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Epidemiological Surveillance of pertussis in Minas Gerais: temporal trends and spatial patterns (2014–2024)

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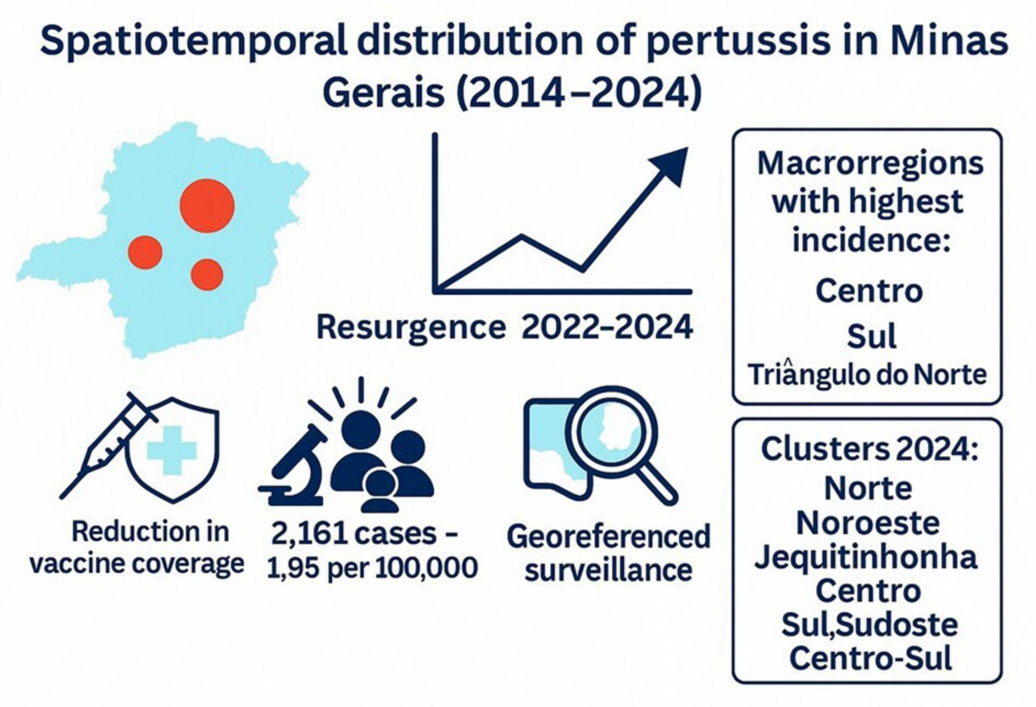
Highlights

- *After a decline between 2015 and 2021, there was a marked resurgence of pertussis cases starting in 2022, with two major high-risk clusters identified in 2024.*
- *The macro-regions Central (6.47), South (3.86), and Northern Triângulo (2.42) reported the highest incidence rates.*
- *The reemergence of the disease may be associated with decreased vaccination coverage and socioeconomic factors.*
- *High-risk clusters are observed in both the northern and southern macro-regions of the state.*

Graphical Abstract



Abstract

Pertussis is an acute respiratory infection with worldwide distribution that can be prevented through immunization and represents a significant risk to child health. This study aimed to analyze the spatiotemporal distribution of pertussis in Minas Gerais between 2014 and 2024, identifying high-risk areas and the temporal dynamics of the disease. This was a population-based ecological study using secondary data from the Minas Gerais Health Surveillance Portal. Generalized Additive Models (GAM) and spatial scan statistics were applied to detect spatiotemporal clusters. In Minas Gerais, 2,161 cases of pertussis were confirmed, with an average incidence of 1.95 per 100,000 inhabitants. The highest incidences were observed in the Central (6.47/100,000), Southern (3.86/100,000), and Northern Triângulo (2.42/100,000) macro-regions. The GAM-based graphical analysis revealed a decline in risk between 2015 and 2021, followed by a resurgence beginning in 2022. High-risk clusters were identified at different time points, particularly in 2024, involving the Northern, Northwestern, Jequitinhonha, Central, Western, Southern, Southwestern, and Central-Southern macro-regions. The study identified a cyclical and heterogeneous pattern of pertussis in Minas Gerais, with recrudescence after 2022 and high-risk clusters in vulnerable regions. These findings reinforce the need for continuous and georeferenced surveillance, with a focus on socioeconomically vulnerable areas, to prevent disease reemergence and support effective public health policies.

Keywords: Pertussis. Spatiotemporal Analysis. Epidemiological Monitoring.

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INTRODUCTION

Pertussis is an acute infection caused by the bacterium *Bordetella pertussis*. This respiratory-transmitted disease, present worldwide, is preventable by immunization and poses a significant risk to child health. It primarily affects the respiratory system, including the trachea and bronchi, and manifests as episodes of dry coughing. Transmission occurs mainly through direct contact between an infected individual and a susceptible one, via droplets expelled when coughing, speaking, or sneezing[1].

