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Original Research

Research on Spatiotemporal Evolution and Population Exposure Mortality Risk of $PM_{2.5}$ in Shandong Province

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Abstract

The research focuses on the spatiotemporal evolution and population exposure mortality risk of $PM_{2.5}$ in Shandong Province from 2014 to 2023, and the $PM_{2.5}$ exposure risk assessment model and the health effect assessment model are employed. The results showed that the annual average concentrations of $PM_{2.5}$ ranged from 16.80 to 108.70 μg/m^3, with a significant decreasing trend. The exposure level of the population showed a significant decreasing trend at a rate of 3,054,300 persons /year, with the average number of exposed people being the highest in the cities in the central region and the lowest in the Shandong Peninsula. There is an obvious spatial matching relationship between population density and $PM_{2.5}$ concentration, with a higher risk of $PM_{2.5}$ population exposure. The annual average of $PM_{2.5}$ exposure was associated with all-cause mortality; the reduction of $PM_{2.5}$ concentration is more conducive to the reduction of the mortality rate from respiratory diseases. The overall distribution of the total number of deaths from exposure showed a spatial pattern of more in the south and west and less in the north and east. The research results can provide scientific references to formulate air environment prevention and control policies and improve the health level of the population in Shandong Province.

Keywords: $PM_{2.5}$, population exposure, health burden, shandong province

Introduction

The direct harm of air pollution that humans experience is primarily its impact on human health. Currently, air pollution is the fourth leading risk factor for global diseases and deaths [1]. $PM_{2.5}$, as the most representative atmospheric pollutant, is characterized by its small particle size, widespread sources, and complex physical and chemical composition, which is closely related to various public health benefits [2]. It is absorbed by the human body through the respiratory system, deposited in the upper respiratory tract, and reaches other organs through the circulatory system, inducing a series of diseases. In recent years, with the rapid development of industrialization and urbanization in China, $PM_{2.5}$ pollution has become increasingly severe. According to the Global Burden of Disease (GBD) study, $PM_{2.5}$ pollution caused approximately 4.14 million premature deaths worldwide in 2019, with more than 1/4 coming from China, significantly higher than

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other countries [3]. Faced with the increasingly severe public health issues, since China first promulgated the Ambient Air Quality Standards GB3095-2012 in 2012, which included $PM_{2.5}$ concentration monitoring into the routine air quality monitoring system, it has successively introduced the Air Pollution Prevention and Control Action Plan (2013-2017), the Three-Year Action Plan to Win the Blue Sky Defense War (2018-2020), and the Continuous Air Quality Improvement Action Plan (2023-2025), aiming to reduce atmospheric $PM_{2.5}$ concentrations. With the implementation of the three Air Ten Articles policies, Chinese air quality has significantly improved [4, 5]. However, 80% of the population is still exposed to environments with annual average $PM_{2.5}$ concentrations exceeding China's secondary ambient air quality standard (35 $\mu g/m^3$) [6]. Therefore, the study of the spatiotemporal variation of $PM_{2.5}$ and the risk of exposure to death has attracted widespread attention in the academic community.

In terms of spatiotemporal evolution on a national scale of China, studies by Zhou Peng et al. [7], Xia Xiaosheng et al. [8] and Zhou Zhihao et al. [9]. They have found that the annual variation of $PM_{2.5}$ concentrations generally shows a downward trend, with the highest concentrations in winter and the lowest in summer, and significant differences in spatial distribution between the eastern and western regions. On a regional scale, scholars have conducted studies based on typical areas such as the Beijing-Tianjin-Hebei region [10], the Pearl River Delta [11], and the Yangtze River Economic Belt [12], as well as provincial scales such as Jiangsu Province [13], Anhui Province [14], and Henan Province [15], with a relatively comprehensive scope of research. In terms of health burden, although many scholars have estimated the impact of $PM_{2.5}$ concentration changes on health burden in recent years, the focus has been mainly on the national level [16-18] and some developed areas such as the Beijing-Tianjin-Hebei region [19], the Yangtze River Delta [20] and the Pearl River Delta [11, 21], as well as some smaller regional levels like Shanghai [22], Gansu Province [23], and Henan Province [24]. Shandong Province, located on the eastern coast of China, downstream of the Yellow River, neighboring the Beijing-Tianjin-Hebei region to the north and the Yangtze River Delta to the south, is China's economic powerhouse and the second most populous province. It is also becoming an important area for air pollution research. Currently, the study of the spatiotemporal characteristics of $PM_{2.5}$ pollution in Shandong Province is relatively comprehensive [25-27], but the research period still needs to be further improved. In terms of attributable health, only Li Xiaoyi has used the Integrated Exposure Response (IER) model to assess the health benefits of $PM_{2.5}$ in Shandong Province in 2016 [28], and there is a lack of related research. In summary, the academic community lacks research on the spatiotemporal evolution and health burden of $PM_{2.5}$ in Shandong. Based on this, to evaluate the health benefits brought by regional clean air actions, this paper, on the basis of previous studies, broadens the research period and changes the research perspective to assess the spatiotemporal evolution and health risks of $PM_{2.5}$ pollution in Shandong Province from 2014 to 2023, in order to provide bitterly a theoretical basis for formulating regional refined air pollution prevention and control policies, and to achieve economic benefits and harmonious regional development.

Materials and Methods

Study Area

Shandong Province is located on the eastern coast of China, which is downstream of the Yellow River. The latitude of Shandong is between 34°23' N and 38°17' N, and the longitude is between 114°48' E to 122°42' E. The territory includes both the peninsula and inland areas; the Shandong Peninsula protrudes into the Bohai Sea and the Yellow Sea, facing the Liaodong Peninsula across the sea; the inland part borders Hebei, Henan, Anhui, and Jiangsu provinces from north to south. Shandong Province has 16 prefecture-level cities under its jurisdiction. According to the regulations for the division of weather forecast areas, it is divided into four regions: the northwest of Shandong (Liaocheng, Dezhou, Binzhou, Dongying), the central part of Shandong (Jinan, Zibo, Weifang, Taian), the south of Shandong (Heze, Jining, Zaozhuang, Linyi, Rizhao), and the Shandong Peninsula (Qingdao, Yantai, Weihai). The topography within the province is complex, generally divided into basic landform types such as plains, platforms, hills, and mountains. Shandong Province has a mild climate, belonging to the warm temperate monsoon climate, and is a key production area for grain and economic crops in the country, with relatively abundant mineral resource reserves [26]. According to statistical data released by the Shandong Provincial Bureau of Statistics, the permanent population of Shandong Province is approximately 101.23 million at the end of 2023. The gross domestic product of Shandong province amounted to approximately 9.21 trillion yuan, with economic strength ranking among the top in the nation, making it one of China's most populous and economically powerful provinces.

