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Cardiovascular Diseases Mortality in Mexican Municipalities: A Spatio-Temporal Approach

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Abstract

Noncommunicable diseases (NCDs) accounted for approximately 74% of all deaths globally in 2022. Among the deaths from NCDs, the leading causes is cardiovascular disease (CVD), which represents approximately 32% of all global deaths. Furthermore, estimates indicate that over three-quarters of CVD deaths occur in low- and middle-income countries such as Mexico. Therefore, the goal of this study is to analyze the spatio-temporal patterns of mortality from cardiovascular diseases across Mexican municipalities from 2010 to 2019. We used a spatial Bayesian hierarchical regression model based on the Integrated Nested Laplace Approximation (INLA) and implemented in the R-INLA package to study the spatial pattern of mortality from cardiovascular diseases in Mexican municipalities. The modeling process revealed that the best model for both populations under and over 60 years old was the spatio-temporal model with space-time interaction. Overall, the purely spatial results suggest that the relative risks for both age groups (under and over 60 years old) do not have a consistent spatial pattern in 2019. On the other hand, the spatio-temporal results show that the interactions are stronger for the population over 60 years of age. This paper demonstrates the importance of assessing not only the spatial pattern of deaths, but also simultaneously incorporating temporal trends. With the understanding that this relationship (space-time) cannot be neglected, first the results of a purely spatial model are presented and, soon after, this model is expanded and the spatio-temporal results of mortality from cardiovascular diseases across Mexican municipalities from 2010 to 2019 are shown.

Keywords Cardiovascular mortality · Mexico · Municipalities · Spatio-temporal analysis · Integrated nested laplace approximation (INLA)

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Introduction

Noncommunicable diseases (NCDs) accounted for approximately 74% of all deaths globally in 2022 (World Health Organization, 2022). Their health consequences for individuals, families, and health systems worldwide are strongly negative, although they disproportionately affect people in developing countries, where 77% of all NCDs deaths occur (Yusuf et al., 2004; Zhao et al., 2015; World Health Organization, 2022"). Among NCDs, cardiovascular disease (CVD) is the leading cause of death, accounting for approximately 32% of all global deaths (Roth et al., 2017a, 2017b; Baptista & Queiroz, 2019a, 2019b; Baptista et al., 2020; World Health Organization, 2021).

The World Health Organization (WHO) (2021) estimates that over three-quarters of CVD deaths occur in low- and middle-income countries. Although efforts are ongoing in these nations, the public health impact of CVD mortality can vary due to a range of factors, including population aging, genetic predisposition, lifestyle, healthcare infrastructure, socioeconomic conditions, and access to medical care (Okwuosa et al., 2016; Roth et al., 2020; WHO, 2021). Faced with this picture of silent epidemic and the importance of a reduction in CVD mortality, the United Nations Sustainable Development Goals (SDG) established an ambitious target that aims to reduce by one third the risk of premature deaths from this one and other NCDs by 2030 (United Nations, 2021).

However, to achieve this goal, it is necessary to understand how CVD mortality affects the most diverse countries. Efforts to address CVD mortality should consider the unique characteristics of each country's population and consider tailored approaches to prevention, diagnosis, and treatment. Most studies relating to CVD deaths and their brunt have focused on developed countries (Reddy, 2002; Roth et al., 2017b; Lopez & Adair, 2019; Adair & Lopez, 2020; Baptista et al., 2020; Mehta et al., 2020). In addition, researches addressing this issue have focused on specific causes, such as ischemic heart disease and stroke (Nowbar et al., 2014; Kim et al., 2015; Gupta & Wood, 2019).

In Mexico, as result of several decades of rapid epidemiological and demographic changes, marked by sizeable improvements in mortality and living standards, opposite trends in particular causes of death have been observed. For instance, cardiovascular diseases, homicides, diabetes, and kidney diseases have increased over the last 30 years, even as maternal and neonatal disorders, respiratory infections, tuberculosis, and enteric infections continued to fall over the same period (Aburto et al., 2018; GBD, 2019). Between 1990 and 2000 life expectancy at birth increased by 1.4 years for females (from 75.0 to 76.4) and 2.9 years for males (from 68.0 to 70.9). However, between 2000 and 2019, life expectancy at birth slowed its progress for women and entered a period of stagnation for men, with homicides is at the heart of this stagnation for males in Mexico (Aburto et al., 2016; INEGI, 2023).