Between 1990 and 2019, a global decline in age-standardized incidence and mortality rates was observed; however, regions such as Sub-Saharan Africa, North America, Western Europe, and Australia showed upward trends[2]. In Brazil, the expansion of vaccination coverage with the tetravalent and DTP vaccines reduced incidence from 10.6 per 100,000 inhabitants in 1990 to 0.32 per 100,000 in 2010. Nevertheless, the disease resurged between 2011 and 2014 (peak of 4.2/100,000), followed by a gradual decline until 2018 (1.0/100,000)[3].

Between 2018 and 2021, the states of São Paulo, Pernambuco, Paraná, and Minas Gerais recorded the highest numbers of pertussis notifications. Among the confirmed cases during this period, Pernambuco, São Paulo, and Minas Gerais accounted for 25%, 17%, and 11% of the total, respectively, with a national incidence of 0.4 cases per 100,000 inhabitants[1]. From 2019 to 2023, all 27 federative units reported and confirmed cases of the disease, with Pernambuco showing the highest number of confirmations, followed by Minas Gerais, São Paulo, Paraná, Rio Grande do Sul, and Bahia, indicating the persistent circulation of the pathogen[4].

In July 2024, the Pan American Health Organization (PAHO) issued an alert for the Region of the Americas due to the increase in pertussis cases, mainly attributed to reduced vaccination coverage during the COVID-19 pandemic. According to PAHO, since 2012 there has been an annual decline in the number of reported cases, reaching the lowest record in 2022. However, a significant increase was observed in 2024, with more notifications in the first quarter of that year than during all of 2023[5].

Simultaneously, the Brazilian Ministry of Health reported a pertussis outbreak in Bolivia, emphasizing the importance of increasing sensitivity in detecting suspected cases and strengthening timely prevention and control actions in all Brazilian states, particularly those bordering Bolivia[6].

In this context, spatial epidemiology describes and analyzes the geographic variations of diseases in relation to demographic, environmental, behavioral, socioeconomic, genetic, and infectious factors, emphasizing risk mapping, correlation analysis, and cluster detection. Advances in Geographic Information Systems (GIS), statistical methods, and high-resolution georeferenced data have created unprecedented opportunities to explain local patterns[7].

In Minas Gerais, despite the number of notifications between 2018 and 2021, no studies were found integrating spatial and temporal analyses of pertussis incidence. Considering the disease's historical trajectory, robust studies are needed to determine the distribution and evolution of its behavior, especially following fluctuations in vaccination coverage and within the post-pandemic context.

Therefore, this study aimed to analyze the spatiotemporal distribution of pertussis cases in Minas Gerais between 2014 and 2024, to identify high-risk areas and understand the epidemiological dynamics of the disease in the state, using Generalized Additive Models and space–time scan statistics.

METHODS

This was a population-based ecological study that analyzed all annually reported and confirmed cases of pertussis in Minas Gerais, according to the municipality of residence, between 2014 and 2024. The units of analysis were the 853 municipalities of the state and its 16 Health Macro-Regions, following the official regionalization established by the State Health Secretariat (SES)[8].

Minas Gerais is one of the 27 federative units of Brazil, located in the Southeastern region of the country. It covers an area of 586,513.983 km², ranking fourth among the largest states by territorial extension, and is the second most populous state in the country, with an estimated population of 20.5 million inhabitants. It also has the largest number of municipalities in Brazil[8].

According to the State Health Department (SES), through the latest Regionalization Master Plan (Minas Gerais, 2023), these municipalities are grouped into 16 health macro-regions, as shown in Figure 1:

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Centro (101 municipalities), Centro-Sul (51), Extremo-Sul (53), Jequitinhonha (31), Leste (51), Leste do Sul (53), Nordeste (57), Noroeste (33), Norte (86), Oeste (53), Sudeste (94), Sudoeste (51), Sul (50), Triângulo do Norte (27), Triângulo do Sul (27), Vale do Aço (35)[8].