Data Sources

The raster data of $PM_{2.5}$ concentration was obtained from the China High Air Pollutants (CHAP) dataset provided by China's National Tibetan Plateau Data Centre (TPDC) for Shandong province from 2014 to 2023, with a spatial resolution of 1 km. Population distribution data were obtained from Oak Ridge National Laboratory’s Land Scan, which is at a roughly 1 km spatial resolution (https://landscan.ornl.gov). Baseline mortality data for each disease were obtained from the China Cause of Death Surveillance Dataset

[29]. This dataset originates from the National Mortality Surveillance System (NMSS), administered by the Chinese Center for Disease Control and Prevention (China CDC). Recognized as one of China's most authoritative official mortality statistical resources, it serves as a critical foundation for public health research and policy-making.

In addition, considering data availability, the population distribution data and the baseline mortality data for diseases have not been made public up to 2023. The population distribution data has been updated to 2022, and the baseline mortality data for each disease has only been updated to 2021. Since the missing data are all unpublished, it is impossible to perform interpolation on them. However, the amount of missing data is small, and the research results still have high evaluation value and practical significance.

Research Methodology

$PM_{2.5}$ Exposure Risk Assessment Model

In order to quantify the spatial and temporal differences in population exposure to $PM_{2.5}$-polluted environments, the actual $PM_{2.5}$ population exposure risk in Shandong Province was explored. Considering the spatial relationship between population density and $PM_{2.5}$ concentration, the $PM_{2.5}$ population-weighted annual mean concentration was adopted as a characterization of population $PM_{2.5}$ exposure as an important indicator reflecting the regional $PM_{2.5}$ population exposure level [30, 31]. It integrates the population distribution and $PM_{2.5}$ concentration, which can better reflect the population exposure concentration. Comparing the difference between the population-weighted annual mean $PM_{2.5}$ concentration and the arithmetic annual mean $PM_{2.5}$ concentration can assess the risk of $PM_{2.5}$ population exposure in Shandong Province. If the population-weighted annual mean concentration of $PM_{2.5}$ is greater than the arithmetic annual mean concentration of $PM_{2.5}$, it indicates that the more densely populated area has higher $PM_{2.5}$ concentration, and the population density and $PM_{2.5}$ concentration in this area show an obvious spatial matching relationship, and conversely, if the population-weighted annual mean concentration of $PM_{2.5}$ is less than the arithmetic annual mean concentration of $PM_{2.5}$, it indicates that the more densely populated area has lower $PM_{2.5}$ concentration, and the population density and $PM_{2.5}$ concentration in the area did not show a significant spatial matching relationship.

The relevant calculation formula:

$$C_{\mathrm{pop}} = \frac{\sum_{i=1}^{n} C_i P_i}{\sum_{i=1}^{n} P_i} \tag{1}$$

$$C_{\mathrm{mean}} = \frac{\sum_{i=1}^{n} C_i}{n} \tag{2}$$

where C_{pop} denotes the population-weighted annual mean concentration of $PM_{2.5}$, C_{mean} stands the arithmetic annual mean concentration of $PM_{2.5}$, i indicates the i-th image element of the raster image, n is the number of image elements of the raster image, and Ci and Pi denote the concentration of $PM_{2.5}$ in the i-th image element and the number of the population, respectively [32, 33].

Health Effect Assessment Model

This study would reveal the association between $PM_{2.5}$ concentration and human health. We applied an epidemiological exposure-response function to calculate the chronic mortality caused by this pollutant. Specifically, attributable deaths from $PM_{2.5}$-related diseases were estimated from the human health effect function given in Equation (3) [34].

$$\Delta Mort = y_n \left(\frac{R-1}{R}\right) Pop \tag{3}$$

where ΔMort is the disease-specific mortality caused by $PM_{2.5}$ exposure, and y_n is the baseline mortality rate for a specific disease, which is a given disease in a limited population under a condition. In this study, y_0 is the all-cause mortality rate, y_1 is the baseline mortality rate of respiratory diseases in China, and y_2 is the baseline mortality rate of cardiovascular diseases in China. Pop is the population for each grid cell, and R is the relative risk for the specific disease, which can be calculated by using the integrated-risk function.

The log-linear exposure-response function (Equation 4) is used to estimate the adverse health effects of ambient air pollution. R is the relative risk of a given disease due to long-term exposure to an air pollutant, which is a relevant health point in epidemiological studies [35].

$$R = \exp\left[\beta\left(C - C_0\right)\right] \tag{4}$$

Where C is the annual average $PM_{2.5}$ concentration, and C_0 is the concentration threshold, if the concentration is below the threshold, it does not generate any risk and is not involved in the subsequent calculations. In this paper, the concentration threshold is calculated using the second-level national ambient air quality standard in China (35 μg/m³). β is the exposure response coefficient, which expresses the additional risk of health effects (mortality or morbidity, etc.) per unit increase of air pollutants, to improve the accuracy of the assessment results, this paper selects the appropriate β from the meta-analysis literature in China to more accurately reflect the real situation in China. reflect the real situation in China [36]. The final selected β was 0.00038

