Statistics on spatial scanning: methodological tutorial with application to fetal mortality in Brazil, 2014-2023

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Abstract

Objectives: to develop a systematic tutorial on the application of statistics on spatial scanning using the discrete Poisson model, covering its theoretical assumptions to its analytical implementation for the detection of spatial clusters of risk for fetal mortality.

Methods: statistics on spatial scanning with calculation of relative risk,on the application of the technique on fetal mortality in Brazil between 2014 and 2023, the unit of analysis was thecities. The maximum radius included up to 10% of births. The null hypothesis was rejected when $p<0.05$ for the most probable cluster. For secondary clusters, spatial overlap was not permitted. The tutorial was structured based on theoretical and methodological foundations of the technique, its applications and limitations in fetal mortality.

Results: 11 clusters were formed within 1,961 cities in the Northeast, North, Southeast, and Central-West regions, which were statistically significant, representing 25% of births and accounting for 39.7% of deaths. Cluster 1 presented a 37% risk of fetal death and included 697 cities in the Northeast and Southeast regions.

Conclusion: Statistics on spatial scanning are a tool that can be applied to health surveillance in monitoring fetal mortality. Recognizing the geographic location and risk of each region is an additional advantage that aids in the effective management of resources.

Key words *Fetal mortality, Vital statistics, Health Information Systems, Spatial analysis, Epidemiological monitoring*

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Introduction

In epidemiology, temporal, spatial, and population dimensions are classic approaches for delineating epidemiological profiles and enabling public health interventions.[1] By understanding the spatial dynamics of health events, it is possible to characterize their occurrence, identify areas of higher risk, and contribute to the planning of strategic actions tailored to the needs of specific regions.[2]

Methods and techniques for spatial analysis allow to handle georeferenced data from different layers and the processing of additional information derived from them,[3] by verifying the existence of spatial patterns and determining whether they are random or not.[4] Their implementation, through geoprocessing, utilizes tools for collection, processing, manipulation, and presentation of georeferenced data.[5]

Research using spatial analysis permits to detect spatial patterns of fetal mortality, identify areas at higher risk for such deaths, and the support of action planning in areas requiring priority attention from managers to restruct the maternal and child health network.[6] It also enables to monitor the effectiveness of the proposed actions to reduce these deaths.[7]

Fetal mortality is related to maternal and child health; however, it was not explicitly addressed separately in the *Objetivos de Desenvolvimento Sustentável* (ODS) (Sustainable Development Goals), although it is indirectly covered in targets 3.1 and 3.2, which aim to reduce maternal mortality and prevent avoidable deaths of newborns and children, respectively.[8] The visibility given to maternal and infant mortality favors the prioritization of interventions, their monitoring, and consequently the reduction of these problems.[9] Meanwhile, fetal deaths remain unnoticed by society and public authorities because they are not the focus of particular attention.[10] Therefore, this tutorial focuses on the applicability of spatial analysis to fetal mortality as an example of the use of statistics on spatial scanning technique.

Some researches have used statistics on spatial scanning technique for the spatial analysis of fetal mortality,[11–13] yet gaps persist in the use of spatial analysis methods in the decision-making process and in the development of health policies.[9] The reflections and considerations presented here aim to contribute to the public health by identifying tools that assist in identifying spatial inequalities in maternal and child health conditions and the weaknesses of the healthcare network across different regions.

This tutorial is intended for undergraduate and post graduate students, researchers in the fields of Public Health, Biostatistics, Health Geography, and Maternal and Child Health, as well as technical professionals and managers working in the State and Municipal Health Departments, particularly in the health surveillance sector, especially in epidemiological surveillance and surveillance of infant and fetal deaths. The tutorial assumes that the reader has prior knowledge of epidemiology, biostatistics, and geoprocessing.

After reading the article, it is expected that the reader will be able to: understand the application of statistics on spatial scanning under the discrete Poisson model, covering everything from its theoretical assumptions to the analytical implementation for detecting spatial clusters of risk for fetal mortality.