Despite the changes in mortality observed in Mexico, CVD has been the leading cause of death for a few decades, although the percentage is lower than the global average (e.g., 22.69% vs. 32.84% in 2019) (GBD, 2019) and there is an important geographic disparity within the country. While in 1990 CVD mortality varied between 10.5% in the state of Chiapas and 24.0% in Nuevo Léon, in 2019 the varia-

tion was from 16.7% in Quintana Roo to 26.9% in Sonora (GBD, 2019). Therefore, evaluating and understanding this heterogeneity is important to establish effective public health policies to prevent deaths from cardiovascular disease to achieve the third Sustainable Development Goal (SGD) in the country.

The main goal of this paper is to analyze the spatio-temporal patterns of mortality from cardiovascular diseases across Mexican municipalities from 2010 to 2019. For this purpose, we used a spatial Bayesian hierarchical regression model (Besag et al., 1991; Banerjee et al., 2004; Sparks et al., 2013) based on the Integrated Nested Laplace Approximation (INLA) (Rue et al., 2009). The study of CVD mortality in small areas and over multiple years in Mexico is unknown to us. In other words, this is a first effort that seeks to contribute to the understanding of mortality from cardiovascular diseases in Mexican municipalities using a spatio-temporal approach.

Materials and Methods

Data Source

Data on mortality from cardiovascular diseases comes from the National Institute of Statistics and Geography (INEGI) and are publicly available online (https://www.inegi.org.mx/programas/mortalidad/). Death statistics provide all the basic elements to determine and compare the characteristics of mortality in different geographic areas of the country. A total of 1.6 million deaths from diseases of the circulatory system (International Classification of Diseases [ICD] I00–I99) were examined for the 2010–2019 period, disaggregated by age (under 60 years old and over 60 years old) and municipality (2,456). Furthermore, population data with the same breakdowns were obtained from the National Population Council (CONAPO), which is also publicly available online (https://www.gob.mx/conapo).

Data Quality

Reliable vital statistics systems, such as mortality registries, are fundamental for the efficient planning and evaluation of public policy and to better understand the impacts of regional differentials. However, the lack of better data quality, problems with completeness of death registration, and inaccuracy of age information (Luy, 2010; Queiroz et al., 2020) are still important limitations for mortality studies in Mexico, although the quality of mortality data has steadily improved over time (Glei et al., 2021; CONAPO, 2023).

Using a set of demographic methods, a study conducted in 2017 evaluated the effectiveness of civil registration systems for capturing deaths. The study indicates that Mexico has been ranked since 2002 as having a complete vital registration system (Wang et al., 2017). Similar results, although using a composite index derived from different dimensions, consider vital registration systems in Mexico to be of "very high quality" (Phillips et al., 2014). Finally, data on the completeness of death registration with cause-of-death information provided by The World Bank (2023) shows that the percentage for Mexico in 2016 was 100%. However, there is some evi-

dence that these estimates may be unrealistic for Latin American countries (Queiroz et al., 2020).

As reported by Glei et al. (2021), when evaluating unadjusted mortality estimates for Mexico during 1990–2016, estimates using the SEG method found a result of 0.86 for men in 2000–2005 fit to ages 5+to 65+, suggesting that deaths are 14% under-registered relative to the population. On the other hand, the corresponding GGB estimate was 1.26; that is, deaths were 26% over-registered relative to the population. They further found that mortality rates appear suspiciously low at all ages, but there is evidence that infant and child mortality is substantially underestimated. As mortality from CVD is not representative up to the age of 30 years (Baptista & Queiroz, 2019a, 2019b), this has little impact on our analyses.