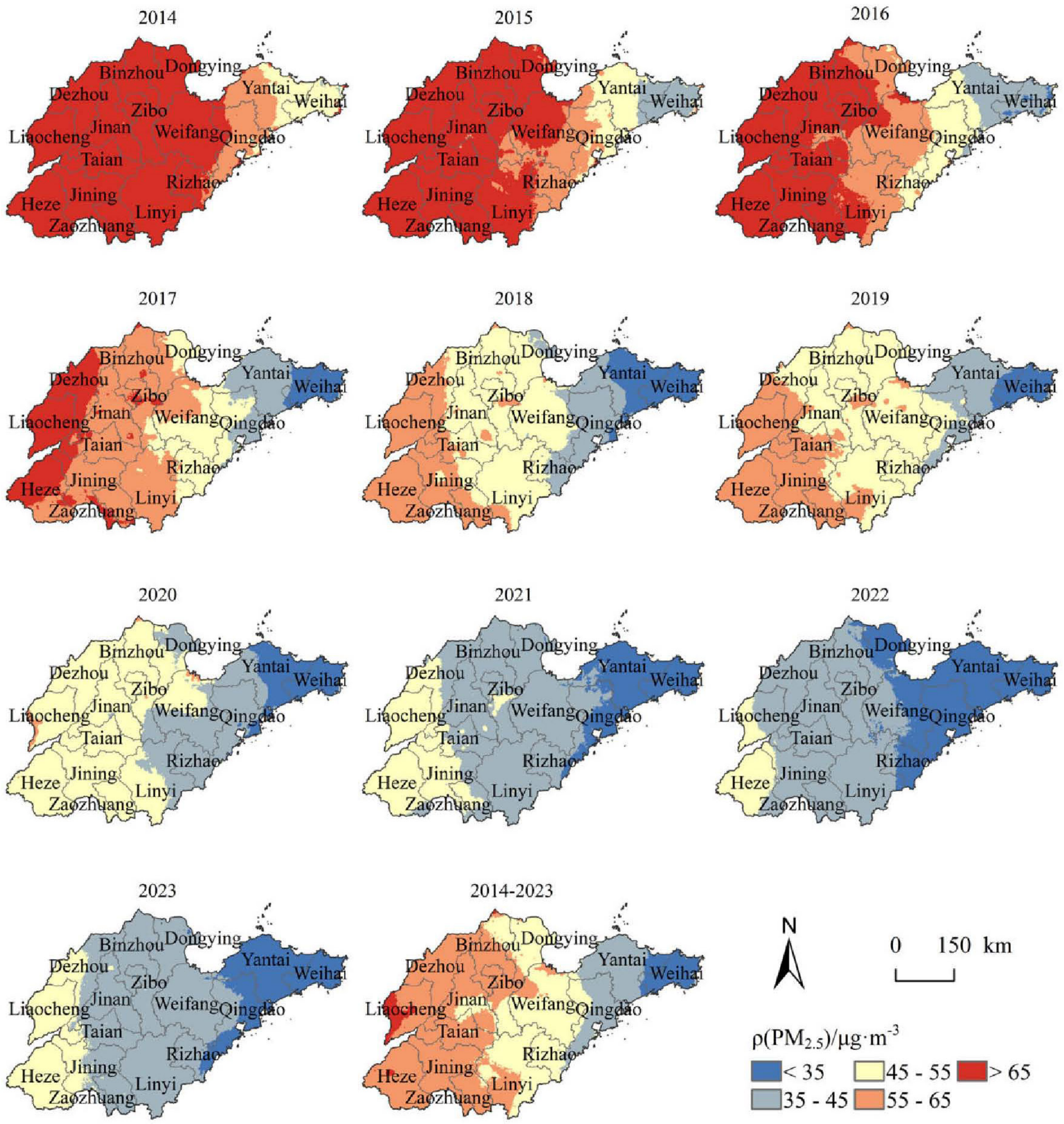

Fig. 1. Spatial and temporal distribution of annual average mass concentration of $PM_{2.5}$ in Shandong from 2014 to 2023.

(0.00031-0.00045) for all-cause mortality, 0.00051 (0.0003-0.00073) for respiratory disease mortality, and 0.00044 (0.00033-0.00054) for cardiovascular disease mortality.

Results and Discussion

Spatial and Temporal Evolution Characteristics of $PM_{2.5}$ Annual Mean Concentration

The spatial and temporal distribution and change status of the annual mean mass concentration of $PM_{2.5}$ in Shandong Province from 2014 to 2023 are shown in Fig. 1.

In time, the annual mean $PM_{2.5}$ concentration in Shandong Province during the study period ranges from 16.80 to 108.70 μg/m^3, of which the worst year in terms of $PM_{2.5}$ in terms of air quality is 2014, and the lowest value of $PM_{2.5}$ mass concentration is still higher than China's secondary ambient air quality standard (35 μg/m^3), and the highest value is the annual mean $PM_{2.5}$ mass concentration in the study period The highest value is the very high value among the highest values of annual average mass concentration of $PM_{2.5}$ in the study period, and the exceeding of the standard is serious. The best year of air quality is 2021, and the very low value among the lowest values of annual average mass concentration of $PM_{2.5}$ in the study period is located this year, and then the lowest value of annual average mass concentration appears to be slightly increased, but the highest value is still on the trend of decreasing. Comprehensive analysis shows that the overall $PM_{2.5}$ mass concentration in Shandong Province during the study period shows a significant decreasing trend, and the effect of pollution prevention and control is remarkable.