The concepts and methods discussed were structured based on references from scientific articles published in journals indexed in the Latin American and Caribbean Health Sciences Literature (LILACS) and the Public Medical Literature Analysis and Retrieval System Online (PubMed) databases, as well as the Scientific Electronic Library Online (SciELO). The search in these databases was conducted without time restrictions using the keywords "fetal mortality" and "spatial analysis" and "stillbirth" and "spatial analysis" in Portuguese, English, and Spanish. The SaTScan™ User Manual,[14] utilized and also available for consultation on the website of this spatial analysis program. The explanations and considerations were organized into the following topics: Statistics on spatial scanning: theoretical and methodological foundations; applications of statistics on spatial scanning to fetal mortality: methodological possibilities and limitations.

The relative risk (RR) was calculated, and spatial analysis was performed by using the statistics on spatial scanning technique via the free-access SaTScan™ 10.0.2 program. This program allows to detect clusters, which consist of spatial agglomerations with an aggregation of events that do not occur purely by chance. The identification of clusters is the main focus of spatial statistics research.[5]

To illustrate the application of statistics on spatial scanning to fetal mortality, data from Brazilian cities (2014–2023) regarding fetal deaths and total births (fetal deaths and live births) were used, extracted from the *Sistemas de Informações sobre Mortalidade* (SIM) (Mortality Information Systems) and the *Sistema de Informação sobre Nascidos Vivos* (Sinasc) (Live Birth Information System) and obtained from the electronic platform of the *Departamento de Informática do Sistema Único de Saúde* - DATASUS[15] (Department of Information Technology of the Public Health System). The data used were accessed on November 17, 2025.

The SIM and Sinasc are required to record all vital events through the digital entry of information from the *Declaração de Óbito* (DO) *e Nascidos Vivos* (DNV) (Death Certificate and Live Birth Certificate). These certificates are standardized forms with unique serial numbers distributedNationwide by the Ministry of Health. The DO must be completed by physicians for deaths occurring

from the 20th week of gestation onward. The DNV may be issued by physicians, members of the nursing staff, or administrative staff of health services or civil registry offices.[16]

The study did not require approval from a Research Ethics Committee, in accordance with Resolutions No. 466/12 and 674/22 of the National Health Council, as it utilized aggregated secondary data in the public domain that does not allow for individual identification.

Statistics on spatial scanning: theoretical and methodological foundations

Statistics on scanning are used to identify and evaluate clusters of cases in a temporal, spatial, or spatiotemporal configuration.[14] This is achieved by gradually scanning a window over time and/or space, specifying the number observed and expected cases within it at different locations.[14] The scan window is characterized by an interval (in time), a circle or an ellipse (in space), or a cylinder with a circular or elliptical base (in space-time).[14]

According to the nature of the data, statistics on spatial scanning use different probabilistic models: Bernoulli (a single random experiment with only two possible and mutually exclusive outcomes), discrete Poisson, or space-time permutation (count data); multinomial model (categorical data); ordinal model (ordered categorical data); exponential model (survival time data); normal model (other continuous data).[17]

In the case of fetal deaths in Brazil (2014 to 2023), statistics on spatial scanning were used, and the discrete Poisson probability model was adopted because fetal deaths by municipality during the study period were considered count data. The statistic on spatial scanning technique examines the occurrence of a health event in the population by creating circular windows of different sizes and locations, whose centers traverse the surface of the map to encompass a set of nearby neighbors corresponding to a geographic area. An infinite number of distinct circles are created, and each circle may form a cluster.[14]

The discrete Poisson model has fundamental assumptions that are essential for interpreting the identified clusters: independence of events; constant rate within each area (intra-area homogeneity); population-risk proportionality; and the problem of areas with small populations (Supplementary Table 1). Understanding these assumptions is essential for discussing the possibilities and limitations of applying statistics on spatial scanning in studies on fetal mortality.[14,18]