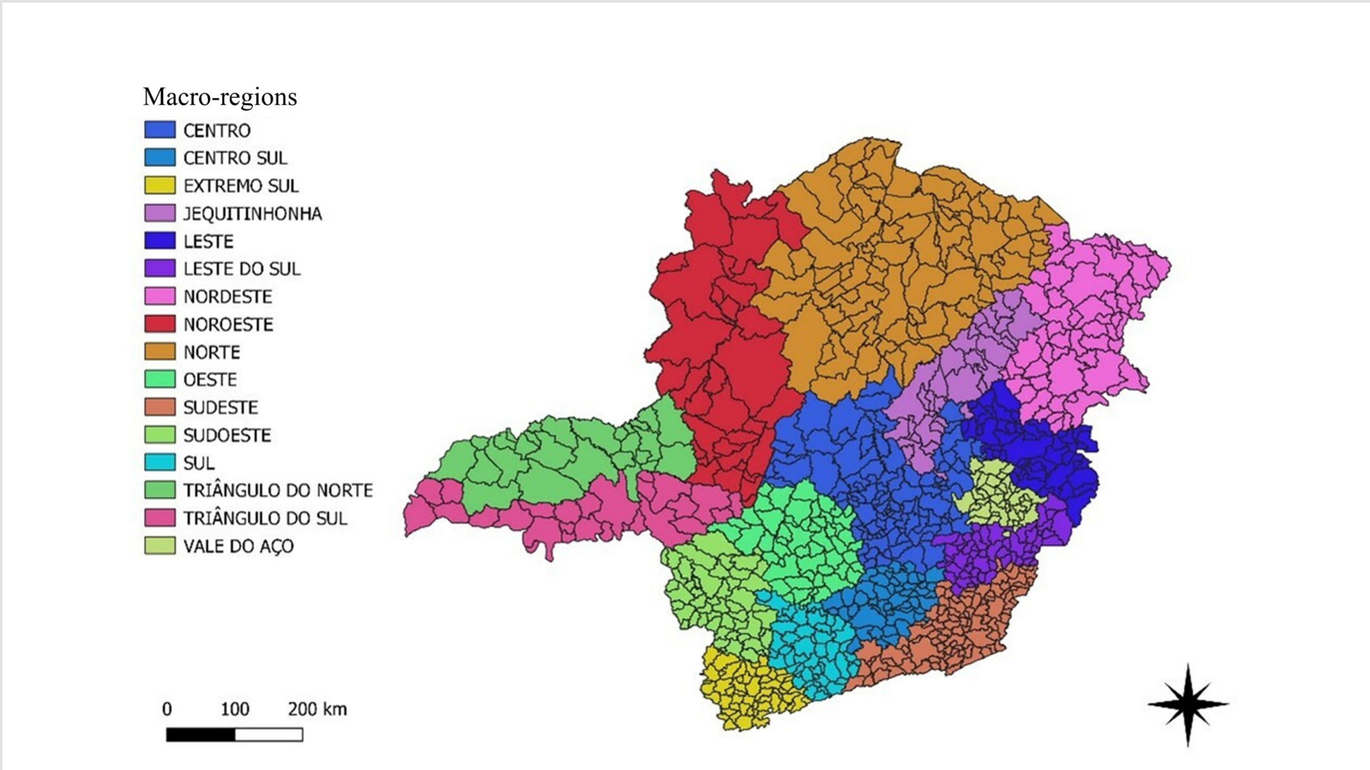

Figure 1 - Health Macroregions of Minas Gerais.

This study used secondary, annually aggregated data without participant identification, and all information presented is publicly available. Therefore, it was not submitted to a Research Ethics Committee, as it qualifies for exemption according to the Brazilian National Health Council Resolution No. 510, dated april 7, 2016[9].

Data were obtained from the Health Surveillance Portal (TABNET/DataSUS Technology)[10] of the Minas Gerais State Health Secretariat. Since the dataset comprises aggregated and publicly available information, there was no individual recruitment, follow-up loss, or matching. Population data used for incidence calculations were drawn from the Brazilian Institute of Geography and Statistics (IBGE) 2010 Census[11] for cases up to 2021 and the 2022 Census[12] for cases up to 2024.

For the construction of thematic maps, the cartographic base used was the digital mesh of Minas Gerais and its 853 municipalities, provided by the IBGE[13].

Data referring to the number of confirmed pertussis cases per municipality of residence, by health macro-region and year of notification, were extracted. The incidence rate was calculated by dividing the number of cases by the corresponding reference population (according to the census) and multiplying the result by 100,000 inhabitants. The average incidence for each macro-region and municipality was obtained by summing the annual incidence rates and dividing by the number of years in the study period.

A descriptive analysis was then conducted, presenting the distribution of mean incidence rates, followed by spatiotemporal analyses to identify patterns of disease distribution over time and space. The methodologies employed included Generalized Additive Models (GAM) for incidence modeling and spatial–temporal scan statistics using the Software for the Spatial, Temporal and Space-Time Scan Statistics (SaTScan), version 10.2.5[14], a free software tool designed to detect statistically significant clusters.

The annual temporal variation in pertussis risk was assessed using a Generalized Additive Model (GAM), an extension of generalized linear models that allows for the incorporation of nonparametric smoothing functions for explanatory variables. The model assumed that the annual count of disease cases followed a Poisson distribution, appropriate for modeling rare and discrete events such as annual notifications of infectious diseases.

To adjust for differences in population size across years and locations, an offset term was included, represented by the natural logarithm of the total resident population in each analysis unit and year. This term allows the model to estimate a rate (cases per inhabitant) rather than absolute counts, ensuring comparability among areas with distinct population sizes.

The main explanatory variable was the year of notification, treated as a continuous numeric variable and modeled using a smoothing spline function. This approach enables the identification of nonlinear temporal patterns — capturing gradual increases or decreases in incidence without assuming a predefined functional form (e.g., linear or quadratic). Such smoothers are particularly valuable in epidemiological contexts where disease behavior may vary complexly over time[15,16].

In addition to the purely temporal model, an interaction term between the year of notification and the health macro-region of residence was included, allowing for the evaluation of whether temporal risk patterns differed across regions. This approach enables the identification of regional variations in temporal trends, highlighting macro-regions exhibiting atypical or concerning behavior in the evolution of pertussis incidence.

