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Air Pollution and Covid-19: An Ecological Study in Mainland Portugal
Poluição Atmosférica e Covid-19: Um Estudo Ecológico em Portugal Continental

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Abstract

Air quality stands out as an important determinant of health, as its degradation was associated with around 4.2 million premature deaths in 2019, primarily due to heart and respiratory problems. It is shown that the elderly, the children, and individuals with pre-existing health conditions are simultaneously more sensitive to the impacts of air pollution and Covid-19, due to their fragile immune systems. Scientific evidence has shown the consequences of exposure to air pollutants to respiratory system diseases, emphasizing that it could be an important factor in explaining the spatial pattern of Covid-19 incidence and mortality. The aim of this study is to analyze the spatial association between air pollutant $PM_{2.5}$ and the incidence and mortality of Covid-19 during March and December of 2020 in mainland Portugal. Weighted geographical models (GWR), were applied to identify and understand patterns, as well as explanatory factors in this relationship. The results obtained through the GWR models reveal that the pollutant $PM_{2.5}$ has an association that varies in space. The incidence rate is higher in the southern, central, and northern regions of the country. The results of this study contribute to the analysis and assessment of the impact of air pollutants on human health, specifically in relation to health outcomes associated with Covid-19. It became evident that the concentration of $PM_{2.5}$ is an important factor in explaining Covid-19 incidence rate in Portugal.

Keywords: $PM_{2.5}$, Covid-19 Incidence and Mortality, Air Quality, GWR, Portugal.

Resumo

A qualidade do ar destaca-se como um importante determinante para a saúde, uma vez que a sua degradação está associada a cerca de 4,2 milhões de óbitos prematuros, no ano de 2019, principalmente devido a problemas cardíacos e respiratórios. Não obstante, idosos, crianças e indivíduos com condições de saúde pré-existentes são mais sensíveis aos impactos da poluição atmosférica e da Covid-19, devido ao seu frágil sistema imunitário. Evidência científica retrata a influência da exposição a poluentes atmosféricos na resposta inflamatória no sistema respiratório, destacando que poderá ser um fator importante para explicar o padrão espacial da incidência e mortalidade por Covid-19. O objetivo deste estudo é analisar a correlação espacial e associação entre o poluente $PM_{2.5}$ e a incidência e mortalidade por Covid-19, durante março e dezembro de 2020, em Portugal Continental. Foram aplicados modelos geográficos ponderados (GWR), para identificar e compreender padrões, bem como fatores explicativos desta relação. Os resultados obtidos através dos modelos GWR revelam que o poluente $PM_{2.5}$ apresenta uma associação que varia no espaço. A taxa de incidência é mais elevada na região Sul, Centro e Norte do país. Os resultados deste estudo contribuem para a análise e avaliação do impacto dos poluentes atmosféricos na saúde humana, especificamente nos resultados em saúde associados à Covid-19. Tornou-se evidente que a concentração de $PM_{2.5}$ é um fator importante para explicar a taxa de incidência por Covid-19, em Portugal.

Palavras-Chave: $PM_{2.5}$, Taxa de Incidência e Mortalidade por Covid-19, Qualidade do Ar, GWR, Portugal.

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1. Introduction

The health status of a population in a given place depends on a vast and complex set of biological, cultural, social, economic, and environmental factors, referred to as health determinants (Marmot & Wilkinson, 2005; Marmot et al., 2008; Santana, 2014). Among the dimensions of determinants that influence health, the natural environment (air, water, and land) stands out: air quality is a significant determinant of health as its deterioration threatens the health of communities and natural ecosystems (Santana, 2014).

Air pollution has contributed to several problems affecting the health and well-being of the population, especially in urban areas (Lelieveld et al., 2019). According to the EEA (2013), air pollution is an important risk factor for several diseases, such as respiratory infections, heart diseases, and lung cancer; consequently, it is associated with increased medication use, as well as medical consultations or episodes of hospital emergencies. Prolonged exposure to certain pollutants can even result in premature death due to their toxicity (Guo et al., 2017).