To implement this technique (Figure 1), it is necessary to include the centroids, which are characterized by the geographic coordinate corresponding to the center of the spatial analysis polygon unit.[14] The centroids of Brazilian cities identified from the cartographic grid (*Brasil por municípios* —2024 Edition (Brazil by Municipalities) available on the *Instituto Brasileiro de Geografia e Estatística* (IBGE) (Brazilian Institute of Geography and Statistics) electronic platform, accessed on November 17, 2025, were used (Figure 2).[19]

In the discrete Poisson model, the number of cases in each area is proportional to the size of its exposed population. Thus, the null hypothesis was that the total number of fetal deaths in the country is distributed uniformly across all cities, in proportion to their total number of births. The alternative hypothesis was that the total number of fetal deaths is distributed heterogeneously, resulting in clusters with a high risk of fetal deaths.

As it moves through all the centroids, the radius varies continuously from zero to the maximum radius. This technique scans the study area to locate a circle within the region that has a very high incidence rate inside and a very low incidence rate outside this circle. The objective of the technique is to determine whether the event under study is randomly distributed or exhibits statistically significant clusters.[14]

Under the Poisson assumption, the likelihood function for a specific window is proportional to:

$$\left(\frac{c}{E[c]}\right)^{c}\left(\frac{C\text{-}c}{C\text{-}E[c]}\right)^{C\text{-}c} I(Z)$$

When the program is configured to detect only clusters with a higher than expected risk (high rates):

$$I(Z)=\begin{cases}1, \text{ se } c>E[c]\\ 0, \text{ se } c\leq E[c]\end{cases}$$

When the program is configured to detect only clusters with a lower than expected risk (low rates):

$$I(Z)=\begin{cases}1, \text{ se } c<E[c]\\ 0, \text{ se } c\geq E[c]\end{cases}$$

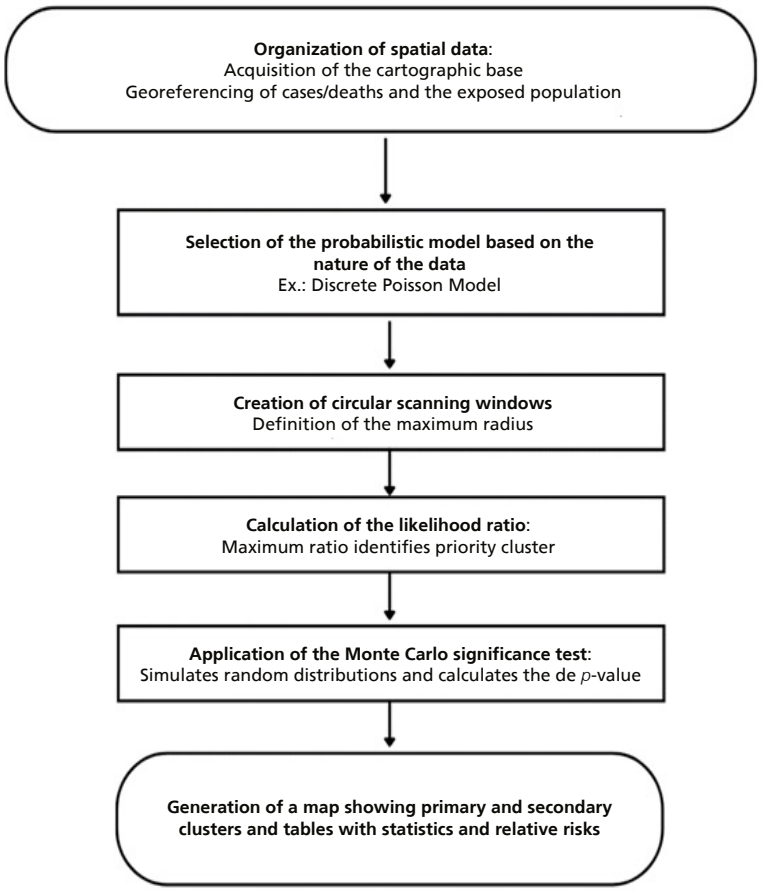
When the program is configured to detect clusters with high or low rates:

$$I(Z)=1$$

Where 'C' is the total number of cases, 'c' is the number of cases observed within the window, and 'E(c)' is the number of expected cases adjusted for covariates within the window under the null hypothesis. When the analysis is conditioned on the total number of observed cases, 'C-E[c]' is the number of expected cases outside the window. I() is an indicator function. Whenever the spatial analysis program is configured to scan only for clusters with high rates, I() equals 1 when the window has more cases than expected under the null hypothesis, and 0 otherwise.[18] When SaTScan™ is configured to scan only for clusters with low rates, the opposite holds. In turn, when the program scans for clusters with either high or low rates, then I() = 1 for all windows.[14]

Figure 1

Stages of spatial scanning modeling.