The spatiotemporal analysis was performed using Kulldorff's spatial — temporal scan statistic[17], implemented through SaTScan™ software. This technique detects statistically significant space–time clusters — areas and periods exhibiting higher (or lower) risk of occurrence compared to the expected risk under the null hypothesis of random case distribution.

A discrete Poisson probability model was used, appropriate for aggregated count data with population information. It was assumed that cases followed a Poisson distribution proportional to the population at risk and that risk remained constant across space and time under the null hypothesis.

Cluster detection was carried out using a moving cylindrical window, where the base represents the geographic area (municipalities) and the height corresponds to the temporal interval (years). The maximum spatial window size was set to 50% of the population at risk, and the maximum temporal window size to 50% of the total study period, ensuring the identification of meaningful clusters without excessive spatial or temporal aggregation. The temporal unit was the year, and the analysis covered the period from 2014 to 2024.

Statistical significance of the clusters was assessed using the likelihood ratio test, with p-values obtained through Monte Carlo simulations (n = 999). Clusters with $p < 0.05$ were considered statistically significant. For each identified cluster, SaTScan provided spatial location, temporal interval, observed and expected case counts, relative risk (RR), likelihood ratio statistic, and p-value.

Primary and secondary clusters identified were represented in thematic maps for interpretation of the spatiotemporal patterns of the investigated event.

For choropleth map construction, QGIS[18] (open-source software) was used, and statistical analyses were performed in R (open-source software) using the following packages: mgcv, $ggplot_2$, tidyverse, ggthemes, geobr, dplyr, sf, spdep, gridExtra, RColorBrewer, and ggspatial.

RESULTS

A total of 2,161 confirmed cases of pertussis were reported in Minas Gerais between 2014 and 2024. The state's mean incidence during the analyzed period was 1.95 per 100,000 inhabitants. As shown in Table 1, the macro-region with the highest incidence was the Central region (6.47/100,000), followed by the Southern (3.86/100,000) and Northern Triângulo (2.42/100,000) regions. Conversely, the lowest incidences were observed in the Southern East (0.66/100,000), Northeastern (0.58/100,000), and Eastern (0.36/100,000) macro-regions. Notably, some regions displayed high variability in incidence rates within their territories, particularly the Central, Southern, and Southwestern macro-regions, which presented elevated standard deviations.

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Table 1 - Mean incidence of pertussis per 100,000 inhabitants, by Health Macro-Region of Minas Gerais, 2014–2024.

Health Macro-Region	Mean*	Standard Deviation	95% CI (Lower)	95% CI (Upper)
Central	6.47	76.67	1.96	10.98
Southern	3.86	19.83	2.20	5.52
Northern Triângulo	2.42	12.09	1.04	3.79
Southwestern	2.21	20.17	0.54	3.88
Extreme South	1.95	11.68	1.00	2.90
Jequitinhonha	1.47	10.08	0.40	2.54
Western	1.46	8.37	0.78	2.14
Southeastern	1.22	13.80	0.38	2.06
Vale do Aço	1.19	7.06	0.49	1.90
Northwestern	1.19	5.94	0.58	1.80
Southern Triângulo	1.05	5.53	0.43	1.68
Central-South	0.87	5.82	0.39	1.36
Northern	0.71	3.98	0.45	0.96
Southern East	0.66	4.30	0.31	1.01
Northeastern	0.59	3.08	0.34	0.83
Eastern	0.36	2.74	0.14	0.59

*Mean annual incidence, considering the years 2014–2024 for each Health Macro-Region, weighted by the number of municipalities per region.
Source: Authors (2025).

