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Association of socioeconomic indicators with COVID-19 mortality in Brazil: a population-based ecological study

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Abstract

The article presents an analysis of the spatial distribution of mortality from COVID-19 and its association with socioeconomic indicators in the north-eastern region of Brazil - an area particularly vulnerable with regard to these indicators. This population-based ecology study was carried out at the municipal level in the years 2020 and 2021, with analyses performed by spatial autocorrelation, multiple linear regression and spatial autoregressive models. The results showed that mortality from COVID-19 in this part of Brazil was higher in the most populous cities with better socioeconomic indicators. Factors such as the onset of the COVID-19 pandemic in large cities, the agglomerations existing within them, the pressure to maintain economic activities and mistakes in the management of the pandemic by the Brazilian federal Government were part of the complex scenario related to the spread of COVID-19 in the country and this study was undertaken in an attempt to understand this situation. Analysing the different scenarios is essential to face the challenges posed by the pandemic to the world's health systems.

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Introduction

On March 11, 2020, the World Health Organization (WHO) characterized the disease coronavirus 19 (COVID-19), caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), as a pandemic (WHO, 2022a). This declaration marked the beginning of the world's largest public health crisis of modern times (Hawkins *et al*., 2020), with significant social and economic impacts that require ongoing monitoring and study (Andrade *et al*., 2020). Social inequalities related to access to housing, employment, education, basic sanitation and health care continue to play a role in mortality and disease burdens, especially in regions with significant economic disparities (Bambra *et al*., 2020; Castro *et al*., 2021; Hawkins *et al*., 2020; Kim & Bostwick, 2020). As of March 21, 2023, there were approximately 761 million confirmed cases of COVID-19 in the world, which resulted in approximately 6.9 million deaths (WHO, 2022b). The disease had already killed more than 700,000 people in Brazil by the end of March, with around 37,000 ongoing cases (Brazil Ministry of Health, 2022).

Several studies have sought to spatially relate COVID-19 and its effects with socioeconomic indicators, aiming at a better understanding of the behavior of the pandemic in different territories and scenarios, associating these indicators with the increase or decrease in morbidity due to the disease (Kathe & Wani, 2021; Manda *et al*., 2021; You *et al*., 2020). Spatial analysis has become an important tool to analyze disease dissemination patterns, magnitude, and space-time clusters (Cavalcante & Abreu, 2020; Hallal *et al*., 2020), contributing with predictions, response strategies and assessments of the control measures implemented by public policies.

A spatial regression analysis conducted in China revealed the impacts of socioeconomic factors related to urban development on the spread of COVID-19. Demographic density and a high proportion of elderly people were associated with increased morbidity from COVID-19, while gross domestic product (GDP) and hospital density were associated with lower morbidity (You *et al*., 2020). In the United States, socioeconomic, epidemiological, and political factors have been identified as driving geographic differences in the impact of COVID-19. Higher proportions of Hispanics and African Americans, greater income inequality and a higher incidence and prevalence of chronic diseases were associated with higher rates of mortality in the pandemic. The rigor of social distancing measures (Stringency Index) in neighboring territories was associated with lower mortality from the disease, with the direct positive relationship being explained by the early and long restriction in large cities that saw the first outbreaks of cases and deaths (Kathe & Wani, 2021). A study carried out in Africa showed not only that the prevalence of COVID-19 was associated with factors such as GDP per capita, government transparency and the proportion of elderly people, but also that it was highly dependent on the prevalence in neighbouring countries (Manda *et al*., 2021).

In Brazil, the first projections already indicated that socioeconomic indicators, the local health system's capacity and urban mobility would have an impact on the distribution of the disease (Castro *et al*., 2021; Figueiredo *et al*., 2020; Raymundo *et al*., 2021). Social inequalities and the ineffective response of the federal government accelerated the spread of the disease. The north-eastern region of the country, which is not only the second most populous area according to the Brazilian Institute of Geography and Statistics [*Instituto Brasileiro de Geografia e Estatística*] (IBGE, 2022), but also the one with the socioeconomic indicators indicating the strongest vulnerability, was expected to be most heavily affected (Andrade *et al*., 2022; Coelho *et al*., 2020). Until December 2021, the Northeast was the second region in this respect, with most cases and deaths amounting to 48,100,973 cases and 1,163,510 deaths. Nevertheless, the mortality rate (208.12 deaths/100,000 inhabitants) was the lowest among the regions of Brazil (Brazilian Ministry of Health, 2022).