Studies have been suggesting that exposure to air pollution effects populations unequally (Verbeek, 2019; Shen et al., 2020; Fergunson et al., 2021; Brazil, 2022). In the literature the concept of environmental injustice is used to describe how unequal environmental burdens is influenced by socioeconomic status: socioeconomically vulnerable individuals tend to live in areas with higher levels of road traffic and industrial activity due to the affordable cost of housing, as well as working in locations more exposed to harmful environmental conditions (WHO, 2010; Ortiz et al., 2019; Banzhaf et al., 2019; Ferguson et al., 2021; Frolick et al., 2022; Brazil, 2022).

According to the World Health Organization (WHO) (2020), Covid-19 is an extremely contagious disease that primarily affects the respiratory system. It is recognized in the literature that environmental, social, demographic, as well as genetic factors play an important role in the risk of contagion and the severity of the Covid-19 disease (Costa & Costa, 2020; Dias et al., 2022; Banik et al., 2020). Among these, air pollutants such as $PM_{2,5}$, NO_2 and PM_{10} are considered important factors despite the mechanisms of its impacts are still not fully understood (Ali and Islam, 2020; Sheppard et al., 2023). The common interpretation is that air pollutants exposure impacts the inflammatory and immune response in the respiratory system, which, due to prolonged exposure, becomes fragile and vulnerable to viruses and diseases, including Covid-19 (Wu et al., 2020; Wang et al., 2020).

Thus, the aim of this study is to analyze the spatial association between long-term exposure to the air pollutant particular matter with a diameter of 2.5 micrometers ($PM_{2.5}$) and the incidence and mortality of Covid-19 during March and December 2020 in mainland Portugal. As far as the authors know, this study represents the first research in Portugal to specifically examine the geographical impact of air pollution on the incidence and mortality rates associated with Covid-19 and it build up from the knowledge produced by several works such as Costa & Costa, 2021; Almendra et al., 2021b; Almendra et al., 2021c; Costa & Costa, 2020; Nogueira et al., 2020; Vieira et al., 2020; Azevedo et al., 2020; Marques et al., 2021; Sousa et al., 2021; Silva et al., 2022; Barbosa et al., 2022.

2. Data and Methods

2.1. Data

2.1.1. Air Pollutants

Air pollutant datasets were collected from the European air quality database maintained by the EEA through its European Center on Air Pollution and Climate Change Mitigation, called AirBase. EEA (2023) states that this database contains daily data on air quality and air pollutants from networks and individual stations that measure air pollution in the member states of the European Union. The data is then interpolated with other meteorological variables to create a single raster file.

Average yearly $PM_{2.5}$ concentrations were provided by EEA in a raster format, with a resolution of 1 km. Data from the years 2015, 2016, and 2018 was collected while 2017 was not available.

Following the example of previous studies, such as Fattorini & Regoli (2020), the mean concentration of the $PM_{2.5}$. was calculated for each municipality.

2.1.2. Covid-19 Health Outcomes

Incidence and deaths due to Covid-19 data were provided by the Portuguese Directorate General of Health (DGH), through a protocol with CEGOT-UC. The database stores information about individuals who tested positive for Covid-19 in 2020, including the test date, and municipality of residence. In this study, only individuals notified as positive cases for Covid-19, who underwent either a PCR test or a serological test, which was subsequently recorded by the DGH, were included. Furthermore, incidence and mortality rates were calculated regarding Covid-19 cases and deaths in the year of 2020.

2.1.3. Demographic data

The resident population and the aging index for 2020 were collected from the Portuguese National Institute of Statistics (INE).

2.2. Methods

2.2.1. Study Area

The study area is the mainland territory of Portugal (hereinafter referred as Portugal), and the analysis is conducted at the municipal level, which is the most disaggregated administrative level with epidemiological information provided by the Directorate General of Health (DGH).