Differences have also been reported in other studies. In the *Encuesta Nacional de la Dinámica Demográfica* (ENADID) of 1992 and 1997, an omission close to 5% in deaths aged 1 year or older in vital statistics was observed, whereas in the *Base de Datos Nacional del Registro Civil* (BDNRC) of 2019 there was an under-registration of 6% with respect to general deaths. However, recent studies show that the omission in censuses and counts from 1950 to 2010 for persons 3 years of age or older rarely exceeded 3% (Mexican Society of Demography, 2010; Partida, 2017). In summary, evaluating the quality of mortality data in Mexico is a question that needs to be on the research agenda.

Statistical Method

We performed a spatial Bayesian hierarchical regression model (Besag et al., 1991; Banerjee et al., 2004; Sparks et al., 2013) using the Integrated Nested Laplace Approximation (INLA) (Rue et al., 2009). INLA is designed to provide computationally efficient and accurate approximations to the posterior distribution of model parameters. Therefore, we implemented the R-INLA package (Lindgren & Rue, 2015) to assess the spatial pattern of mortality from cardiovascular diseases in Mexican municipalities. We assumed that the number of deaths from cardiovascular diseases, y_i, is modelled using a Poisson distribution, and we can specify a log-linear model for CVD mortality as:

$$y_i \sim \text{Poisson}\left(E_i\theta_i\right) \tag{1}$$

$$\log\left(\theta_i\right) = \beta_0 + u_i + v_i$$

Where $E_i\theta_i$ is the mean defined in terms of the expected number of deaths from CVD in area i (E_i), and θ represents the specific relative risk in area i. β_0 is the intercept that quantifies the average CVD mortality rate in all 2,456 municipalities; u_i is a spatially structured random effect, modelled employing an intrinsic conditional autoregressive distribution (iCAR), $u \sim \text{ICAR}(\text{W}, \sigma_u^2)$ (Besag et al., 1991); and v_i is a spatially unstructured random effect modelled by adopting an exchangeable prior, $v_i \sim \text{Normal}(0, \sigma_v^2)$.

We broaden the first equation by adding a temporal structure and space-time interaction to specify a spatio-temporal dynamic model for CVD mortality. The spatio-

temporal model can be specified as follows (Bernardinelli et al., 1995; Blangiardo et al., 2013):

$$\log(\theta_{it}) = \beta_0 + u_i + \upsilon_i + \varphi_t + \gamma_t + \delta_{it} \tag{2}$$

Where $\varphi_t \sim \mathrm{RW1}$(random walk of order 1) is a temporally structured random effect with variance parameters σ^2_λ, γ_t is a temporally unstructured random effect, $\gamma_t \sim \mathrm{Normal}(0, \sigma^2_\gamma)$, and δ_{it} is the parameter of the interaction space-time that we recognize as $\delta_{it} \sim N(0, \sigma^2_\delta)$. This parameter elucidates differences in the time trend of deaths from CVD across Mexican municipalities; that is, it measures deviations from the main spatial and temporal effects (Knorr-Held, 2000).

There are different procedures for modelling the interaction term, each of which makes different assumptions about temporal and/or spatial structures (see, for example, Knorr-Held, 2000; Blangiardo & Cameletti, 2015). In this study, we assumed that the interaction is given by two unstructured effects, υ_i and γ_t, which means that there is no spatial and/or temporal structure in the interaction. We also take into account the following priors specifications for all precisions (unstructured and structured effects): $\log\tau_u \sim$ logGamma(1,0.1) and $\log\tau_\upsilon \sim$ logGamma(1,0.1), which includes a Gamma(1,0.1) prior to the precision of the random walk and of the spatially and temporally unstructured effects.

Finally, in a Bayesian framework, one way to identify the best model is to compute the Deviance Information Criterion (DIC) (Spiegelhalter et al., 2002), which is a generalization of the Akaike Information Criterion (AIC). DIC is given by Eq. (3). It is the sum of the posterior mean of the deviance ($\bar{D}$), which measures the model fit, and the effective number of parameters (p_D), which represents model complexity. Smaller DIC values provide the best trade-off between the model fit and complexity.

$$\mathrm{DIC} = \bar{\mathrm{D}} + \mathrm{p_D} \tag{3}$$

Results

Exploratory Analysis

Table 1 presents the mean (95% CI), standard deviation, minimum, maximum, as well as the Global Moran's I for the standardized mortality rate (SMR) from CVD mortality. Between 2010 and 2019, the Global Moran's I remain positive and suggests the presence of spatial autocorrelation, with a significant *p-value* under the 99% confidence level, except for 2011. In other words, the SMR from CVD mortality shows a spatially clustered pattern over the years studied, thereby rejecting the null hypothesis of spatial randomness. Based on these statistics, it is feasible to consider the construction of spatial models to achieve the proposed objectives.