The likelihood function is based on the maximum likelihood method to compare the number of observed cases within a scan window with the expected number under the null hypothesis of spatial randomness.[14]

To identify clusters, a likelihood function is created for each scan window and maximized across all of them. The maximum likelihood identifies the most probable cluster, called the primary cluster, which represents the grouping with the lowest probability of having occurred by chance. Secondary clusters are also identified; these are those that yielded high values in the likelihood ratio test. For each cluster, statistics are provided by the spatial analysis program. The '*p*' value is obtained through the Monte Carlo hypothesis test, which compares the maximum likelihood of the real dataset with the maximum likelihoods of the random datasets.[18]

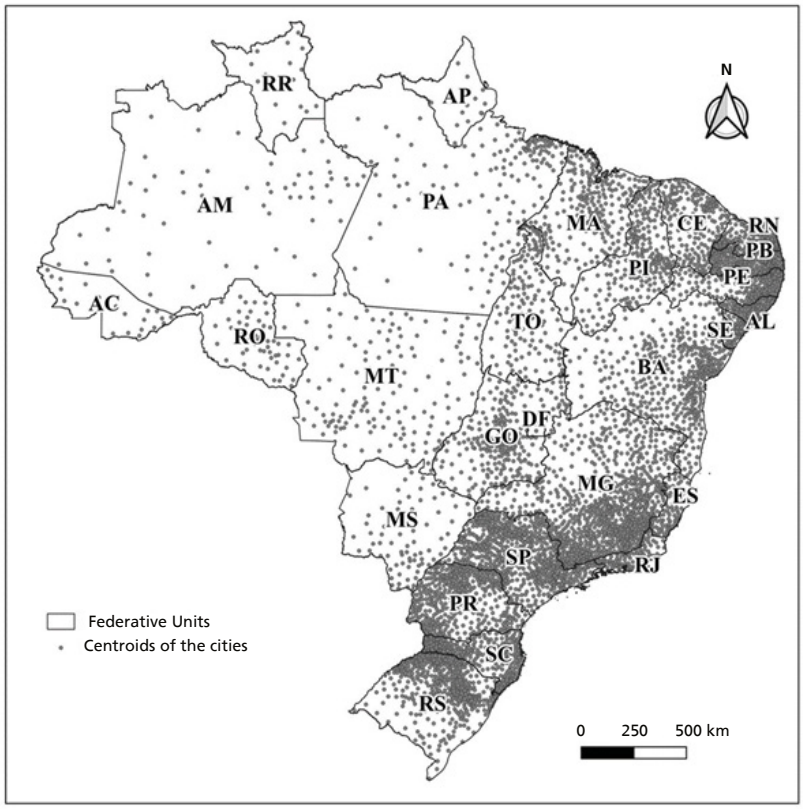
Monte Carlo analysis consists of a series of computational algorithms that operate by repeatedly sampling various possible values, thereby calculating a series of probability distributions. The advantage of this technique is that it allows for greater precision in describing the uncertainty of the variables used, employed primarily when it is not feasible to calculate exact results.[18]

In this article, it was assumed that the maximum radius included up to 10% of the total population. The circular windows assessed the ratio of deaths to births, and by adapting to different radii, they verified the relationship between observed and expected results.[18] The likelihood function was maximized across all windows, and the most likely cluster was identified. The likelihood ratio for this window constituted the statistical test of the maximum likelihood ratio. The distribution under the null hypothesis and the corresponding simulated *p*-value were obtained by repeating the same analytical exercise across a large number of random replicates (999) of the dataset generated under the null hypothesis, in a Monte Carlo simulation. The null hypothesis was rejected when $p<0.05$ for the most likely cluster, indicating that in that locality, the risk of fetal death among all births was observed to be higher than the expected risk in the same locality. As a criterion for secondary clusters, spatial overlap was not permitted. No correction for multiple proportions was used, considering that multiple outcomes were not observed. The maximum number of reported clusters was limited by the SaTScan™ program.