2.2.2. Association between Air Pollutants and Covid-19

Both Ordinary Least Square (OLS) and Geographically Weighted Regression (GWR) models were applied, using ArcGIS software, in order to analyze the geographical pattern of the association between Covid-19 incidence and mortality and the air pollutant $PM_{2.5}$.

OLS is a regression analysis technique and according to the fundamental theoretical assumptions of this technique, the relationship between the dependent variable and the independent variables can be defined as linear where the values of Covid-19 Incidence or Mortality Rate are estimated by the values of $PM_{2.5}$ and Aging Index (Chwialkowski et al., 2023).

Furthermore, Moran's Index was applied to the residuals of the OLS model to evaluate their spatial heterogeneity.

Both simple and adjusted GWR models were developed. This adjustment by ageing index was made due to significant disparities observed in various phases of the pandemic, with the elderly population being the most affected, especially those residing in nursing homes and senior residences (Almendra et al., 2021a).

GWR was developed to address possible spatial variations in the regression coefficients between variables. Consequently, GWR can essentially be seen as an extension of linear regression models that add a level of modeling sophistication by allowing the relationships between independent variables and the dependent variable to vary depending on location (Faka et al., 2023). The spatial structure of the model was defined based on the AIC criterion (i.e., the number of neighbors and the optimal bandwidth).

Essentially, the main difference between the OLS and GWR techniques is that the parameters in the global model are constant, assuming that the effects are evenly distributed across the country,

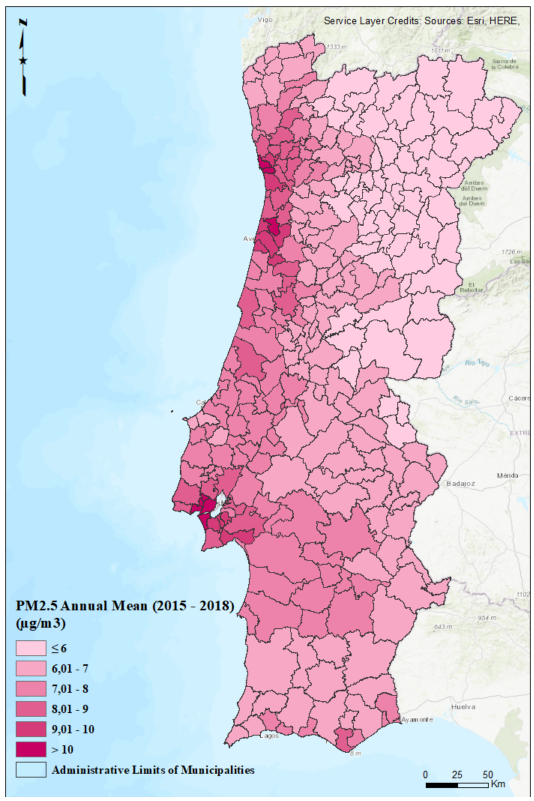

Figure 1
$PM_{2.5}$ Annual Mean in Portugal Mainland (2015, 2016 e 2018) ($\mu g/m^3$).
Source: author's own elaboration based on data from EEA Air Base (2023).

while in the GWR model, the coefficients have location-dependent variability (Isazade et al., 2023).

3. Results

3.1. Mean Concentration of $PM_{2.5}$

Analyzing the variability of $PM_{2.5}$ concentrations in mainland Portugal (Figure 1), it is possible to observe that the concentration of this pollutant is not evenly distributed between the portuguese municipalities. The municipalities that surround and belong to the metropolitan areas have high concentrations of $PM_{2.5}$, often exceeding the levels considered acceptable by the World Health Organization (WHO), which states that annual exposure levels above 5 µg/m³ are associated with adverse health effects (WHO, 2021). The same happens in numerous municipalities in the Central and Algarve region.