Table 1 Descriptive statistics and global Moran's I for the SMR from CVD mortality

Year	Mean[1]	SD	Min	Max	Moran's I[2]
2010	119.11 (116.89,121.33)	56.08	6.34	639.01	0.108***
2011	116.86 (113.82,119.91)	76.95	11.51	2817.43	0.049*
2012	115.23 (113.17,117.29)	52.07	10.47	558.66	0.136***
2013	119.14 (117.13,121.15)	50.88	11.31	754.09	0.110***
2014	122.14 (119.99,124.27)	53.99	4.99	493.09	0.132***
2015	124.91 (122.73,127.09)	55.06	11.28	643.70	0.118***
2016	125.94 (123.74,128.14)	55.53	11.85	650.11	0.083***
2017	127.73 (125.42,130.04)	58.37	16.18	937.58	0.070***
2018	124.38 (122.19,126.58)	55.51	9.72	728.37	0.123***
2019	128.35 (126.19,130.51)	54.60	9.03	476.76	0.103***

[1] SMR from cardiovascular disease (per 100,000). 95% CI are shown in parentheses

[2] Signif. codes: *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

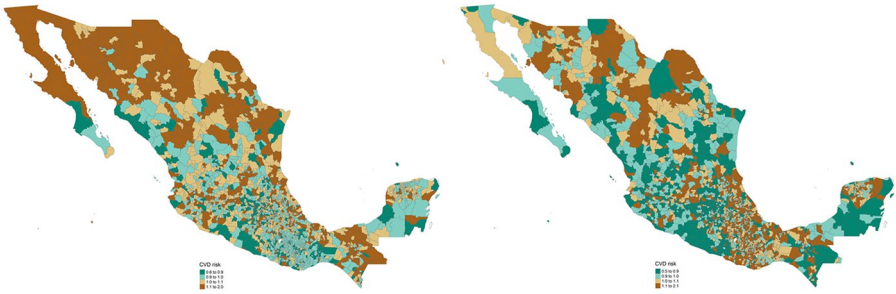

Fig. 1 Spatial distribution of the posterior mean of mortality from cardiovascular diseases in 2019, municipalities, Mexico. Under 60 years old (left) and over 60 years old (right)

Purely Spatial Model

Following the Poisson model specified in the first equation, the estimated relative risks, $\varsigma_{it} = \boldsymbol{exp}(\boldsymbol{u_{it}} + \boldsymbol{v_{it}})$, of mortality from cardiovascular diseases in 2019 for municipalities in Mexico are shown in Fig. 1, both for the population under (left) and over (right) 60 years old. It is noteworthy that the purely spatial model can be estimated independently for all available years, and that, typically, municipalities with relative risk >1 indicate areas with higher risk than expected and, therefore, of greater interest.

It is observed that CVD mortality risks for the population under 60 years old are higher in the northern part of the country, along with the cost of the Gulf of Mexico and the states of Chiapas and Tabasco (southeast). In approximately 50% of the municipalities, the relative risk is >1 and, in some of them, CVD mortality is two

Fig. 2 Specific posterior probability of mortality from cardiovascular diseases in 2019, municipalities, Mexico. Under 60 years old (left) and over 60 years old (right)

Table 2 Deviance information criterion (DIC) for spatio-temporal models

Spatio-temporal models	Under 60 yrs old			Over 60 yrs old		
	$\bar{D}$	p_D	DIC	$\bar{D}$	p_D	DIC
Two temporal effects	92,484.5	1,301.7	93,786.2	149,224.9	2,011.2	151,236.1
Space-time interaction	91,081.5	2,342.4	93,423.9	141,774.1	6,029.5	147,803.6

times as large as on average. On the other hand, in the population over 60 years of age, the variation in CVD mortality risks is less clear, although the northern, eastern, and southwestern parts of the country presented greater relative risks. In this case, approximately 54% of the municipalities had a relative risk > 1, and in some of them, mortality from CVD is even 2.1 times higher than the average.

