups would lead to the exchange of genes and create populations with greater genetic diversity. In this situation, the spread of the virus would be less likely to cause AF in many non-human primates at once, acting as a regulator of virus circulation (WILK-DA-SILVA et al, 2023).

Cunha et al. (2019) analyzed the phylogeography and geopositioning of the YF virus that circulated in the city of São Paulo through the peri-urban area without detectable transmission between humans and towards the Atlantic Forest, causing human dissemination in nearby towns, however, without viral transmission in urban areas. Those who became infected are mainly unvaccinated people who live in peri-urban areas (bordering rural areas) or have had contact with forest areas.

Along these lines, the study by Possas et al. (2018) discusses the complex eco-social factors involved in the unexpected and rapid viral spread in the yellow fever outbreak (2017-2018) in Brazil, which increased the risk of re-urbanization of a disease without urban cases in Brazil since 1942. Among them, the rapid viral spread to the Southeast and southern regions, which led to an exponential increase in the number of yellow fever cases, especially in areas with fragments of the Atlantic Forest close to the peri-urban areas of the leading Brazilian megalopolises, São Paulo and Rio de Janeiro.

They also discuss the peculiarities and similarities of the current outbreak when compared with previous major epidemics, examining several hypotheses to explain the recent unexpected acceleration of epizootic waves in the YFV sylvatic cycle, along with the role of human mobility, NHPs, and mosquitoes in what concerns viral spread. Just like the study by Hill et al. (2020) which shows wild transmission of YFV in highly fragmented forest regions in the state of São Paulo and highlights the importance of continuous surveillance of zoonotic pathogens in sentinel species.

Among the possible causes of the rapid spread of yellow fever is the exacerbated degradation of some Brazilian natural environments due to deforestation, whether by fires or pasture spaces, among others, leading to the destruction of vast areas of forests and forcing the creation of several species of NHP to move to modified environments and suffer from overpopulation in tiny fragments of forests (POSSAS et al., 2018).

In the Southeast coastal region, where the outbreak was analyzed in this study, some factors stand out that may have corroborated the spread of wild epizootic waves of YFV, including the high population density of non-immune NHP on the Southeast coast and the increase in occupation of environments modified by some NHP specimens in areas with the presence of Haemagogus. As shown in the study by Lacerda et al. (2021) on the route in São Paulo, coming from the Triângulo Mineiro, where the virus moved on average 0.9 kilometers (km) per day mainly through mosquitoes, marmosets and capuchin monkeys through forests close to rivers and through Poços de Caldas, where the virus entered the Campinas region and began to move up to 2.7 km/day, mainly through mosquitoes and howler monkeys, among forest fragments.

Our data indicated an increase in the number of municipalities with human cases of YF from 2016 to 2017. There was also a shift in the human cases of the disease from the Vale do Mucuri and Vale do Rio Doce regions in 2017 to the metropolitan region and Zona da Mata in 2018.

The occurrence of epizootic disease in municipalities in Minas Gerais, where there were no human cases, can be partly explained by vaccination coverage. In areas with epidemics, vaccination must occur, especially if the municipalities are aware of the low vaccination coverage (NORONHA; CAMACHO, 2017). This is because these municipalities have corridors with larger areas that can provide greater genetic diversity for primates and reduce their circulation in search of food (OKLANDER; KOWALEWSKI; CORACH, 2010; KELLER, 2002). The state of Minas Gerais has been part of the area with vaccination recommendations since 2008 (BRASIL, 2018). However, this fact did not prevent epidemics, probably due to heterogeneous vaccine coverage (https://www.saude.mg.gov.br/febreamarela) and the flow of unvaccinated people from other areas of Brazil and abroad. The YF epidemic in Minas Gerais signals the need to improve disease surveillance, maintain an alert attitude toward patients with suggestive clinical conditions, promote continuing education, and intensify vaccination in susceptible populations at risk areas (COSTA; BENTES; TEIXEIRA, 2017).

In Brazil, there are ongoing surveillance efforts to detect cases of YF in non-human primates as an alert system (ALMEIDA et al., 2014). While this alert system to prevent epidemics in humans can be effective, recent outbreaks in southeastern Brazil have shown that, in some cases, such surveillance may not give results in the time required to trigger concrete actions, especially in areas with high and low population vaccination coverage rates (CHILDS et al., 2019). The rapid detection of YF through active environmental surveillance (timely identification of viral circulation in primates) and the prompt response with emergency vaccination are essential to control epidemics and outbreaks (BRASIL, 2014).

Different studies show significant losses of case records during georeferencing in this context. These losses can occur due to failures at the addresses of the Notifiable Diseases Information System (Sinan) (CARVALHO; MAGALHÃES; MEDRONHO, 2017; MAGALHÃES; MATOS; MEDRONHO, 2014). The lack of information from the street, especially in peripheral areas and slums, lack of standardization and irregular numbering of residences, and non-standard digital urban maps, among other aspects, compromise the capture of reality through geoprocessing and hinder decision-making (SKABA et al., 2004). Besides, georeferencing can be a costly and time-consuming phase of analyzing spatial data, which are limiting factors for the development of this type of study.

In our study, we had no loss during georeferencing human cases and NHP epizootics. No loss occurs because all georeferencing was considering buffers created based on environmental elements involved in the disease transmission process. For this reason, the methodology is a viable strategy for identifying risk areas on the analyzed scale.

5. Conclusions

The study limitation is related to the determination of the exact site of human infection and the NHP epizootics. Human case records are of likely infection sites, and addresses are incomplete and generally linked to the municipality. The NHPs epizootic records originate from dead NHP, and it is not possible to indicate the exact location of the infection.

In conclusion, the results showed that the methodology adopted in this study allowed the identification of the principal risk areas, mapping the possible path of the virus. Studies of this type can serve as a decision support tool, helping to define areas with priority vaccination and disease vector control. It is important to note that the success of YF control lies in identifying the environmental and behavioral factors that explain how endemic-epidemic processes occur (SABROZA; TOLEDO; OSANAI, 1992). These factors include knowing the distribution of vectors, reservoirs, and hosts, risk behaviors in the human population, and identifying and protecting susceptible groups. This study also opens perspectives for the deepening of spatial analyses that can support monitoring these factors and guide measures for the prevention and control of new YF epidemic outbreaks.

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