3.2. Covid-19 Incidence Rate in Portugal Mainland

By assessing the spatial pattern of the Covid-19 incidence rate (Figure 2), it is possible to observe that the distribution does not follow a homogeneous pattern. The metropolitan areas (Lisbon and Porto) and the municipalities surrounding them have a high incidence rate. In the case of Lisbon Metropolitan Area, it is possible to highlight the municipalities: Loures which has an incidence rate of 4745,27 cases per 100 000 inhabitants, Amadora (4518,41/100 000 inhabitants), Lisboa (4159,42 /100 000 inhabitants). And, for Porto Metropolitan Area it is possible to highlight the municipalities of Póvoa de Varzim (7392,42/100 000 inhabitants), Vila do Conde (7270,02/100 000 inhabitants), and Valongo (6078,88/100 000 inhabitants).

Municipalities bordering Spain also stand out, such as: Vimioso (7302,9/100 000 inhabitants), Chaves (6320,8/100 000 inhabitants) and Marvão (6322,4/100 000 inhabitants).

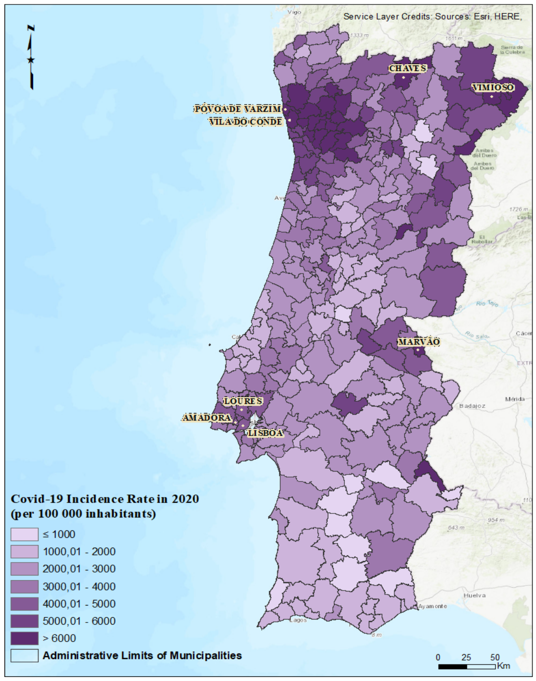

Figure 2
Covid-19 Incidence Rate in Portugal Mainland, 2020 (per 100,000 inhabitants).
Source: Author's own elaboration based on Directorate-General of Health database for Scientific purposes (2023).

3.3. Covid-19 Mortality Rate in Portugal Mainland (2020)

Similarly to the incidence rate, the spatial pattern of the Covid-19 mortality rate does not follow a heterogeneous pattern (Figure 3). A higher mortality is observed in municipalities from the interior of Portugal, especially bordering Spain. It is possible to highlight the municipalities of Mourão which has a mortality rate of 425,35 per 100 000 inhabitants; Idanha-a-Nova (347 09/100 000 inhabitants); Mértola (322,26/ 100 000 inhabitants) and Vimioso (313,32/100 000 inhabitants). Nevertheless, it is also possible to emphasize some municipalities with lower Covid-19 mortality rate such as Olhão (6,72/100 000 inhabitants); Silves (10,59/100 000 inhabitants); Lousã (11,76/100 000 inhabitants) and Campo Maior (12,43/100 000 inhabitants).