The objective of this study was to analyse the spatial distribution of mortality from COVID-19 and its association with socioeconomic indicators in the northeast region of Brazil in the years 2020 and 2021, looking for hypotheses for the lower mortality despite the region's great inequality and social vulnerability. It is worth mentioning that the characterization of the pandemic in South America received less attention than in Europe and North America (Mena *et al*., 2021).

Materials and Methods

Site and design

We conducted a population-based ecological study on COVID-19 mortality in the north-eastern region of Brazil, from March 2020 to December 2021. The units of analysis were the 1,794 municipalities contained in the nine states or Federative Units [FU] in this area (Figure 1), which in 2020 had 57,374,243 inhabitants (about 27% of the population of Brazil) distributed over an area of 1,554,291.744 km^2, corresponding to about 18% of the country (IBGE, 2022).

Data

The dependent variable was the COVID-19 mortality rate in the municipalities of the Northeast of Brazil, notified and collected in the official communication website on the epidemiological situation, which is updated daily by the Ministry of Health (https://covid.saude.gov.br/) and calculated using the number of deaths as the numerator and the population of the corresponding year as the denominator (*i.e.* result per 100,000 inhabitants). Mortality is considered a more reliable indicator than incidence due to the number of asymptomatic undiagnosed patients, access to

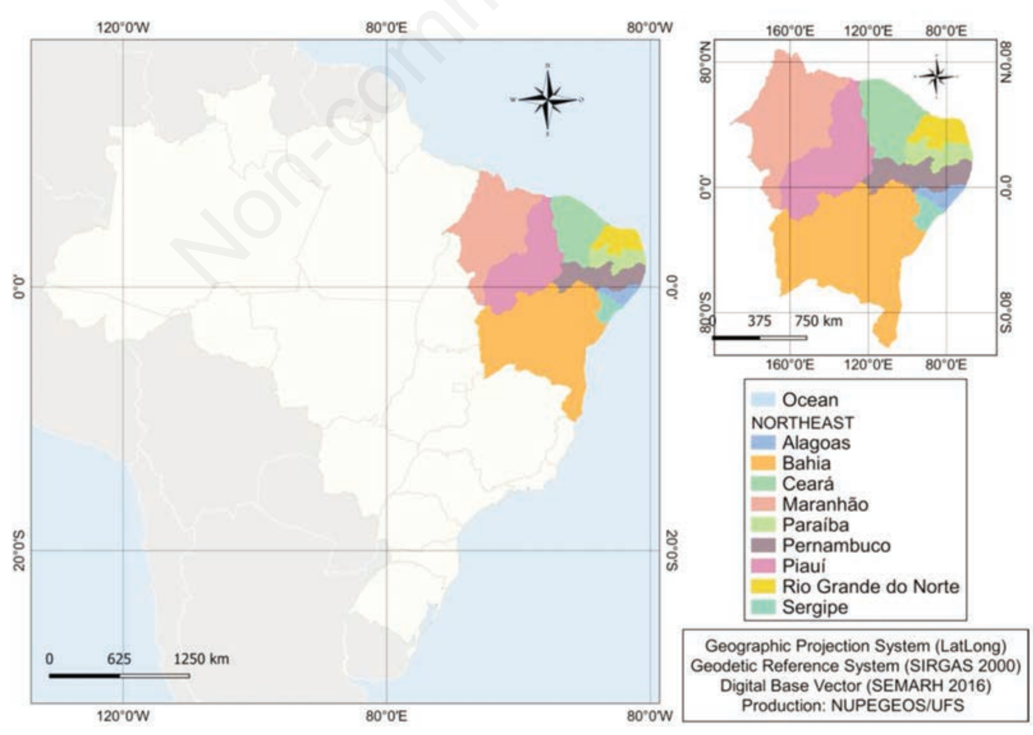

Figure 1. The study area in the states of north-eastern Brazil.