The relative risk was calculated as the estimated risk within the cluster divided by the estimated risk outside the

Figure 2

Map showing the centroids of the cities in Brazil.



AC=Acre; AM=Amazonas; RR=Roraima; RO=Rondônia; AP=Amapá; PA=Pará; MT=Mato Grosso; MS=Mato Grosso do Sul; GO=Goiás; DF=Distrito Federal; TO=Tocantons; MA=Maranhão; PI=Piauí; CE=Ceará; BA=Bahia; SE=Sergipe; AL=Alagoas; PE=Pernambuco; PB=Paraíba; RN=Rio Grande do Norte; MG=Minas Gerais; ES=Espírito Santo; RJ=Rio de Janeiro; SP=São Paulo; PR=Parana; SC=Santa Catarina; RS=Rio Grande do Sul.

cluster.[20] It was calculated as the observed value divided by the expected value within the cluster, divided by the observed value divided by the expected value outside the cluster:

$$RR=\frac{c|E[c]}{(C\text{-}c)/(E[C]\text{-}E[c])}=\frac{c/E[c]}{(C\text{-}c)/(C\text{-}E[c])}$$

Where 'c' is the number of observed cases within the cluster and 'C' is the total number of cases in the dataset. Since the analysis is conditioned on the total number of observed cases, 'E[C]=C'.[14]

In the case of fetal deaths in Brazil (2014 to 2023), 11 statistically significant clusters were identified, comprising 1,961 cities located in all States of the Northeast Region and in States of the North Region (Amazonas, Pará, Acre, Tocantins, Amapá, Roraima); Southeast (*Minas Gerais, Espírito Santo, Rio de Janeiro*); Central-West (*Mato Grosso, Goiás, Mato Grosso do Sul*); and the Federal District (Central-West). These clusters account for 25% of the country's total births and concentrated 39.7% of fetal deaths. Cluster 1, comprising 697 cities located in the States of *Pernambuco, Alagoas, Piauí, Sergipe, Bahia* (Northeast Region), and Minas Gerais (Southeast). In this cluster, the risk of total births resulting in fetal death was 37% higher compared to other cities (Figure 3, Table 1).

Applications of statistics on spatial scanning to fetal mortality: methodological possibilities and limitations