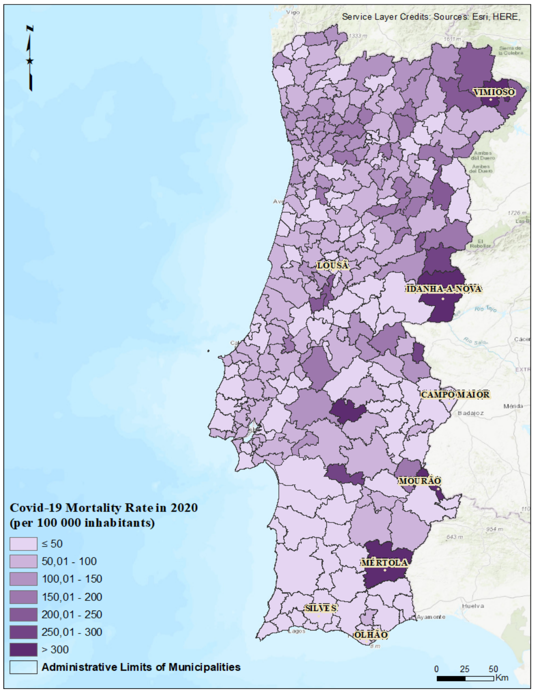

Figure 3
Covid-19 Mortality Rate in Portugal Mainland, 2020 (per 100,000 inhabitants).
Source: Author's own elaboration based on Directorate-General of Health database for Scientific purposes (2023).

3.4. OLS Models

Table 1 indicates the regression results of the global OLS models for the association between Covid-19 (incidence and mortality) and $PM_{2.5}$ mean. The model concerning the Covid-19 incidence rate, presents a positive coefficient for the $PM_{2.5}$. The pollutant $PM_{2.5}$ is a statistically significant predictor, at the 95% confidence level. Moran's I was applied to the OLS model residuals, showing a significant positive spatial autocorrelation.

Analyzing the results for the Covid-19 mortality rate, the model presents a negative coefficient for the $PM_{2.5}$ (-8.2). Such as in the Covid-19 incidence rate $PM_{2.5}$ is statistically significant at the 95% confidence level. OLS model residuals present a significant positive spatial autocorrelation.

Table 2 presents the regression results of the global OLS model for the association between Covid-19 (incidence and mortality) and $PM_{2.5}$ adjusted by the aging index. The model regarding the Covid-19 incidence rate, presents a positive coefficient for the $PM_{2.5}$ mean (163,9); $PM_{2.5}$ is statistically significant. Additionally, the aging index coefficient, concerning the Covid incidence rate, shows a negative association, while the Covid-19 mortality rate indicate a non-significant positive association. The OLS residuals present a significant positive spatial autocorrelation.

Contrary to the non-adjust model, the Covid-19 mortality rate is positively associated with $PM_{2.5}$ (0,8) despite not being statistically significant. Even so, the OLS residuals, after applying Moran's I, present a significant spatial autocorrelation.

The spatial pattern of the residuals, confirmed by Moran's I, shows that the OLS model cannot fully explain the spatial heterogeneity of the influencing $PM_{2.5}$ supporting the need for developing GWR models.

3.5. Geographically Weighted Association Between Covid-19 and $PM_{2.5}$ Concentration (GWR)

Figure 4 presents the coefficients resulting from the application of GWR models to assess the association between health outcomes and the pollutant $PM_{2.5}$. It is possible to observe a positive association in most of the country (Fig. 4A); also the association between Covid-19 incidence and $PM_{2.5}$ tends to be more intense in municipalities with a higher concentration of this pollutant.

The coefficients showing a positive association were higher along the northern region, while in the central inland region, municipalities bordering Spain displayed negative coefficients, suggesting an inverse relationship. However, the models adjusted by ageing

Table 1
OLS Model

	Variable	Coefficient	Std. Error	Robust Std.	Robust_t	Robust_Pr	VIF
Covid-19 Incidence Rate	Intercept	1714.0	619.1	539.3	3.1	0.001	--------
	$PM_{2.5}$ Mean	226.4	87.3	78.4	2.8	0.004	--------
Covid-19 Mortality Rate	Intercept	138.0	22.5	21.5	6.4	0.000	--------
	$PM_{2.5}$ Mean	-8.2	3.1	2.7	-2.9	0.003	--------

Source: author's own elaboration.