the healthcare system and the surveillance capacity of this system (Lu *et al*., 2021; Mena *et al*., 2021). The co-variables that represent the socioeconomic and health indicators were collected from the 2010 demographic census of the IBGE and the United Nations Development Program (UNDP), which is available on the website of the Brazilian Institute for Applied Economic Research [*Instituto de Pesquisa Econômica Aplicada*] (https://ipea.gov.br/portal/). The definitions of each indicator, the source and year of collection can be found in the *Supplementary Materials.*

The selection of indicators for this study was informed by previous research examining the relationship between the incidence and mortality of infectious diseases and various socioeconomic, health, and social vulnerability factors in Brazil (Araújo *et al*., 2020; Coelho *et al*., 2020; Da Silva *et al*., 2022). These indicators encompassed a range of factors, including demographic density, economic activity, social inequality (measured by the Gini index, Dependency Ratio and the employed percentage of the population over 18 years of age), access to healthcare (percentage of the population with health insurance), non-communicable disease mortality coefficient, as well as the municipal Human Development Index (MHDI) and its dimensions of income, longevity, and education.

Spatial correlation analysis

To minimize instability caused by random fluctuations of coefficients, particularly in municipalities with small populations and limited events, the crude COVID-19 mortality rates were smoothed using the local empirical Bayesian smoothing method (Assunção *et al*., 1998). Subsequently, the spatial autocorrelation analysis according to the Global Moran's index (*I*) (Moran, 1950) was used to investigate the existence of patterns of occurrence in space of the phenomenon under study. A spatial proximity matrix was developed using the contiguity criterion and the Global Moran's *I* was calculated. The results with statistical significance $p<0.05$ indicate regions with spatial structures highly probable of contributing to the occurrence of deaths from COVID-19 (Anselin, 2010).

Subsequently, the occurrence of local spatial autocorrelation was evaluated by the local indicators of spatial association (LISA) (Anselin, 2010), which determines the dependence of local data on the characteristics of their neighbors enabling the identification of spatial association patterns that may indicate the occurrence of clusters of municipalities. The Moran scattering diagram, based on the Local Moran's *I*, was used to identify critical, risk and transition areas, compare the value of each municipality with its neighbors and verify the existence of spatial dependence, in addition to identifying spatial patterns. This diagram was represented by Moran's Map, in which only municipalities with statistically significant differences ($p<0.05$) were considered. This way, the spatial quadrants were generated, such as i) Q1 (high/high or hotspots - positive values, positive means) and Q2 (low/low or cold spots - negative values, negative means), which indicate points of positive spatial association or similarity to its neighbours, that is, areas where the mortality rates from COVID-19 are in agreement, or ii) Q3 (high/low - positive values, negative means) and Q4 (low/high - negative values, positive means), which indicate points with negative spatial association, that is, transitional areas.

Global spatial regression analysis

The association of the social health determinants with mortality from COVID-19 was investigated using multiple linear regression and spatial autoregressive models. For the construction of the model, Spearman's correlation between the dependent variable and the independent variables was applied to select the positive and negative correlations at the 5% significance level. The Shapiro-Wilk test (Shapiro & Wilk, 1965) was applied to verify the distribution of the dependent variable. Spearman's correlation coefficient is a more suitable nonparametric alternative for variables that do not have two-dimensional normal distribution (Vieira, 2010), such as those observed in this study. Regarding the classification of the degree of correlation, a weak correlation was considered at $0<\rho<0.4$; moderate at $0.4\leq\rho\leq0.7$; and strong at $0.7<\rho<1.0$. Multiple linear regression was performed in order to select the variables with a high likelihood of being explanatory factors. All variables pre-selected with Spearman's correlation were incorporated into the multiple linear regression model and excluded according to a significance level of <0.05 (stepwise selection) and a variance inflation factor (VIF) >10. Statistical significance of results was analyzed using t-statistics analysis (Vieira, 2010). The obtained result was tested using the ordinary least squares (OLS) estimator and the spatial lag model (Anselin *et al*., 2006). The Lagrange multiplier (Anselin & Bera, 1998) was the statistical test used to evaluate the fit of each model. The performance of each model was evaluated using the coefficient of determination R^2 (goodness of fit), the Akaike information criterion (AIC) and the Schwarz criterion. LISA was calculated to identify areas with spatial dependence and their relationship with neighbours. The results of this analysis were represented in a spatial autocorrelation map (Anselin & Bera, 1998).