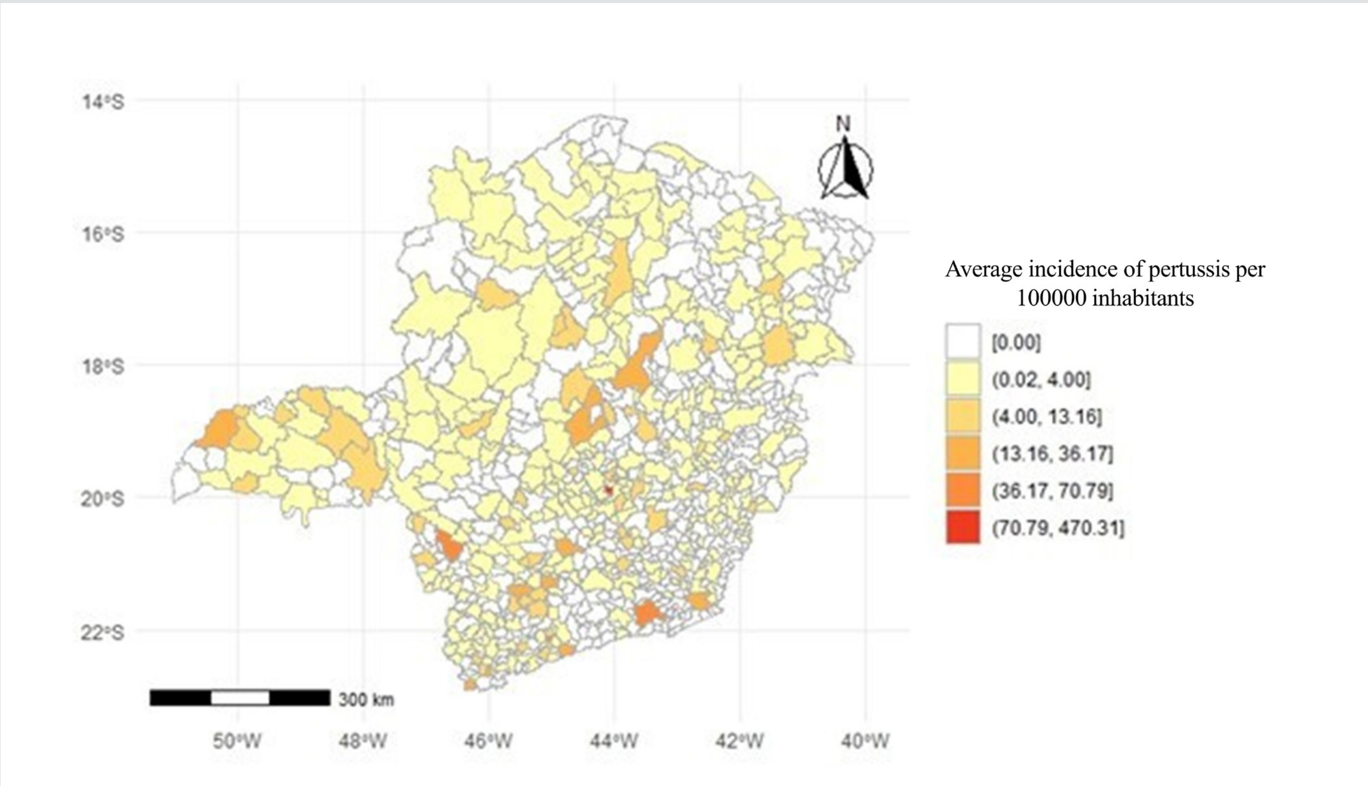

Figure 2 - Spatial distribution of the mean incidence rate of pertussis, 2014–2024, Minas Gerais.

Figure 2 shows the spatial distribution of these rates by municipality, considering all 853 municipalities of Minas Gerais. A heterogeneous distribution of average rates is evident, with some macro-regions containing municipalities with high rates, such as the Central, Southern, Southwestern, and Southeastern macro-regions.

Figure 3 - Smoothed curves of the temporal effect on the risk of pertussis occurrence according to purely temporal GAM models for the entire state (Figure 3) and considering an interaction term with the health macro-regions (Figure 3a), Minas Gerais, 2014–2024.