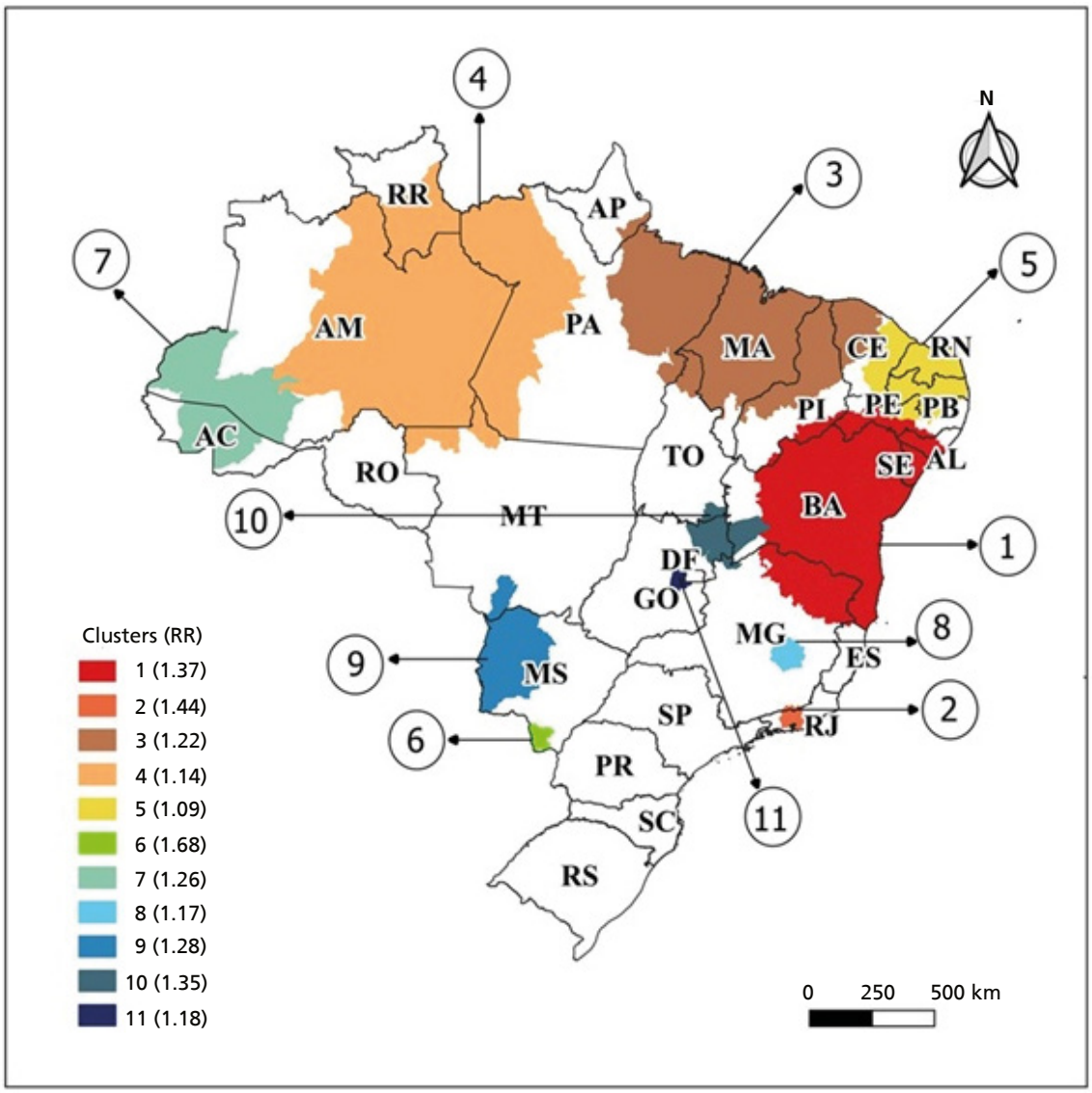
The statistics on spatial scanning technique allows us to observe whether the distribution of fetal deaths follows a random pattern or exhibits clusters.[12,21] The application of this technique enables multiple tests to be conducted to test hypotheses regarding the existence of an elevated risk of fetal death in specific locations.[17] Statistics on spatial scanning have implications for the formulation, monitoring, and evaluation of policies, as well as for the design of future public health initiatives.[21]

By highlighting the spatial distribution patterns of fetal deaths, it is possible to assist managers in planning and allocating resources more effectively, directing interventions toward areas that require improvement in maternal and child health indicators and the strengthening of prenatal and obstetric care services.[22] To strengthen prenatal care services, it is essential to ensure six or more prenatal visits beginning in the first trimester of pregnancy, including vaccination, laboratorial testing, timely diagnosis, and appropriate treatment to help reduce mortality.[8]

The restructuring of the maternal and child health network is based on improving the quality of antepartum

Figure 3

Clusters of fetal death risk (n=298,021). Brazil, 2014–2023.