Software

The descriptive analysis was performed using the Jeffreys's amazing statistics program. (JASP) software (JASP team, 2022, version 0.16.2). For the univariate spatial analysis, the software TerraView from the National Institute for space research - *Instituto Nacional de Pesquisas Espaciais* (INPE) in Brazil, version 4.2.2, and QGIS from the Open Source Geospatial Foundation (OSGeo), version 2.18.2, were used. The GeoDa software from the Spatial Analysis Laboratory, University of Illinois, Urbana, Champaign, United States (version 1.14) was used for the spatial regression analysis.

Results

A total of 120,019 deaths were recorded in the north-eastern region of Brazil from March 2020 to December 2021 (Brazil Ministry of Health, 2022). Considering data from across the country, mortality was 294.58 deaths per 100,000 inhabitants. No state in the Northeast reached this mortality rate. The states of Ceará and Sergipe had coefficients with more than 250 deaths per 100,000 inhabitants, while the state of Maranhão had the lowest mortality: 145.07 deaths per 100,000 inhabitants (Table 1).

The spatial distribution of crude COVID-19 mortality showed higher concentrations in the coastal region, mainly in the north of the state of Ceará and in the south of the states of Piauí and Bahia (Figure 2A). After smoothing by the Bayesian estimator, concentration hotspots remained in the coastal region and in the states of Ceará and Sergipe, southern Bahia and Piauí (Figure 2B).

The Moran map analysis identified areas classified according to the mortality rates of the municipalities. Regions with clusters of high mortality rates were identified in the states of Ceará, Sergipe and Alagoas, in addition in the south of the states of Piauí and Bahia. Clusters with low mortality rates were identified in the north and east of the state of Maranhão and in diffuse regions in the states of Bahia and Pernambuco (Figure 3). The concentration of mortality on the coast of the north-eastern region coincided with the population and economic concentrations found in the region. In fact, 8 of the 9 capitals of the north-eastern states are located on the coast, and this is where the highest population densities, most tourist and service centres and greater urban mobility can be found.

The VIF was calculated for each socioeconomic and health indicator to measure the multicollinearity between them. High VIF values (>5) could affect the estimation of the regression coefficients due to multicollinearity (Montgomery *et al.*, 2006). VIF showed no evidence of multicollinearity (Table 2).

The analysis was performed using the OLS model. The indicators HDI-longevity (coefficient 115.939, $p<0.01$) and HDI-education (coefficient 67.5104, $p<0.01$) had the highest positive associations with mortality from COVID-19; while the Gini index (coefficient -113.19, $p<0.01$) and HDI-income (coefficient -84.4405, $p=0.03$) had the highest negative associations (Table 3).

A spatial lag model analysis was also performed. As in the OLS, the HDI-longevity (coefficient 18.7917, $p=0.37$) and HDI-education (coefficient 10.4933, $p=0.34$) axes had the highest positive associations with mortality from COVID-19, and the Gini index (coefficient -33.4417, $p=0.01$) and the HDI-income (coefficient -67.9286, $p<0.01$) had significant negative correlations (Table 4).

The linear regression model showed an $R^2=0.20$ and a AIC of 18625 with spatial autocorrelation of the residuals analysed by the Moran's $I = 0.60$, $p<0.05$. The spatial lag model presented the best performance in explaining the factors associated with mortality from COVID-19 in the northeast region, with $R^2=0.77$ and a reduction of the AIC to 16794 (Table 3).

Discussion

Deaths from COVID-19 were widespread in all states in the Northeast. The Moran map demonstrates that the mortality coefficient had a spatial aggregation pattern, which means that the negative impacts of COVID-19 did not reach everyone equally. The higher demographic densities were associated with higher mortality as was also observed in Italy (Ilardi *et al.*, 2021) and in England - at the local authority level - where population density was a stronger predictor of mortality than deprivation (Bray *et al.*, 2020). The demographic concentration on the coast of north-eastern Brazil contrasts with the low demographic density of most of its municipalities. According to IBGE (2022), 1, 608 of the 1,794 municipalities in the region, have less than 50 thousand inhabitants (89.6%) and 1,154 have less than 20 thousand inhab-

Table 1. COVID-19 mortality rate in the North-eastern states of Brazil.