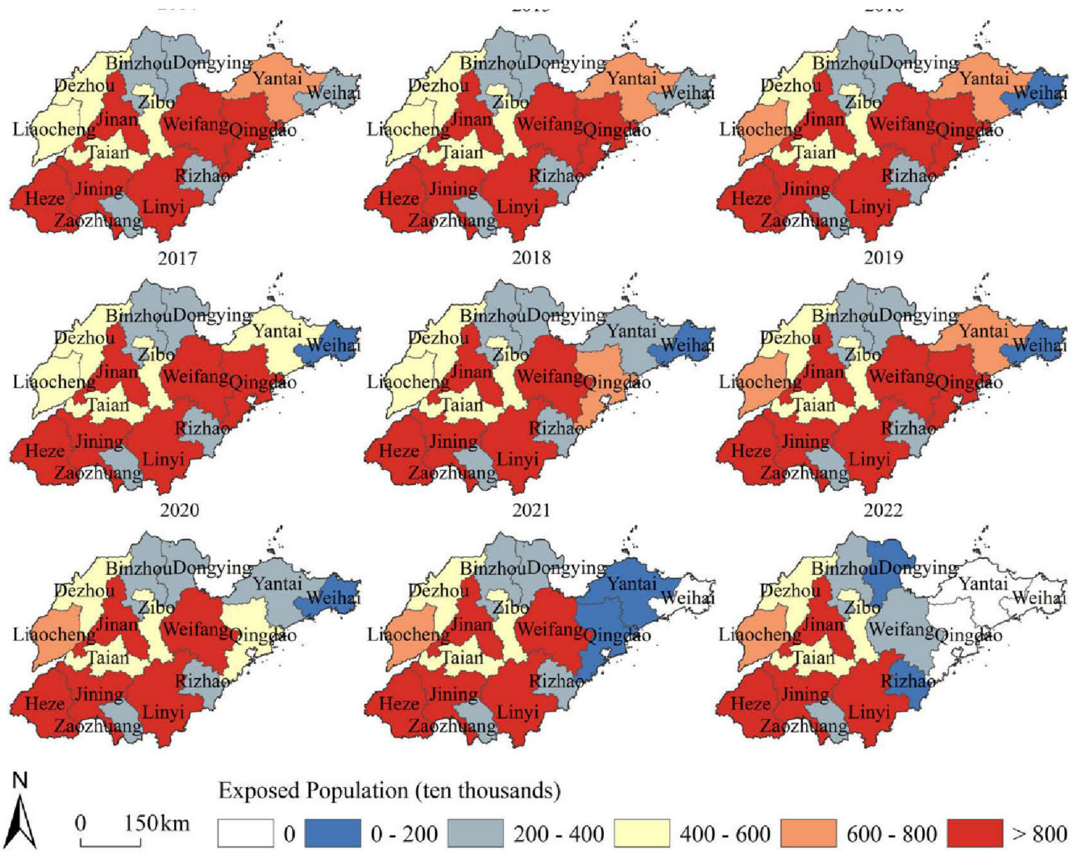

Fig. 2. Distribution of exposed population in Shandong Province from 2014 to 2022.

Spatially, the distribution pattern is high in the south and low in the north, high in the west and low in the east. Analyzing the distribution of average $PM_{2.5}$ concentrations in Shandong Province over the past 10 years, it could be seen that the high concentration areas are mainly concentrated in the west and southwest, specifically in Dezhou, Liaocheng, Heze, Jining and Zaozhuang. Low concentration areas are mainly concentrated in the northeast, in Qingdao, Yantai and Weihai.

It is worth noting that Shandong Province's policy on cleaning the environment has made great progress in the past 10 years, judging from the annual average concentration limit of 35 $\mu g/m^3$ for $PM_{2.5}$ set by China's Ambient Air Quality Standards (GB 3095-2012), but the global Air Quality Guidelines (AQG) set by the World Health Organization (WHO) in 2005, the limit standard for annual average concentration of $PM_{2.5}$ is 10 $\mu g/m^3$, and the AQG will be further tightened to 5 $\mu g/m^3$ in 2021. From a global perspective, the air pollution situation in Shandong Province still faces serious challenges.

Population Exposure Levels

The exposed population in each prefecture-level city can be obtained by overlaying the raster data of annual average concentration of $PM_{2.5}$ mass concentration ≥35 $\mu g/m^3$ with the raster data of population density, and the population exposure in each year is shown in Fig. 2. Temporally, the total annual exposed population declined from 97.6638 million in 2014 to 68.5805 million in 2022, showing a significant downward trend at a rate of 3.0543 million per year, and the regression equation passed the test at a significance level of 0.01. Weihai has achieved a breakthrough with zero exposed population since 2021, and the exposed population in Weihai, Yantai, and Qingdao was zero in 2022. The air control actions have achieved remarkable results in Shandong Province in the past nine years.

Spatially, the prefecture-level cities in central Shandong had the highest average exposed population over the years, at 6.8398 million, followed by the southern regions, at 6.7481 million, and the least, in the Shandong Peninsula, at 3.8863 million, with an extreme range of 2.9535 million. Through linear fitting, the Shandong Peninsula had the fastest reduction rate in average exposed population over the years, at 0.8156 million per year, followed by central Shandong, at 0.0993 million per year, and the slowest in the northwest of Shandong, at about 0.0159 million per year. The Shandong Peninsula passed the significance level test at 0.01, showing a significant downward trend, while the central and northwest regions did not pass the significance level test. In terms of individual cities, Weifang had the highest average exposed population

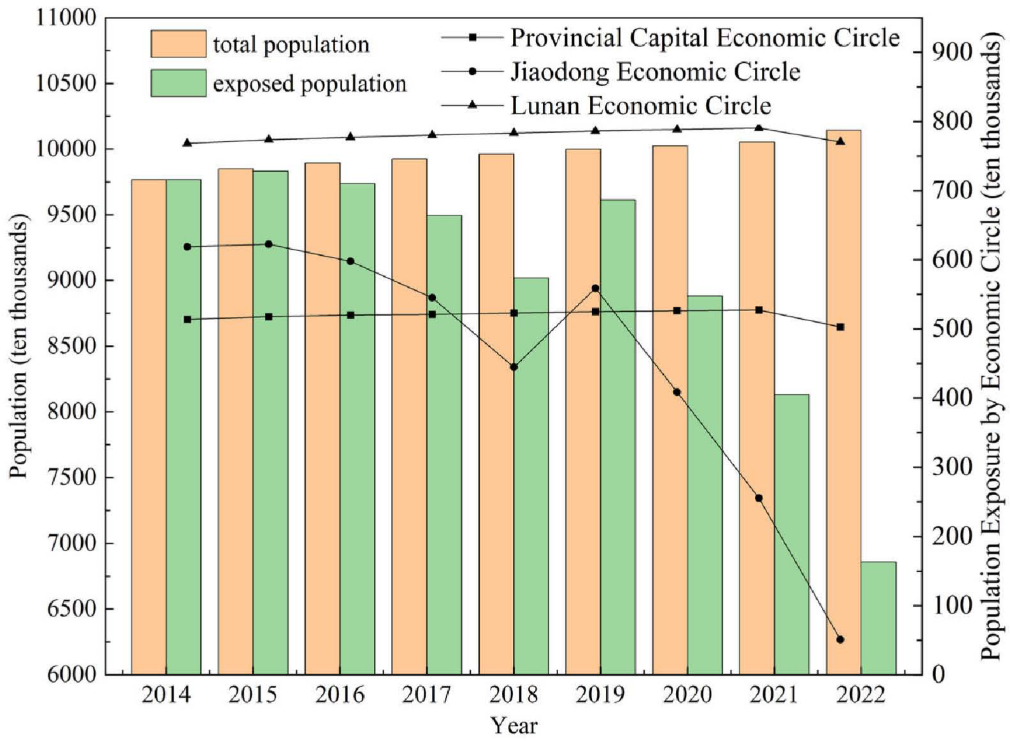

Fig. 3. Composite of total and exposed population in Shandong Province from 2014 to 2022.

over the years, at 8.5910 million, followed by Heze, at 8.6541 million, and the least in Weihai, at 0.8292 million.