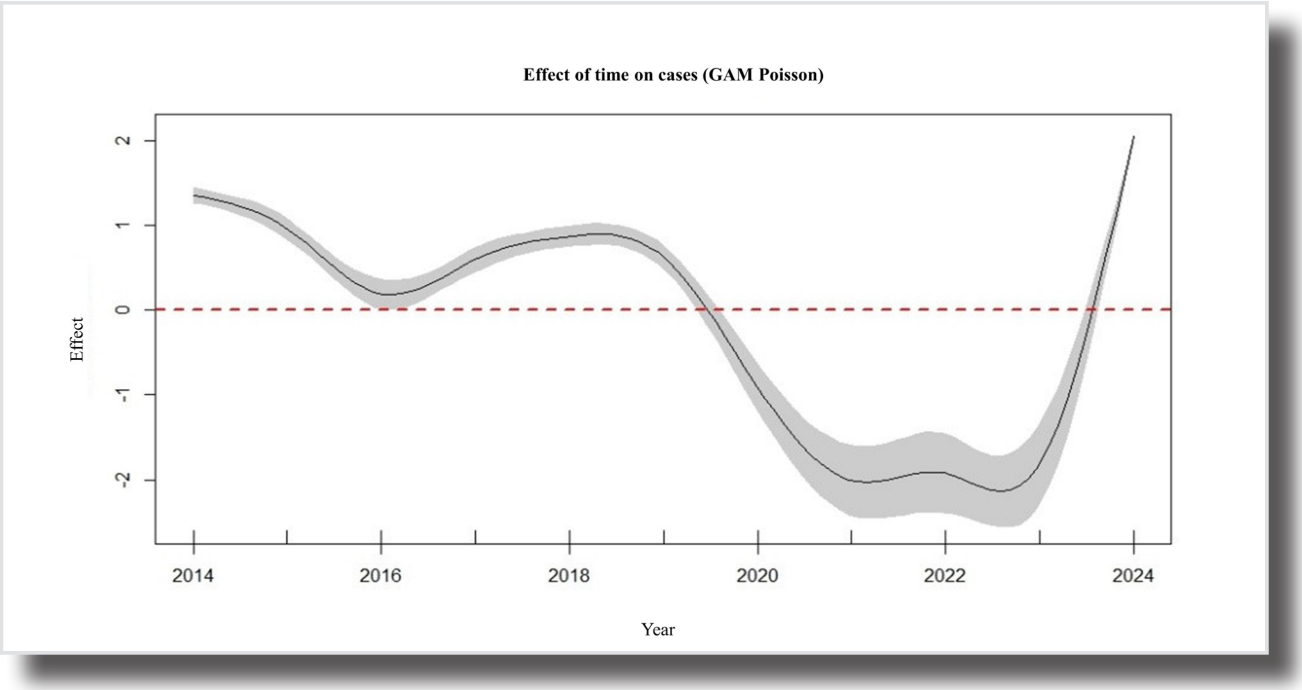

Figure 3a - Smoothed curves of the temporal effect on the risk of pertussis occurrence for Minas Gerais.

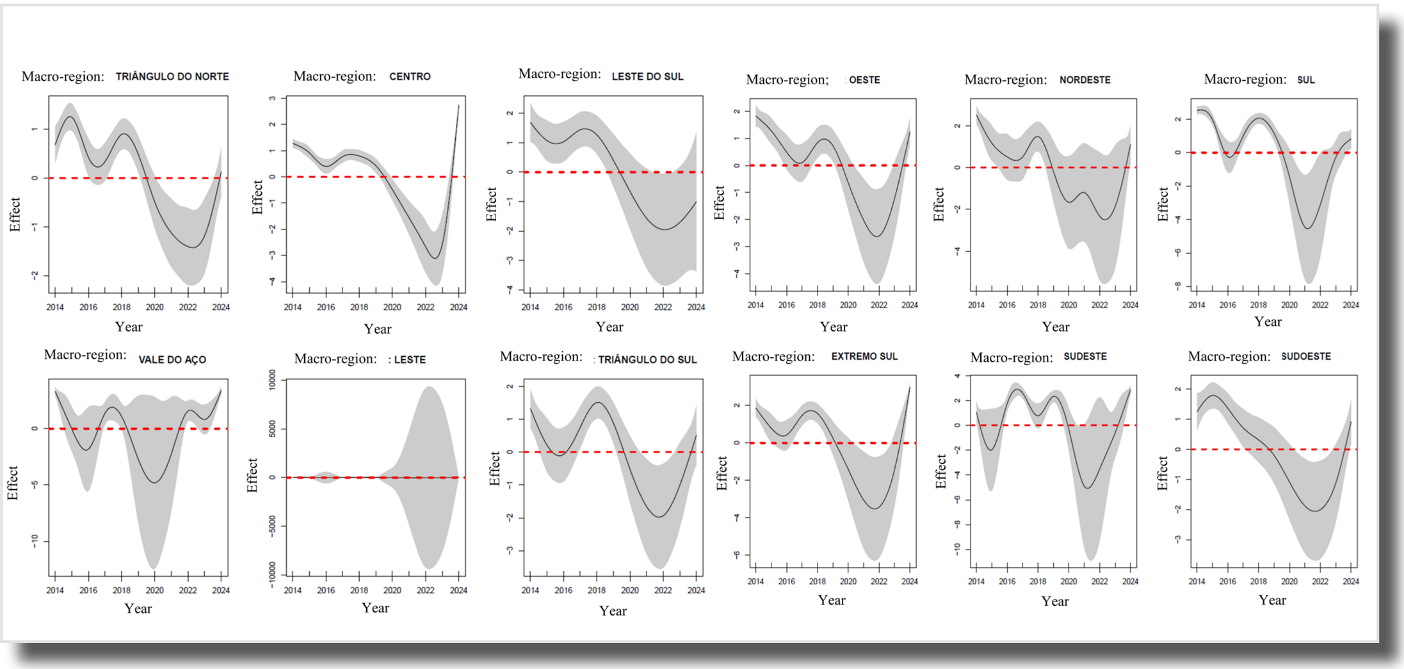

Figure 3b - Smoothed curves of the temporal effect on the risk of pertussis occurrence according to purely temporal GAM models including an interaction term with the health macro-regions of Minas Gerais, 2014–2024.

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The GAM model (Figure 3a) shows a smoothed temporal effect on pertussis incidence between 2014 and 2024 in the state of Minas Gerais, with significant variation throughout the period. A peak was observed between 2014 and 2015, followed by a marked decline from 2018 to 2021, and a renewed upward trend beginning in 2022 and continuing through 2024. The red dashed line at y = 0 represents the point of null risk, where values above zero indicate an increase in relative risk and values below zero indicate a reduction in risk.

The GAM model incorporating an interaction term by health macro-region (Figure 3b) revealed distinct temporal behavior patterns of pertussis across Minas Gerais between 2014 and 2024. Notably, most regions showed a decline in risk starting in 2020, with resurgence from 2022 onward. The risk became increasingly positive, especially from 2024, with emphasis on the Central macro-region. The Eastern macro-region exhibited a near-zero risk of occurrence throughout the entire study period.