State	Deaths (no.)	Mortality (/10,0000)
Alagoas	6383	189.67
Bahia	27,506	183.55
Ceará	24,806	268.45
Maranhão	10,377	145.07
Paraíba	9596	236.36
Pernambuco	20,447	211.34
Piauí	7275	221.17
Rio Grande do Norte	7572	212.64
Sergipe	6057	259.02

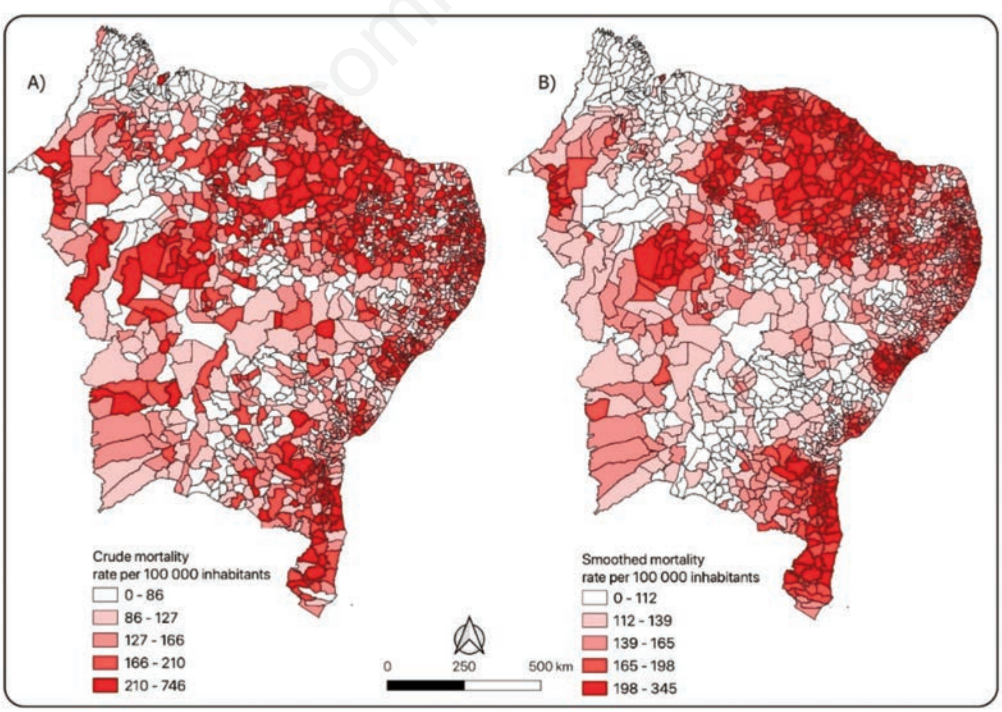

Figure 2. Spatial analysis of mortality rates in the north-eastern region of Brazil from 2020 to 2021. A) Crude mortality rate per 100,000 population; B) Bayesian smoothed mortality rate.

itants (64.32%). Thus, demographic concentration promotes greater contact between people and agglomerations, facilitating the spread of infectious diseases in large cities as previously reported by Ribeiro *et al*. (2020).

The scenario reflects a characteristic of the spread of COVID-19 in Brazil. The first cases were diagnosed in municipalities with high demographic density, greater economic activity, and less social vulnerability, which confounds the influence of vulnerability indicators on dissemination (Castro *et al*., 2021). Until May 6, 2020, more than 80% of the municipalities with less than 10,000 inhabitants had no cases of COVID-19. During the period, the 44 cities with a very high MHDI had a higher incidence and mortality of COVID-19 (De Souza *et al*., 2020). However, the demographic aspect, economic and political assisted us by pointing in the direction of find additional hypotheses for the reason why municipalities with less social vulnerability did present higher COVID-19 mortality.

Brazil was already grappling with an economic and political crisis, which was further aggravated by the pandemic. The precariousness of employment security in this challenging context, coupled with the apprehension of losing one's job, compelled many individuals to persist working, even at the expense of exposing themselves to the risks of the disease. (Maciel *et al*., 2020). In the 2019-2022 period, the federal government assumed an attitude towards the pandemic denying its public importance. In his discourse and actions, the president pointed to the importance of taking care of the economy as well as saving lives but focused on a false dichotomy and criticized the restrictive measures necessary to combat the pandemic. He even went as far as encouraging crowds, downplaying the need for facemasks and supported the use of medications without scientific evidence for the treatment of COVID-19 (Andrade *et al*., 2022; Calil, 2021; Castro *et al*., 2021). This scenario contributed to the spread of the pandemic, especially in centers where the economic activity was high.