Table 2

OLS Model Adjusted by the Aging Index

	Variable	Coefficient	Std. Error	Robust Std.	Robust_t	Robust_Pr	VIF
Covid-19 Incidence Rate	Intercept	2428,5	994,9	746,9	3,2	0,001	--------
	$PM_{2.5}$ Mean	163,9	110,7	79,8	2,0	0,041*	1,60
	Aging Index	-1,0	1,1	1,0	-0,9	0,325	1,60
Covid-19 Mortality Rate	Intercept	33,6	0,0	0,1	2,5	0,011	1,60
	$PM_{2.5}$ Mean	0,8	3,9	3,5	0,2	0,805	1,60
	Aging Index	0,1	0.0	0.0	2.5	0.011*	1,60

Legend: * < 0.05

Source: author's own elaboration.

index (Fig. 4B), show a slightly different pattern, as the coefficients resulting from the association between the incidence rate and $PM_{2.5}$ are higher in municipalities of the southern coastal and northern interior.

Figure 4C shows the coefficients resulting from the association between Covid-19 mortality rate and $PM_{2.5}$. Most of the country's municipalities, exhibit negative $PM_{2.5}$ coefficients, revealing an inverse relationship, with the exception of municipalities from the Lisbon metropolitan area, northern coastal municipalities, the coastal Alentejo, and the western Algarve. However, after adjusting the model for the aging index (Fig. 4D), the pattern presents important differences, it can be observed that, despite the municipalities in the northern and central regions near the border still displaying negative coefficients, southern municipalities have high positive coefficients.

4. Discussion

This study analyzes the spatial association between $PM_{2.5}$ and the incidence and mortality of Covid-19, during March and December 2020, in mainland Portugal, using OLS and GWR, to identify, and understand patterns, as well as explanatory factors in this relationship. OLS models showed a significant positive association between Covid-19 incidence and $PM_{2.5}$ and a negative non-significant association between Covid-19 mortality and $PM_{2.5}$. After adjusting by aging index, the association between the incidence and $PM_{2.5}$ remained positive and significant and the association between mortality changed direction. The OLS residuals show a significant spatial correlation in both models (simple and adjusted).

GWR models showed that the regions of the north and the Lisbon Metropolitan Area displayed the strongest associations between $PM_{2.5}$ and the incidence rate. In addition, observing the results from GWR for the mortality rate, most of the country's municipalities reveal an inverse relationship that partly shifted direction after adjusting for the aging index, highlighting the role of ageing in explaining the patterns of mortality due to Covid-19.

According to Wu et al. (2020), prolonged exposure to $PM_{2.5}$ impacts the respiratory system, making it fragile and vulnerable to viruses and diseases, including Covid-19. An exploratory study conducted by Yu et al. (2021), at country level for the entire globe, also used GWR to analyze the association between Covid-19 incidence and mortality rate with $PM_{2.5}$ concentration. They concluded that $PM_{2.5}$ concentrations influence the spatial patterns of Covid-19 outcomes across the study area. Nevertheless, this trend is not applicable to all countries, some countries present lower $PM_{2.5}$ concentrations but higher incidence and mortality rates (i.e., Russia, Spain, the Uk, and Iran). Another study conducted by Middya & Roy, at district-level, in India, using GWR models to study the association between Covid-19 mortality rate and $PM_{2.5}$ adjusted by total population, age, education, and households with at least 9 persons, concluded that in the western districts of India there is a strong positive association between $PM_{2.5}$ and Covid-19 mortality, whereas in the other districts, there is no such strong association. According to the authors, this heterogeneous distribution is related to many underlying factors, such as demographic, socioeconomic, and environmental pollution variations between different districts of India. Similarly, the results obtained in our study also point out spatial differences and spatial inequa-