In 2021, the Development and Reform Commission of Shandong Province issued the 14th Five-Year Plan for the Integrated Development of the Provincial Capital Economic Circle, which explicitly proposed three major Economic Circles in Shandong Province, including the Provincial Capital Economic Circle, Jiaodong Economic Circle and Lunan Economic Circle. Specifically, the Provincial Capital Economic Circle includes seven cities: Jinan, Zibo, Taian, Liaocheng, Dezhou, Binzhou, and Dongying. The Jiaodong Economic Circle encompasses five cities: Qingdao, Yantai, Weihai, Weifang, and Rizhao. The Southern Shandong Economic Circle consists of four cities: Linyi, Zaozhuang, Jining, and Heze. The three Economic Circles are taken as the basic unit to study the changes in their exposed population (Fig. 3), aiming to provide a scientific basis for promoting sustainable development in the region, protecting public health, and realizing a comprehensive green transformation of economic and social development through the implementation of the 14th Five-Year Plan for Ecological and Environmental Protection in Shandong Province. In addition, considering that changes in the total population will have an impact on the results, a comparative analysis of the total population and the exposed population was conducted based on the existing results.

During the period between 2014 and 2022, the $PM_{2.5}$ mass concentration was greater than 35 μg/m^3 in 2014, and its total population was consistent with the number of exposed population, and the number of exposed population increased in 2015 and 2019 compared with the previous year, but the $PM_{2.5}$ mass concentration in 2015 was lower than that of the previous year, and the reason for this was related to the increase in the total number of people, and the total population of Shandong Province during the nine years. The total population showed a trend of increasing year by year. Among them, the increase in the number of exposed people in 2019 was related to the increase in the total number of people, in addition to the increase in $PM_{2.5}$ mass concentration compared to the previous year.

In terms of the three major Economic Circles, the Lunan Economic Circle had the highest multi-year average number of exposed populations per city at 7.7994 million, followed by the Provincial Capital Economic Circle at 5.1971 million, and the smallest was the Jiaodong Economic Circle, with a multi-year average of 4.5586 million exposed population per city. Among them, the Provincial Capital Economic Circle and Lunan Economic Circle showed an increasing trend in the number of exposed populations in each city on average for many years, with an increase rate of 0.01 million persons per year and 1.47 million per year, respectively, which did not pass the test of significance level, and Jiaodong Economic Circle had a decrease rate of 6.227 million per year, which passed the test of 0.01 significance level. The overall change is relatively unbalanced, and in the future, it is necessary to increase policy management in the Provincial Capital Economic Circle and the Lunan Economic Circle in order to achieve balanced development.

Table 1. Population-weighted and arithmetic mean annual concentrations of $PM_{2.5}$ in prefecture-level cities of Shandong Province from 2014 to 2022.

Area	Population-weighted average $PM_{2.5}$ concentration (μg/m^3)					Arithmetic average $PM_{2.5}$ concentration (μg/m^3)				
	2014	2016	2018	2020	2022	2014	2016	2018	2020	2022
Jinan	86.86	72.80	54.24	48.77	38.88	83.95	69.93	53.31	48.33	39.40
Qingdao	60.78	50.00	38.80	37.20	29.95	62.06	51.03	39.63	38.41	30.92
Zibo	85.75	69.31	53.54	49.91	40.27	80.81	65.77	51.13	47.09	38.63
Zaozhuang	85.47	71.08	57.15	52.16	41.61	83.42	70.17	56.49	51.37	41.08
Dongying	79.96	65.35	49.51	46.47	34.92	77.63	61.32	47.52	45.24	33.80
Yantai	56.50	44.02	33.87	34.25	27.62	56.89	44.40	34.17	34.10	27.90
Weifang	74.91	60.88	48.52	45.81	35.08	74.42	60.33	47.52	45.05	34.86
Jining	87.44	71.08	56.16	51.72	43.29	86.73	70.99	56.57	51.59	43.11
Taian	84.34	70.23	55.13	50.51	41.31	84.45	70.16	54.99	50.16	41.19
Weihai	48.27	35.94	27.28	26.45	23.16	49.40	36.82	28.11	27.10	23.93
Rizhao	68.77	56.04	44.72	40.34	33.48	68.99	55.53	44.66	40.49	33.96
Linyi	80.29	64.07	51.49	45.97	38.23	78.01	63.22	50.79	45.34	37.85
Dezhou	92.77	74.68	55.74	49.60	41.28	92.02	74.10	55.64	49.57	41.29
Liaocheng	96.20	78.05	60.30	53.47	44.56	96.20	77.73	60.35	53.51	44.62
Binzhou	83.98	69.27	52.58	48.01	38.22	83.42	68.11	51.86	47.64	37.36
Heze	91.34	73.27	59.43	52.98	46.64	91.12	73.07	59.50	53.03	46.61
Shandong	78.98	64.13	49.90	45.85	37.41	78.09	63.29	49.51	45.50	37.28

Exposure Risk Assessment

The arithmetic annual average concentration of $PM_{2.5}$ in Shandong Province from 2014 to 2022 was 54.74 μg/m^3, showing a decreasing trend year by year, of which only Weihai's multi-year average $PM_{2.5}$ arithmetic annual average concentration reached the national-level standard of 35 μg/m^3 (Table 1). By 2022, six cities, namely Qingdao, Dongying, Yantai, Weifang, Weihai, and Rizhao, have already reached the national-level standard for arithmetic annual average concentrations.

In order to quantify the spatial and temporal differences in population exposure to $PM_{2.5}$ pollution and to explore the actual $PM_{2.5}$ exposure risk of the population in Shandong Province, this study considers the spatial relationship between population density and $PM_{2.5}$ concentration, compares the difference between the population-weighted annual mean concentration of $PM_{2.5}$ and the arithmetic annual mean concentration of $PM_{2.5}$. The results of the difference between the population-weighted annual mean concentration of $PM_{2.5}$ and the arithmetic annual mean concentration of $PM_{2.5}$ in Shandong Province are shown in Fig. 4. The population-weighted annual mean concentration of $PM_{2.5}$ in Shandong Province is higher than the arithmetic annual mean concentration of $PM_{2.5}$ from 2014 to 2022, which indicates that the population density and the concentration of $PM_{2.5}$ in the provincial area show an obvious spatial matching relationship, with the population density areas with higher population density have higher $PM_{2.5}$ concentrations, while areas with lower population density have higher $PM_{2.5}$ concentrations, and the overall $PM_{2.5}$ population exposure risk is lower.