RR=relative risk.

and intrapartum care.[23] For this, it is essential to expand and improve the quality of human resources and the number of beds in clinical and surgical obstetrics, as well as in maternal and neonatal intensive care unit (ICU), particularly in the areas identified as priorities by the spatial analysis.[22]

These actions can help reduce travel time to specialized health services, preventing pregnant women from having to travel extensively within the health system and contributing to the survival of both mother and baby.[24] The impacts of public health interventions can also be monitored through studies that utilize statistics on spatial scanning.[21]

The application of this technique during the design and evaluation phases can increase the effectiveness of health interventions.[25] However, the main disadvantage of statistics on spatial scanning is that there is a possibility of detecting a cluster larger than its actual size, as the circular scan may incorporate areas with a low number of cases that are surrounded by areas with a high number.[18]

Other limitations of this technique include the use of centroids that concentrate cases at a single geographic point, which may lead to data inaccuracies in areas with very large intra-municipal territorial dimensions. Similarly, the use of circular or elliptical windows assumes that clusters have a regular shape, which may not reflect reality. There may be difficulty in detecting multiple overlapping clusters, as the program tends to identify only the cluster with the highest likelihood ratio. The sensitivity parameters for selecting the maximum radius of the scanning window directly influence the size and location of the detected clusters; very high values

Table 1

Characteristics of fetal death clusters (n=298,021). Brazil, 2014 to 2023

Cluster	Nº. of cities	Nº of deaths		% Deaths	% Births	Relative Risk	*p*
		Observed	Expected				
1	697	39,048	29,596	13.2	2.9	1.37	<0.0001
2	30	10,923	7,650	3.7	2.6	1.44	<0.0001
3	543	35,274	29,630	11.9	10	1.22	<0.0001
4	68	10,242	9,031	3.5	3	1.14	<0.0001
5	508	**15,925**	14,668	5.4	4.9	1.09	<0.0001
6	5	299	178	0.1	0.1	1.68	<0.0001
7	14	1,035	819	0.3	0.3	1.26	<0.0001
8	45	2,031	1,741	0.7	0.6	1.17	<0.0001
9	14	780	609	0.3	0.2	1.28	<0.0001
10	28	495	366	0.2	0.1	1.35	<0.0001
11	9	1,103	931	0.4	0.3	1.18	0.0018

can overestimate the results, and very low values can underestimate them. Edge effects may also occur, where areas at the boundaries of the study region are less likely to be included in the circular windows.[14,18]

Differential underreporting is a problem that must be acknowledged when interpreting the results of spatial scan statistics, as it is possible that the underreporting of fetal deaths is not homogeneous across Brazil and produces systematic differences in the distribution of mortality clusters. Added to this is the risk of the ecological fallacy, as analysis conducted with aggregated data cannot be extrapolated to individual data.[14,18]

In some situations, the use of statistics on spatial scanning is not recommended. For example, when the objective of the study is to estimate individual risk and causal risk factors, as the detection of clusters does not allow for such results. In the analysis of rare events with few cases, many areas without reports, and in very small populations, spatial scanning should also not be used, as unstable and highly sensitive clusters may be identified. Another limitation for applying this method is events that are distributed along river routes, or in confined and highly irregular areas, since the actual clusters could be distorted by the circular shape of the scan windows, which could overestimate or underestimate the cluster area.

Other alternative methods can also be used for detecting spatial clusters and have advantages and disadvantages compared to statistics on spatial scanning. The Local Moran's Index (LISA) is a measure of local spatial autocorrelation designed to identify areas with values similar to or divergent in relation to their neighbors. Its advantages include not requiring a specific geometric shape and enabling the detection of priority areas for intervention, as well as clusters with high rates among neighbors with high rates. However, unlike the statistic on spatial scanning, it is not a probabilistic risk model and is sensitive to the definition of a neighborhood matrix.[4]

FleXScan represents a scanning statistic that expands the search by connecting neighboring areas, making it more suitable for detecting clusters of events distributed along the river routes, roads, or irregular areas,[26] unlike SaTScan™, which uses circular or elliptical windows to scan the map surface. Standard Bayesian rate smoothing methods, on the other hand, do not perform formal hypothesis testing for clusters in the same way as SaTScan™.[27]