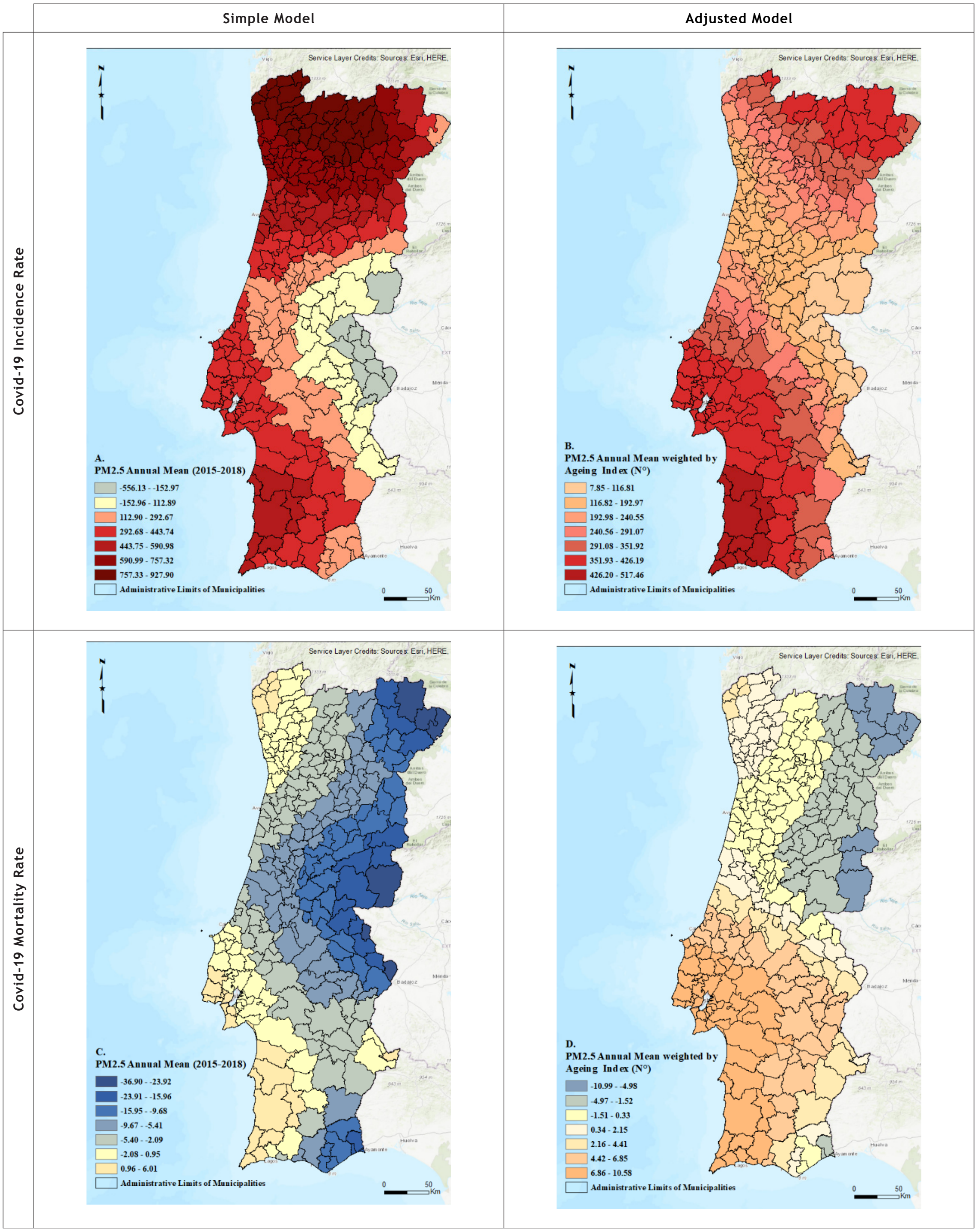

Figure 4

Geographical Distribution of GWR Coefficients for the Air Pollutant $PM_{2.5}$.

Key: A. Covid-19 Incidence Rate Weighted by $PM_{2.5}$ Annual Mean Concentrations (2015, 2016 and 2018), in Portugal; B. Covid-19 Incidence Rate Weighted by $PM_{2.5}$ Annual Mean Concentrations (2015, 2016 and 2018) and Weighted by Aging Index, in Portugal Mainland (Nº); C. Covid-19 Mortality Rate Weighted by $PM_{2.5}$ Annual Mean Concentrations (2015, 2016 and 2018), in Portugal Mainland; D. Covid-19 Mortality Rate Weighted by $PM_{2.5}$ Annual Mean Concentrations (2015, 2016 and 2018) and Weighted by Aging Index, in Portugal Mainland (Nº).