The situation in each prefecture-level city is as follows: (1) The population-weighted annual average $PM_{2.5}$ concentrations in Qingdao and Weihai are smaller than the arithmetic annual average $PM_{2.5}$ concentrations, indicating that the population density and $PM_{2.5}$ concentrations in the region do not show an obvious spatial matching relationship, and that densely populated areas have lower population densities and lower population exposure risks. (2) There are population-weighted annual mean $PM_{2.5}$ concentrations that are greater than the arithmetic annual mean $PM_{2.5}$ concentration, with a higher risk of population exposure in Zibo, Zaozhuang, Dongying, Weifang, Linyi, and Binzhou. (3) Yantai and Liaocheng both have only one year with a difference greater than 0, and their population exposure risk is small, while Jinan, Jining, Tai'an, and Dezhou all have only one year with a difference less than 0, and their population exposure risk is large. Since 2020, the population-weighted annual average $PM_{2.5}$ concentration in Rizhao City has been smaller than the arithmetic annual average $PM_{2.5}$ concentration, indicating that the $PM_{2.5}$ concentration corresponding to areas with higher population density tends to gradually decrease, and the risk of population exposure to $PM_{2.5}$ gradually decreases (Fig. 4).

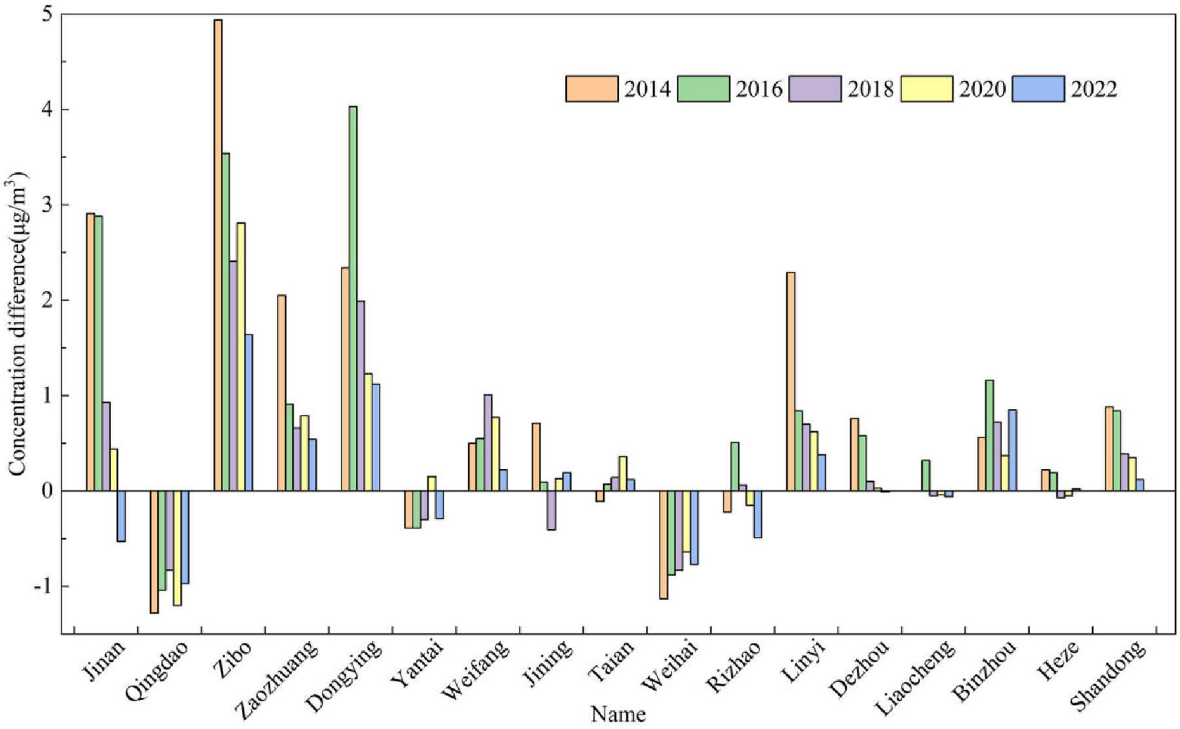

Fig. 4. Difference between population-weighted and arithmetic annual average concentration of $PM_{2.5}$ in Shandong Province from 2014 to 2022.