Figure 2 presents the specific posterior probability (PP) that the CVD mortality risk in 2019 was greater than 1, $\boldsymbol{p}(\varsigma_{it} > 1 \mid \boldsymbol{y})$. Red indicates high-risk municipalities, generally defined by PPs above 0.8 (excess risk). Overall, for both populations under and over 60 years old, it was observed that the northern part of the country, as well as the states of Chiapas and Tabasco, in the southeast, and Guanajuato in the north-central region, concentrated the municipalities with a higher risk of CVD mortality in 2019. Furthermore, for the population over 60 years of age, some municipalities in the eastern region present excess risk.

Spatio-Temporal Model

We extended the purely spatial model (Eq. 1) to include a temporal component. Furthermore, to specify a spatio-temporal dynamic model (Eq. 2), we assume that the space-time interaction is given by two unstructured effects. This interaction is used to capture any other effects that are not explained by the main factors of space and time.

One possible way to evaluate the fit and determine the best model is through the Deviance Information Criterion (DIC) (Eq. 3). DIC provides a balance between model complexity and goodness-of-fit. Therefore, Table 2 shows the posterior mean of the deviance ($\bar{\boldsymbol{D}}$), the effective number of parameters ($\boldsymbol{p_D}$), and DIC values for both age groups (under and over 60 years old), as well as for the two spatio-temporal models (more information on the INLA model results can be found in supplementary material S1-S4).

For both populations under and over 60 years old, the lowest DIC values are observed for the spatio-temporal model with space-time interaction. This suggests that this model has the best fit, despite the added complexity (p_D). Therefore, this paper focuses on the results of this model.

Figure 3 shows the posterior mean of the interaction between space and time δ_{it} to examine the geographic variability of the municipality-specific differential trend. For a given year, municipalities with high space-time interaction may be highlighted as having unusually high or low levels of CVD mortality, that is, above or below the baseline spatial and temporal risk. This interaction helps discover patterns that may be neglected in purely spatial or temporal analyses (Luan et al., 2016).

It is observed that space-time interactions are stronger for the population over 60 years old (right), although the geographic variation is heterogeneous. In other words, there are municipalities with higher (dark green) and lower (brown) levels of CVD mortality that, respectively, are above and below the baseline spatial and temporal risk.

The posterior probabilities (PPs) for space-time interactions, $p(exp(\delta_{it}) > 1 \mid y$, are presented in Fig. 4. As can be seen, particularly for the population over 60 years of age (right), only a handful of municipalities show evidence of an interaction greater than 1, changing over the years.

Posterior probability can be explained as the Bayesian tantamount of p-value (Meng & Dempster, 1987) ranging from 0 to 1, allowing hot spot municipalities to be sorted based on the strength that $exp(\delta_{it}) > 1$. The closer the PP is to the extremes (0 and 1), the more robust the evidence that municipalities are cold and hot spots in space-time, respectively.