The space–time scan analysis (Figure 5) identified significant high-risk clusters ($p < 0.05$) in four distinct periods: 2014–2015 (Northern macro-region, RR = 9.94; Southeastern macro-region, RR = 36.82); 2014–2016 (Jequitinhonha macro-region, RR = 48.46); 2017–2018 (Central macro-region, RR = 4.80); and 2024, with one cluster involving mainly the Northern, Jequitinhonha, Central, and Northwestern macro-regions (RR = 2.28), and another cluster involving primarily the Western, Southern, Southwestern, Central-South, and Central macro-regions (RR = 12.21).

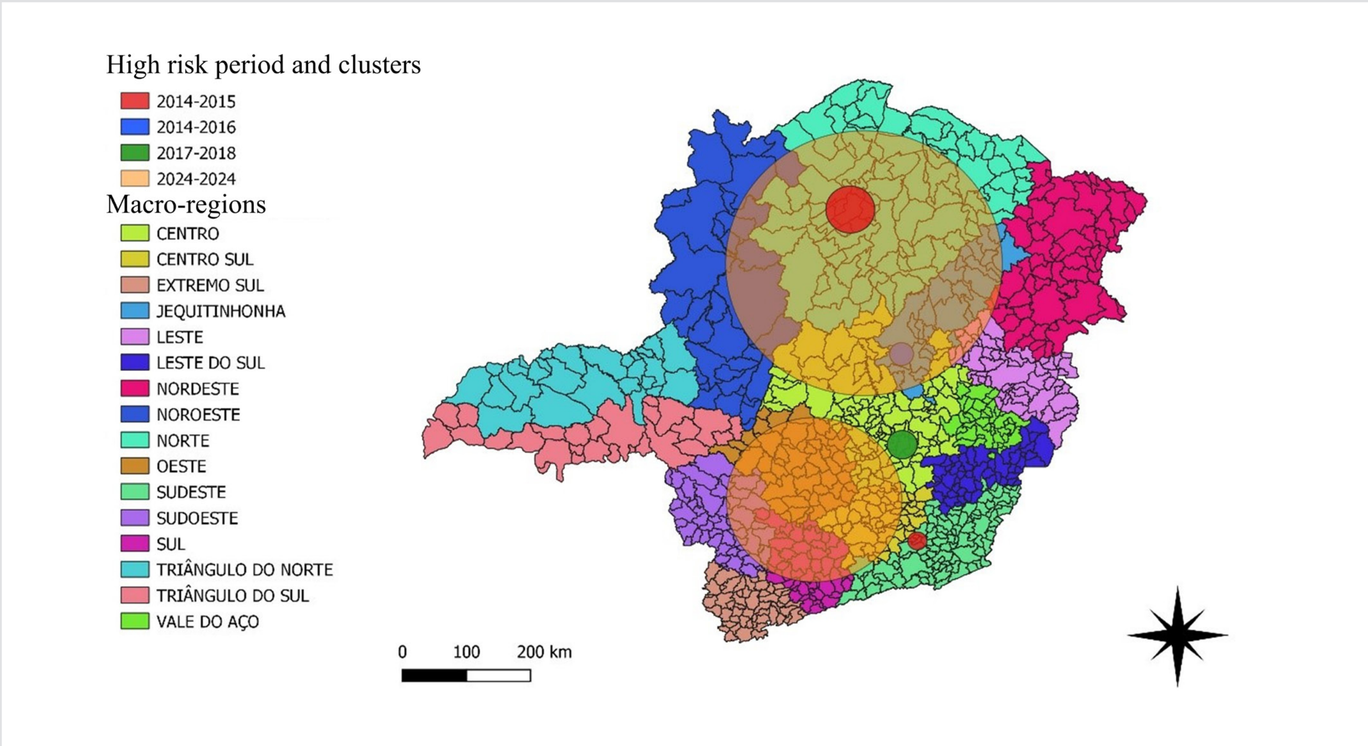

Figure 4 - Spatiotemporal Cluster Mapping of High-Risk Areas for Pertussis Occurrence in Minas Gerais Considering Health Macroregions, 2014 to 2024.

DISCUSSION

This study identified strong spatiotemporal heterogeneity in pertussis distribution in Minas Gerais, particularly in specific macro-regions such as the Central region, which showed a high standard deviation and the greatest increase in risk in 2024 according to the GAM model, indicating the presence of municipalities with very high incidence rates. The high population density in this region is also an important risk factor for the transmission of respiratory diseases.

The spatiotemporal analysis of pertussis cases in Minas Gerais between 2014 and 2024 reveals a current scenario of increased risk. The disease exhibited an initial peak (2014–2015), a decline until 2021, and a sharp resurgence beginning in 2022, culminating in 2024 with two major high-risk clusters — one encompassing mainly the Northern and Jequitinhonha-Mucuri macro-regions, and another in the South/West, both intersecting the Central macro-region. A recent review of national time series data[19] identified the same post-2015 decline and gradual recovery beginning in 2021, suggesting an accumulation of susceptible individuals due to declining vaccination coverage, a phenomenon intensified during the pandemic.