Tourism is one of the main economic activities in north-eastern Brazil. The coast of the region receives an inflow of national and international tourists, which facilitated viral circulation thereby increasing incidence and mortality. Keeping the economy running and failing to adopt restrictive measures exacted a high price, especially in cities with strong economic activity and better socioeconomic indicators. In these regions, coupled with a fragile public transport system, high-risk agglomerations for COVID-19 infection were observed (Maciel *et al*., 2020; Martins-Filho *et al*., 2021; Rocha *et al*., 2021). However, it should be noted that this attitude of denial brought about by the Federal Government was not adopted by all governors of the Brazilian states, which contributed to a political polarization in the country. The governments of the north-eastern states instituted the Interstate Consortium for Sustainable Development of the Northeast (*Consórcio Interestadual de Desenvolvimento Sustentável do Nordeste*), which carried out relevant actions, such as joint purchase of equipment, establishment of

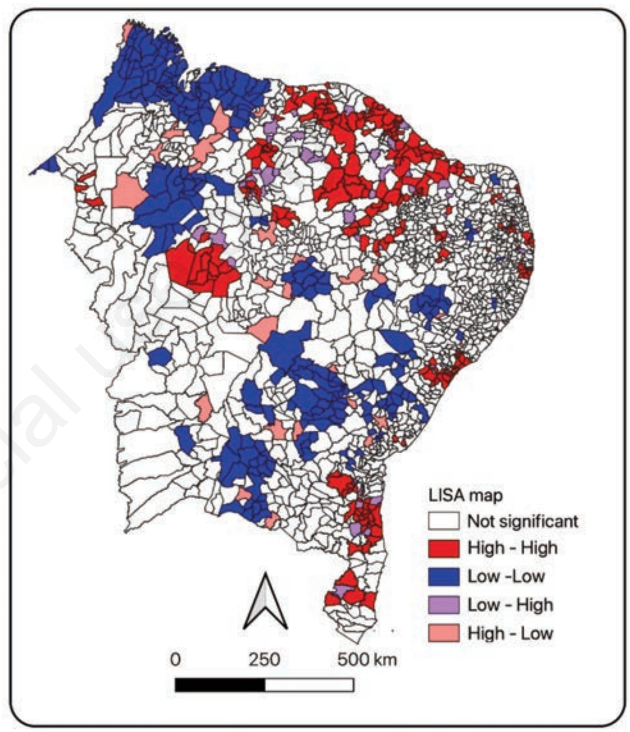

Figure 3. Spatial autocorrelation analysis map using LISA (local indicators of spatial association).

Table 2. Correlation of the COVID-19 mortality rate with socioeconomic and health indicators.

Indicator	Spearman's correlation Rho	p	Multiple linear regression VIF
Population density	0.274	<0.001	1.295
Percentage of people covered by supplemental health insurance	0.422	<0.001	1.322
Mortality rate by non-communicable diseases	0.319	<0.001	1.080
Percentage of persons ≥18 years of age employed on contract	0.359	<0.001	1.583
Gini index	-0.104	<0.001	1.266
Municipal HDI	0.408	<0.001	Excl*
Municipal HDI - longevity	0.249	<0.001	1.396
Municipal HDI - education	0.328	<0.001	1.731
Municipal HDI - income	0.428	<0.001	3.025
Dependency ratio	-0.338	<0.001	2.297

Rho, a non-parametric test used to measure the strength of association between two variables that varies between 0 and 1; p, level of statistical significance; VIF, variance inflation factor; HDI, human development index; Excl*, excluded from the model due to raising the VIF, which would affect the estimation of regression coefficients due to multicollinearity.

Table 3. Impact of socioeconomic and health indicators on COVID-19 mortality in the north-eastern region of Brazil 2020-2021.