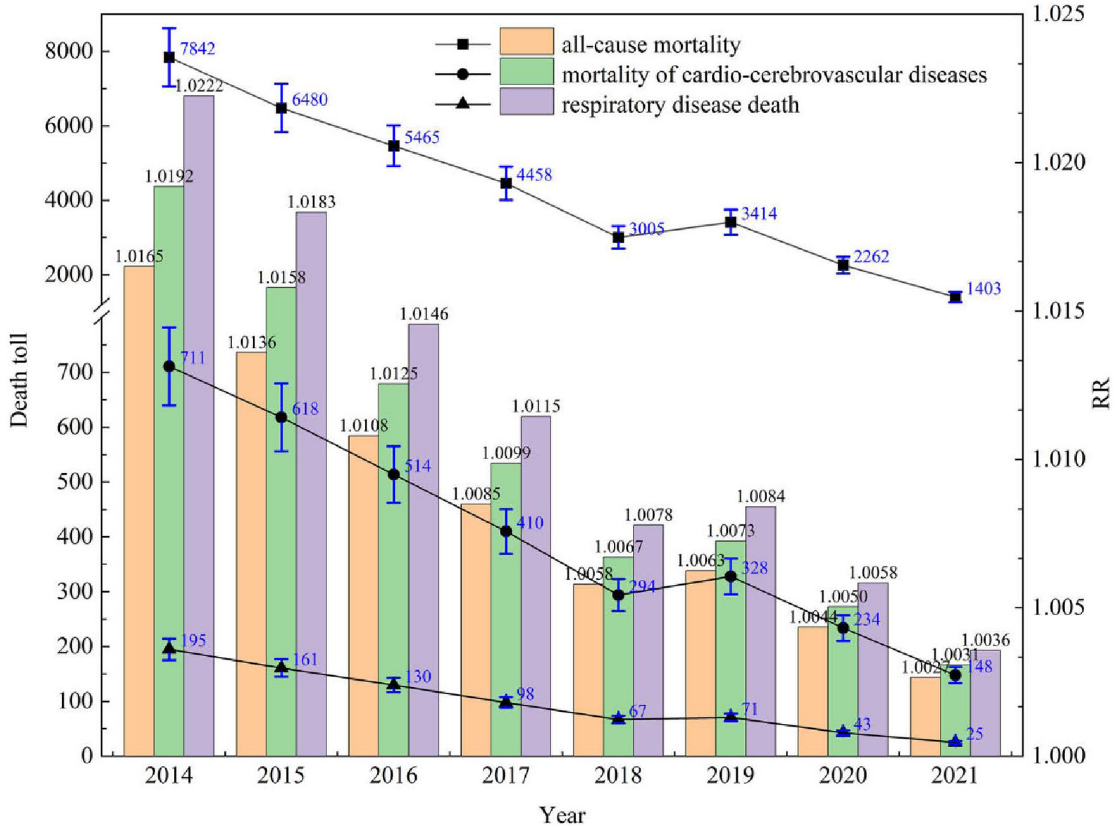

Fig. 5. Health burden of $PM_{2.5}$ in Shandong Province from 2014 to 2021.

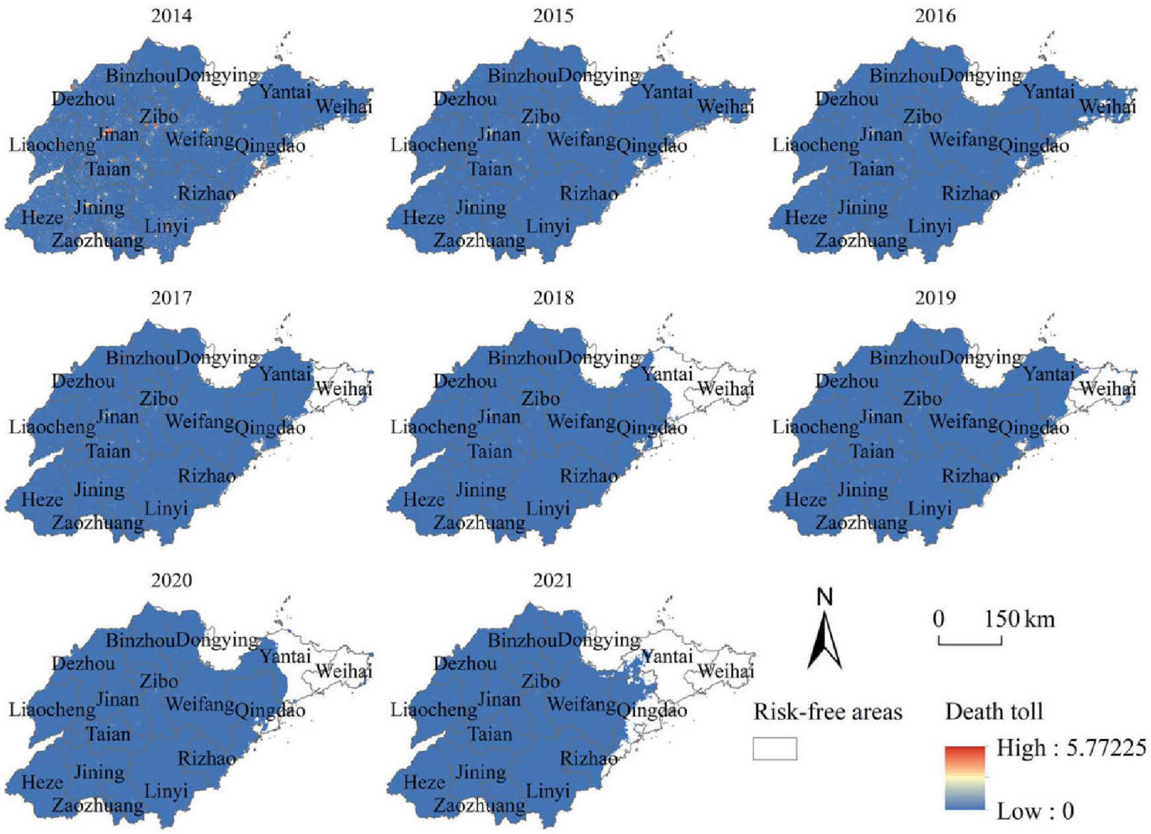

Fig. 6. Spatial distribution of $PM_{2.5}$ health burden in Shandong Province from 2014 to 2021.

Health Burden Assessment

The relative risk of $PM_{2.5}$-related diseases and the number of attributable deaths can be calculated by the log-linear exposure response function and the human health impact function. In this paper, the Chinese ambient air quality level 2 standard (35 μg/m^3) was used as the threshold for calculation, and the results are shown in Fig. 5. The relative risk of respiratory disease deaths from 2014 to 2021 was constantly higher than that of all-cause deaths and cardiovascular and cerebrovascular disease deaths, and the relative risk of all-cause deaths was the smallest. This result indicates that $PM_{2.5}$-exposed people are at greater risk of developing respiratory diseases.

The number of all-cause deaths, respiratory disease deaths, and cardiovascular disease deaths caused by $PM_{2.5}$ concentration exceedance showed a decreasing trend, with the specific changes being 7482 reduced to 1403, 195 reduced to 25, and 711 reduced to 148, respectively, and the largest reduction in the number of deaths is 6,439 for all-cause deaths, and the smallest reduction in the number of deaths from respiratory disease is 170. In contrast to the relative risk calculations, respiratory diseases had the greatest risk but the fewest deaths. This may be due to the fact that all-cause deaths include natural deaths, accidental deaths, unexplained deaths, and many other lethal factors unrelated to $PM_{2.5}$ exposure, such that the baseline mortality rate for all-cause deaths is much higher than that for respiratory diseases, and the relative risk for all-cause deaths is smaller. In terms of the magnitude of the decrease, all-cause deaths decreased by 82.10%, respiratory disease deaths by 86.92%, and cardiovascular disease deaths by 79.19%, with respiratory disease deaths showing the greatest decrease. This shows that lowering $PM_{2.5}$ concentration is more favorable to reduce the mortality rate of respiratory diseases compared to other diseases. This result is consistent with the results of previous studies [37].