Spatial analysis, although essential for epidemiology and fundamental to understanding health events, is still considered complex, which can make it difficult to apply, and it is not being used to its full potential.[28] For the proper implementation of these techniques and interpretation of the results, it is necessary to combine theoretical knowledge with training in the use of computational tools.[29] One strategy to be adopted is the development of courses by educational and research institutions, such as the initiatives of the *Fundação Oswaldo Cruz* (*Curso de Geoprocessamento e Análise Espacial em Saúde*) (Oswaldo Cruz Foundation (Course on Geoprocessing

and Spatial Analysis in Health) and the *Programa de Fortalecimento da Epidemiologia nos Serviços de Saúde* (Program for Strengthening Epidemiology in Health Services)of the Ministry of Health in partnership with the Pan American Health Organization (PAHO).

In the searches of academic databases conducted for the preparation of this tutorial, only three studies were found that resemble the one proposed in this work (Table 2). Studies on fetal mortality that used the statistic on spatial scanning technique can contribute in identifying areas at higher risk for mortality. Discussing this public health problem and providing input for decision-making could guide the allocation of resources toward strengthening care practices that enable the reduction of preventable deaths.[9]

Despite the intrinsic and extrinsic limitations of the method discussed, its potential and applications stand out, and for this reason it can be considered viable for public health. The statistic on spatial scanning technique adopted in this study can serve as another tool for health surveillance to monitor fetal mortality, particularly within the routine operations of death surveillance services. Identifying the exact geographic location and risk of each region is an additional advantage that aids in the effective management of resources.

Table 2

Studies on fetal mortality that used statistics on spatial scanning technique.

Title	Authors (Year of publication)	Applicability of the method
Spatial distribution of stillbirth and associated factors in Ethiopia: a spatial and multilevel analysis	Tesema *et al.*[11] (2020)	An analysis was conducted based on data from the 2016 Ethiopia Demographic and Health Survey. A total weighted sample of 11,375 women was included in the analysis. The Bernoulli model was ajusted to identify areas of higher incidence to explore the spatial distribution of stillbirths.
Spatial analysis of inequalities in fetal and infant mortality from preventable causes	Bonfim *et al.*[12] (2020)	Preventable fetal and infant deaths among residents of Recife, Brazil, were studied. The rates of preventable fetal mortality and preventable infant mortality were calculated for two five-year periods, 2006–2010 and 2011–2015. Statistics on spatial scanning were used for spatial analysis and were related to the social deprivation index. The Poisson model was used.
Spatial patterns of fetal loss and infant death in an arsenic-affected area in Bangladesh	Sohel *et al.*[13] (2010)	Pregnant women from Matlab, Bangladesh, who drank artesian well water during pregnancy between 1991 and 2000, were included in this study. Spatial scanning was applied to identify unique, non-random spatial and spatiotemporal clusters of fetal death and infant We used retrospective spatial and spatiotemporal permutation models and Poisson probability models.

Authors' contribution

Canuto IMB, Bonfim CV, Frias PG, and Silva APSC: contributed to the conception, structuring, analysis, and interpretation of the data, and developed or conducted the critical review of the article, with the aim of ensuring intellectual content consistent with this journal.

All authors approved the final version of the article and declare no conflict of interest.

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Use of artificial intelligence

No artificial intelligence tools were used in the preparation of this manuscript.

Data availability

The entire dataset supporting the results of this study has been published in the article itself.

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Supplementary Table 1

Fundamental assumptions of the Poisson model and conditions for its applicability regarding fetal mortality.

Assumptions	Conditions of applicability
Independence of events	It is assumed that events occur independently; that is, the occurrence of one fetal death does not alter the probability of another occurring within the same observed area or in neighboring areas.
Intra-area homogeneity	It is assumed that the risk is constant within each spatial unit of analysis, such that all births have the same probability of resulting in a fetal death under the null hypothesis.
Proportionality between population and risk	It is expected that the number of deaths is directly proportional to the size of the birth population, implying a uniform distribution of risk and the absence of clusters.
Instability rate in small areas	Areas with small populations may present instability rate, as small variations in the number of deaths can lead to an overestimation of the relationship between observed and expected values, increasing the probability of identifying clusters.