Source: Author’s own elaboration.

lities in the association between Covid-19 mortality rate and $PM_{2.5}$.

Due to the need for a rapid response to the global public health emergency, early publications have analyzed the association between long-term exposure to air pollution and Covid-19, without considering other important factors such as biological and social fragility associated with population aging, which makes these individuals more vulnerable to viruses and diseases like Covid-19 (Chen et al., 2021). The observed difference in patterns suggests that the association between health outcomes and air pollution may change depending on aging.

Demographic factors, such as the age structure of the population, can play an important role in explaining the Covid-19 mortality rate: age is a determining factor in vulnerability to Covid-19 and the disease tends to be severe in the older population, due to the weakening of the immune system throughout life (Chen et al., 2021).

The study of Zhou et al. (2020) based on data from 191 patients in hospitals, in China, established that advanced age is associated with higher odds of death in Covid-19 patients. This result has been confirmed by other studies developed at different scales. A study conducted by Dudel et al., 2020, across six countries, revealed that more than half of the variation in mortality rates can be explained by differences in the age structure of the population; Guo et al. (2020), in their analysis of the characteristics of the new variant of Sars-Cov-2 (Covid-19), determined that the disease tends to progress more rapidly in individuals aged 65 or older, due to their weak immune system.

It is not only the impact of biological fragility associated with this age group that is observed; the conditions in which the elderly population live, such as residing in nursing homes and long-term facilities for dependent elderly individuals, are factors that influence the spread of Covid-19 (Costa & Costa, 2020; Almendra et al., 2021a). According to Team and Manderson (2020), in a literature review, institutional care is limited by residents' ability to pay, inadequate financial support, lack of staff, and overcrowding. Caregivers for the elderly often have minimal training, are poorly protected, receive low wages, and are underemployed. Plus, they do not have sick leave or the right to paid isolation in case of Covid-19 (Almendra et al., 2021a). Residents often share bedrooms, dining rooms, and bathrooms, as well as equipment such as wheelchairs and toilets. In this sense, these facilities provide the necessary conditions for the spread of Covid-19 among vulnerable individuals, who are more likely to have a high fatality rate (Team & Manderson, 2020; Almendra et al., 2021a).

It became evident that the concentration of $PM_{2.5}$ is an important factor in explaining Covid-19 outcomes in Portugal and global (OLS) and local (GWR) models can be utilized to explore such relations. However, additional research is needed to understand different potential driving factors that can influence Covid-19 outcomes in the Portuguese municipalities.

5. Conclusion

The Covid-19 pandemic has brought various consequences for society at different levels. Its impact and long-term repercussions are still the subject of ongoing studies. Identifying spatial patterns, trends, and explanatory factors in the spread of Covid-19 is important for understanding the geographical nature of the disease, allowing the formulation of strategies based on evidence.

The results obtained with the methods used, reveal that long-term exposure to air pollutants is significantly associated with the incidence rate of Covid-19 at the national level. However, this is not clearly observed for the mortality rate, suggesting that municipalities with higher mortality rates from Covid-19 may be less exposed to air pollutants. Nonetheless, other relevant Covid-19 determinants display relevant role in the outcome of this disease and are out of the scope of this text. After adjusting for the aging index, it is possible to identify sets of municipalities where the association is positive. The results obtained should be interpreted with caution, as they do not indicate a protective effect associated with exposure to air pollutants. Further research is needed to understand the internal factors that influence both pollution and mortality rates in these municipalities.

This work provides valuable information for policymakers and local intervention stakeholders to adequately identify risk factors that influence Covid-19, including air pollution. However, further research and an expansion of the variables analyzed are needed to build knowledge about the various factors that modify the association between exposure to pollutants and the incidence and mortality of Covid-19.

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