The number of disease-attributable deaths in areas with $PM_{2.5}$ exposure risk was counted, and the results are shown in Fig. 6. Comparing the total number of all-cause deaths, deaths from respiratory diseases and deaths from cardiovascular diseases from $PM_{2.5}$ exposure in various cities in Shandong Province from 2014 to 2021, it was found that Heze had the highest total number of deaths, about 4,434, followed by Jinan, with about 4,025 deaths, and Weihai had the lowest total number of deaths, about 126. The overall distribution shows a spatial distribution pattern of more in the south and less in the north, and more in the west and less in the east, which is specifically reflected in the distribution status of more in southeastern Shandong, followed by the central region, and the least in the Shandong Peninsula. The total number of deaths from diseases during the 8-year period showed a decreasing trend in general, with a small increase in the number of deaths in 2019 in all other cities except Dezhou and Liaocheng. All the bureaus in Weihai have become a risk-free area by 2021, indicating the best ecological environment.

In terms of the three major Economic Circles, the average total number of deaths in each city is, in descending order, the Lunan Economic Circle, the Provincial Capital Economic Circle and the Jiaodong Economic Circle, specifically 3,574, 2,521 and 1,287, respectively, while the average number of deaths in each year in each Economic Circle is 1,787, 2,205 and 1,430, respectively, with the Provincial Capital Economic Circle having the highest number of people, followed by the Lunan Economic Circle, and the Jiaodong Economic Circle having the least.

Conclusions

This study explored the spatial and temporal evolution characteristics, population exposure levels, exposure risks, and health burdens of $PM_{2.5}$ in Shandong Province using $PM_{2.5}$ concentration data, population distribution data, and baseline disease mortality data from 2014 to 2023. The aim is to clarify the current situation of the population's exposure-related death risk attributed to $PM_{2.5}$ in Shandong Province, and to provide a theoretical basis for better formulating refined regional air pollution prevention and control policies. The main conclusions are as follows:

(1) The spatial and temporal evolution of $PM_{2.5}$ is characterized by an annual average concentration ranged from 16.80 to 108.70 μg/m^3 temporally with a significant downward trend; and a spatial distribution pattern of high in the south, low in the north, high in the west, low in the east, with the high concentration areas mainly concentrated in the west and southwest, and the low concentration areas mainly concentrated in the northeast. The high concentration areas are mainly concentrated in the west and southwest, and the low concentration areas are mainly concentrated in the northeast.

(2) With regard to the exposure level of the population, the total exposed population showed a significant decreasing trend with a frequency of 3.0543 million per year, and the average number of exposed population was the highest in the cities of central Shandong, followed by the southern region, and the least in the Shandong Peninsula. The Shandong Peninsula has the fastest rate of decrease, followed by central Shandong, and the slowest rate of decrease is in northwestern Shandong. In terms of the three Economic Circles, the Lunan Economic Circle has the highest multi-year average number of exposed population per city, and the Jiaodong Economic Circle has the lowest, with a multi-year average of 4.5586 million exposed population per city. Among them, the multi-year average number of exposed population per city in the Provincial Capital Economic Circle and the Lunan Economic Circle shows an increasing trend, and the overall change is relatively unbalanced, so it is necessary to increase the policy management in the Provincial Capital Economic Circle and the Lunan Economic Circle in the future to achieve balanced development.

(3) Regarding exposure risk assessment, the arithmetic annual average concentration of $PM_{2.5}$ is 54.74 μg/m^3 in Shandong Province from 2014 to 2022, showing a decreasing trend year by year. The population-weighted annual average concentration of $PM_{2.5}$ is higher than the arithmetic annual average concentration of $PM_{2.5}$, and there is an obvious spatial matching relationship between the population density and the concentration of $PM_{2.5}$ in the provincial area. The population density and the concentration of $PM_{2.5}$ have an obvious spatial matching relationship. The risk of $PM_{2.5}$ population exposure is high.

(4) With regard to health burden assessment, the relative risk of respiratory disease deaths is constantly higher than that of all-cause deaths from 2014 to 2021 and cardiovascular disease deaths, and the relative risk of all-cause deaths is the smallest. The number of all-cause deaths caused by exceeding $PM_{2.5}$ concentrations is the largest, and the decline is the smallest; the number of deaths from respiratory diseases is the smallest, and the decline is the largest. Reducing $PM_{2.5}$ concentration is more conducive to reducing the mortality rate of respiratory diseases, and the impact is more significant. The overall distribution of the total number of deaths caused by $PM_{2.5}$ exposure shows a spatial distribution pattern of more in the south than in the north and more in the west than in the east, which is reflected in the fact that it is more in the south-eastern part of the mountain, followed by the central part of the region, and least in the Shandong Peninsula. The average total number of deaths in each city, in descending order, is the Lunan Economic Circle, the Provincial Capital Economic Circle and the Jiaodong Economic Circle, and the average number of deaths in each year, in descending order, is the Provincial Capital Economic Circle, the Lunan Economic Circle and the Jiaodong Economic Circle.

Discussion

The study mainly analyzed the spatial and temporal distribution characteristics of $PM_{2.5}$ in Shandong Province, the exposed population, the risk, and the number of attributed deaths. Compared with previous studies, the study area of this paper is more typical, filling the research gap in this segment of Shandong Province, and the spatial and temporal change characteristics of $PM_{2.5}$ are consistent with the results of previous studies [38]. However, the article still has certain deficiencies that need further improvement: (1) The data in the article is limited, and its results cannot accurately reflect the current health burden caused by air pollution in Shandong Province. (2) There are differences in air pollution conditions across different regions. Therefore, the β values required for calculations using the health-effect assessment model also vary. Selecting the β value from a national (Chinese) perspective for calculations in this article inevitably leads to errors. (3) In future research, it is expected that the exposed population can be further refined into urban and rural populations, providing a theoretical basis for formulating differentiated urban development policies. (4) Future research also needs to include more diseases in the end-points of the health burden assessment to make the findings more instructive.

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Conflicts of Interest

The authors declare no conflict of interest.

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