The temporal analysis showed that in 2014, risk started positive but declined until 2016, when it rose again — a pattern observed in most macro-regions. Similar temporal trends have been described in national analyses, showing increasing incidence until 2014 followed by decline after 2015, coinciding with the expansion of the Tdap vaccine for pregnant women[19,20].

Additionally, according to the Ministry of Health Bulletin, the year 2014 falls within a period (2010–2014) of substantial increases in pertussis cases among children aged one to nine years, highlighting the importance of full immunization in this age group[21].

A reduction in risk was observed in 2020, primarily associated with the COVID-19 pandemic, followed by resurgence from 2022 onward. The post-pandemic resurgence of pertussis has also been reported in China, where Wang *et al.*[22] identified a significant increase in pertussis among patients with acute respiratory infections after 2023, linking it to the interruption of natural immune reinforcement during COVID-19 containment measures.

A recent review from Asia described a similar pattern, with epidemics emerging in 2024–2025 and attributing this phenomenon to the global decline in DTP coverage and waning vaccine-induced immunity[23]. The temporal overlap between the 2022–2024 increase in Minas Gerais and international outbreaks supports the hypothesis of a post-pandemic context of heightened population susceptibility.

The spatial and temporal results observed in Minas Gerais from 2014 to 2024 align with the national trend of pertussis recrudescence following a period of very low circulation during the COVID-19 pandemic. Consolidated data from the Brazilian Ministry of Health show that, after only 159 confirmed cases in 2022 and 244 in 2023, Brazil recorded 7,365 cases in 2024 — the highest total since 2014 — raising the national incidence from 0.1 per 100,000 inhabitants in 2023 to 3.5 per 100,000 in 2024[24]. This reversal coincides with the peak documented in the present study, confirming that Minas Gerais mirrors the national epidemic dynamics.

In addition to the Central region and its surroundings, the Northern and Jequitinhonha macro-regions also stood out in the 2024 cluster. This may be associated with the low pentavalent vaccine coverage reported in these macro-regions, as indicated by Pereira *et al.*[25], as well as the high population density of the Central and Southern macro-regions. Contextual factors such as the Human Development Index (HDI) may also help explain the observed cluster patterns: approximately 9% of municipalities in Minas Gerais have a "low" HDI (0.500–0.599), totaling 73 municipalities, of which 64 are concentrated in the Northern, Jequitinhonha, and Rio Doce Valley regions[26]. National evidence points to a direct correlation between less favorable socioeconomic conditions and a lower likelihood of complete childhood vaccination schedules[27].

This study is limited by the ecological nature of the data, which precludes individual-level inferences, and by potential underreporting or delays in notifications within SINAN, especially during the COVID-19 pandemic. Furthermore, it did not examine additional variables such as regional vaccination coverage, which could help explain the low incidence and risk in the Eastern macro-region, nor local detection or immunization strategies — topics that merit further investigation.

CONCLUSION

The findings of this study reinforce the need for targeted strategies such as intensified Tdap vaccination among pregnant women, active case finding among contacts, and continuous surveillance to prevent new epidemic cycles. The study identified a cyclical and heterogeneous pattern of pertussis in Minas Gerais (2014–2024), with resurgence after 2022 and high-risk clusters in areas of high population density (Central macro-region) and in vulnerable regions such as the Northern macro-region. It is likely that declining vaccination coverage, the COVID-19 pandemic, and socioeconomic factors contributed to the disease's reemergence. The results emphasize the need for georeferenced surveillance using space–time analytical techniques to support the development of targeted interventions. Despite its limitations, this study provides valuable evidence to guide public health policies and prevent future outbreaks, highlighting geoprocessing tools as essential instruments for epidemiological monitoring.

CRediT author statement

Conceptualization: Ferreira Júnior, CL; Silva, WS; Carvalho, CDP; Jesus, KD; Cruz, CSS. Methodology: Ferreira Júnior, CL; Carvalho, RDP; Jesus, KD. Validation: Ferreira Júnior, CL; Silva, WS. Statistical Analysis: Ferreira Júnior, CL; Silva, WS; Carvalho, RDP. Formal Analysis: Ferreira Júnior, CL; Silva, WS; Carvalho, RDP; Carvalho, CDP. Investigation: Ferreira Júnior, CL; Silva, WS; Carvalho, CDP; Jesus, KD; Cruz, CSS. Resources: Ferreira Júnior, CL; Carvalho, CDP; Rocha Nunes, MC. Writing – Original Draft Preparation: Ferreira Júnior, CL; Carvalho, RDP; Jesus, KD. Writing – Review & Editing: Ferreira Júnior, CL; Silva, WS; Carvalho, RDP; Carvalho, CDP; Cruz, CSS; Rocha Nunes, MC. Visualization: Ferreira Júnior, CL; Silva, WS. Supervision: Ferreira Júnior, CL; Cruz, CSS. Project Administration: Ferreira Júnior, CL; Cruz, CSS.

All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the workreported in this paper.

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