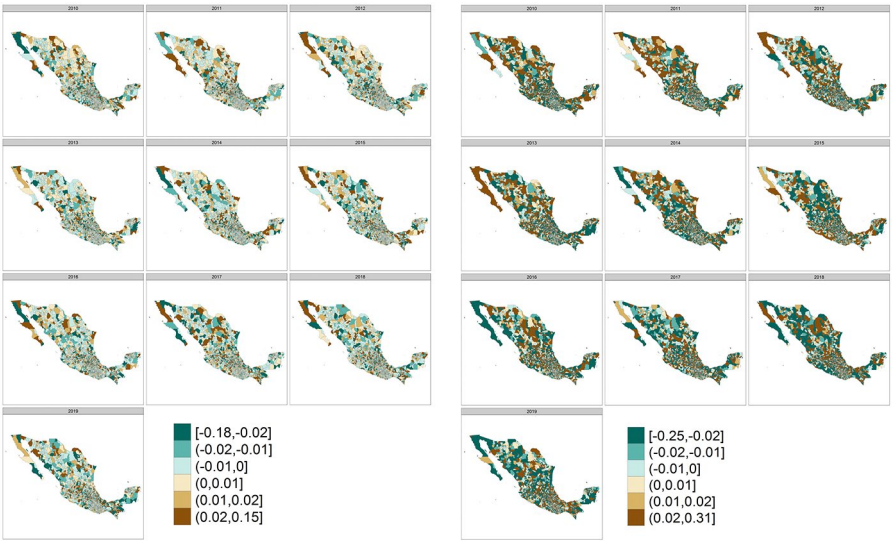

Fig. 3 Posterior mean of the spatio-temporal interaction δ_{it}, municipalities, Mexico. Under 60 years old (left) and over 60 years old (right)

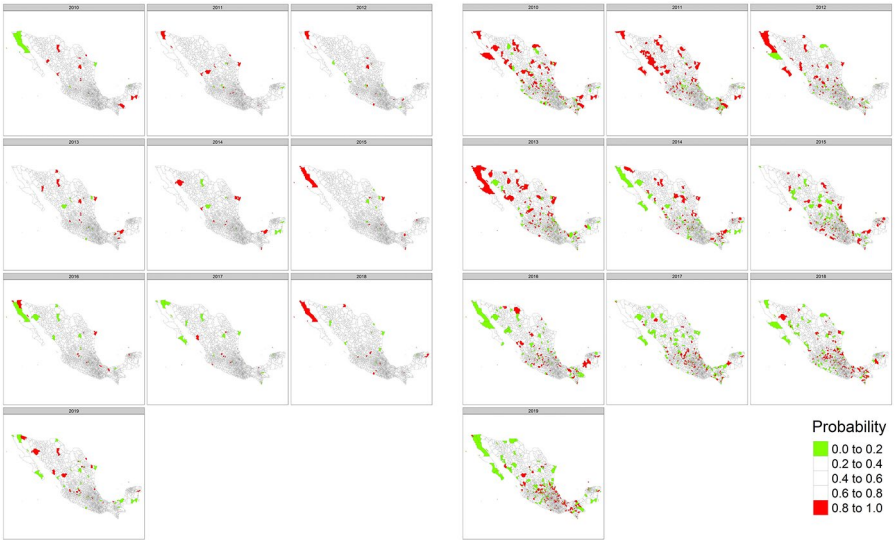

Fig. 4 Posterior probability of the spatio-temporal interaction $\boldsymbol{\delta_{it}}$, municipalities, Mexico. Under 60 years old (left) and over 60 years old (right)

Discussion

Investigating only the spatial pattern of deaths does not allow us to say anything about their temporal variation, which could be equally important and interesting (Blangiardo & Cameletti, 2015). Through the application of a Bayesian hierarchical regression model, we attempt to overcome this, that is, this study assesses not only the spatial pattern of mortality from cardiovascular diseases across Mexican municipalities, but also incorporates the temporal trend (2010 to 2019). In other words, the data are defined by a process indexed by space and time (spatio-temporal model).

The modeling process revealed that the best model for both populations under and over 60 years old was the spatio-temporal model with space-time interaction (Table 2). Based on the DIC analysis, and despite having greater complexity ($\boldsymbol{p_D}$), this model showed the lowest DIC, suggesting a best fit.

Overall, the purely spatial results (Figs. 1 and 2) suggest that the relative risks for both age groups (under and over 60 years old) do not have a consistent spatial pattern in 2019. Approximately one-quarter of municipalities for populations under 60 years of age and one-third of municipalities for populations over 60 years of age are at exceptionally high risk (>1.1). Furthermore, an increased risk, defined by posterior probabilities above 0.8 (excess risk), can be seen in some municipalities in the northern part of the country, as well as the states of Chiapas and Tabasco, in the southeast, and Guanajuato, in the north-central region. On the other hand, the spatio-temporal results (Figs. 3 and 4) show that the interactions are stronger for the population over 60 years of age.