Indicator	OLS model			Spatial lag model		
	Coefficient	T-stat.	p	Coefficient	z-value	p
Population density	0.00936061	3.60	<0.01	0.00375528	2.73	0.01
Percentage of people covered by supplemental health insurance	0.0242367	0.13	0.90	0.0397155	0.41	0.68
Mortality rate by non-communicable diseases	0.0884746	8.20	<0.01	0.00405491	0.71	0.48
Percentage of persons ≥18 years of age employed on contract	0.794091	7.25	<0.01	0.101465	1.75	0.08
Gini index	-113.19	-4.76	<0.01	-33,4417	-2.66	0.01
Municipal HDI	115,939	2.88	<0.01	18.7917	0.89	0.37
Municipal HDI - longevity	67.5104	3.23	<0.01	10.4933	0.95	0.34
Municipal HDI - education	-84.4405	-2.14	0.03	-67.9286	-3.27	< 0.01
Dependency ratio	-0.960395	-4.01	<0.001	-0.274829	-2.16	0.03

OLS, ordinary least squares; T-stat., T-statistics: p, level of statistical significance; HDI, Human Development Index.

Table 4. Model evaluation.

Model evaluation criterion	OLS model	Spatial lag model
R^2	0.202377	0.777181
Log-likelihood	-9302.59	-8386.39
AIC	18625.2	16794.8
Schwarz criterion	18680.1	16855.2

OLS, ordinary least squares; R^2, coefficient of determination; AIC, Akaike criterion.

a scientific committee guiding decisions related to social isolation, creation of sanitary barriers and other measures aimed at mitigating the social effects of the pandemic (Fernandez & Pinto, 2020).

Brazil is part of the group of 20 countries harboring about 50% of the global population that accounted for more than 80% of the estimated global excess mortality from January 2020 to December 2021, according to the WHO (2022c). Mortality from COVID-19 in Brazil was 290.20 deaths per 100,000 inhabitants. Brazil was not expected to be among the epicentres of the COVID-19 pandemic because of its public health system, which is essentially free and universal, a fact that has historically reduced access inequality. However, the lack of coordination on the part of the country's federal government, the crisis and political polarization that disconcerted the measures to contain the pandemic - associated with the social inequality existing in the country -, generated both a greater impact of the disease and disparities in its distribution (Andrade *et al.*, 2022; Castro *et al.*, 2021).

Brazil's continental dimensions and its great demographic, economic and social discrepancies caused very different impacts of the COVID-19 pandemic in its territory. Analyzing this process in the course of a pandemic is an ongoing task as there are many factors that can interfere with the spread and severity of the disease, ranging from available health infrastructure, socioeconomic situation and the epidemiological, age and demographic scenario of a population, to the actions taken by health managers to mitigate the effects of the pandemic, whether to guarantee and support social distancing or to facilitate access to vaccines.

Study limitations

The use of secondary data is subject to underreporting or failure to complete forms. The use of municipalities as units of analysis can hide existing inequalities in different sectors of the municipal territory and the use of data based on the last Brazilian census, carried out in 2010, do not reflect possible changes in the socioeconomic indicators scenario until the analyzed period.

The study opted to use mortality from the disease as an indicator due to the great inequality existing in the Brazilian territory, which impacts the diagnostic and hospital capacity of each municipality. Using indicators such as incidence, hospitalizations or lethality could generate biases related to the population search of the health system for diagnosis, number of asymptomatic cases, local epidemiological surveillance capacity or number of beds available for hospitalization.

Conclusions

The demographic density in the major coastal cities of the region, which also serve as hubs for economic and tourist activities, played a significant role in the concentration of mortality rates in cities with better socioeconomic indicators, as identified by a spatial analysis model with strong explanatory power. Due to the country's size, its inequality regarding socioeconomic indicators and the distribution of health resources, and the polarized political scenario interfering with government actions to combat the pandemic, no single narrative is able to explain the spread of the virus in Brazil (Castro *et al.*, 2021). Impacts of the pandemic will be felt over the years and maintaining ongoing analyses will be crucial in comprehending their effects and facilitating actions to mitigate them. Vulnerability due to low socioeconomic levels infer the importance of coordination between Brazilian federal entities in combating health problems, the need for more aggressive restrictive measures in large cities to combat a pandemic, such as COVID-19, and the necessity of social assistance policies that support the population in times of restriction.

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