To the best of our knowledge, there is a lack of studies on CVD mortality in small areas over an extended period (multiple years) in Mexico. Studies addressing

this topic have focused on specific causes, specific localities and years, cross-sectional population-based representative studies, and risk factors rather than mortality (Acosta-Cázares & Escobedo-de la Peña, 2010; Cortés-Hernández et al., 2014; Cruz et al., 2017; Arroyo-Quiroz et al., 2020; Baptista & Queiroz, 2022). For instance, Anaya and Al-Delaimy (2017) conducted a cross-sectional population-based time series analysis to estimate the effects of some risk factors in Mexican border and non-border municipalities and their association with CVD mortality. The results showed that Mexican municipalities along the border have a significantly higher mortality due to CVD than non-border municipalities in Mexico. These results are in line with our findings, particularly when compared with the purely spatial results.

Dávila-Cervantes (2020a) reported findings from the Global Burden of Disease Study 2017 (GBD, 2017) on CVD in Mexico at a national and subnational scale (states) from 1990 to 2017, in addition to assessing the association between CVD burden and the sociodemographic index (SDI). He states that the CVD burden of disease decreased by approximately 22% over the period studied, and that this decrease occurred both in the country and in all states, with a greater drop in states located in the northern and central regions. In another study, the same author analyzed the trend of cardiovascular diseases in Mexico between 1990 and 2015 at the national level by sex, age groups, and cause of death, as well as its impact on the life expectancy of the population (Dávila-Cervantes 2020b). The results suggest a decrease in mortality due to specific cardiovascular diseases, which has positively contributed to the life expectancy of the elderly. On the other hand, "there are others that have a bearing in an increase in mortality, which decreases the life expectancy of the population, mainly for older adults." In summary, this study contributes significantly to the understanding of CVD mortality in Mexican municipalities (small areas) over a reasonable period (10 years) and can be used as a guide for local planners' decision-making processes. For instance, identifying municipalities with an excess risk of CVD mortality (Fig. 2) and how they interact with and over time (Figs. 3 and 4) is of fundamental importance for the planning and design of public health policies aimed at reducing cardiovascular mortality. In other words, understanding and integrating strategies addressing various aspects of prevention, risk factors, spatial dependence, education, healthcare access, and community involvement, as well as reassessment and adjustments based on outcomes and new evidence, are crucial for the success of public health policies that plan to reduce CVD mortality rates and improve the overall health of communities.

However, there are a few limitations to this research. First, this study is at the aggregate level, and there might be important variations within municipalities and among individuals (ecological fallacy) (Wakefield & Lyons, 2010). Thus, and although this study focuses on small areas, some municipalities (e.g., territorially extensive or with high population density) can be internally heterogeneous. In these cases, further research should investigate individual behavior and its relationship to the macro environment to obtain further knowledge on proper interventions to reduce mortality levels. Second, our study is also limited by the availability of covariates that help to understand trends in CVD mortality across municipalities. The lack of data on some CVD risk factors at the municipal level limits our understanding of the regional effects of CVD (Anaya & Al-Delaimy, 2017). However, I believe that a good

understanding of the spatio-temporal variability of CVD deaths is an important and essential contribution to guiding further research.

Future studies may try to address the limitations raised, particularly including explanatory variables. That is, to analyze possible associations between municipalities with increasing or decreasing trends and potential local risk factors, incorporating those that are stable or changing.

Conclusion

This paper demonstrates the importance of assessing not only the spatial pattern of deaths, but also simultaneously incorporating temporal trends. With the understanding that this relationship (space-time) cannot be neglected, first the results of a purely spatial model are presented and, soon after, this model is expanded and the spatio-temporal results of mortality from cardiovascular diseases across Mexican municipalities from 2010 to 2019 are shown. The modeling process revealed that the best model for both populations under and over 60 years old was the spatio-temporal model with space-time interaction, which corroborates our argument about the importance of taking this relationship into account.

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Data Availability The dataset used are not publicly available due to file size but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing Interests The author declares that there are no competing interests.

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