BILINGUAL PUBLISHING GROUP

**Journal of Geographical Research**

https://journals.bilpubgroup.com/index.php/jgr

ARTICLE

# Spatial Agglomeration and Diffusion of Population Based on a Regional Density Function Approach: A Case Study of Shandong Province in China

***Xiaohan Zhao*, *Yanbin Chen****

*College of Geography and Environment, Shandong Normal University, Jinan, Shandong, 250358, China*

## ABSTRACT

Population density functions have long been used to describe the spatial structure of regional population distributions. Several studies have been conducted to examine the population distribution in Shandong Province, China, but few have applied regional density functions to the analysis. Therefore, based on the 2000, 2010, and 2020 population censuses, this study used monocentric and polycentric regional density functions to study the characteristics of population agglomeration and diffusion in Shandong. This is followed by an in-depth discussion based on population growth rate data and hot- and cold-spot analyses. The results showed that the Shandong Province population was spatially unevenly distributed. Population growth rates were higher in urban centers and counties, with more significant changes in population size in the eastern coastal areas than in the inland areas. As verified in this study, the logarithmic form of the single-center regional density function $R^2$ was greater than 0.8, which was in line with the population spatial structure of Shandong Province. During the study period, the estimated population density of the regional center and the absolute value of the regional population density gradient both increased, indicating a clear and increasing trend of centripetal agglomeration of regional centers over the study period. Overall, the $R^2$ value of the multicenter region density function was higher than that of the single-center region density function. The polycentric regional density function showed that the population density gradient of some centers had a downward trend, which reflected the spatial development trend of outward diffusion in these centers. Meanwhile, the variation in the estimated population density and the population density gradient exhibited differences in the central population distribution patterns at different levels.

***Keywords:*** Regional density functions; Population spatial structure; Shandong Province

*CORRESPONDING AUTHOR:
Yanbin Chen, College of Geography and Environment, Shandong Normal University, Jinan, Shandong, 250358, China; Email: ychen@sdnu.edu.cn

ARTICLE INFO
Received: 5 July 2023 | Revised: 10 August 2023 | Accepted: 14 August 2023 | Published Online: 18 August 2023
DOI: https://doi.org/10.30564/jgr.v6i3.5826

CITATION
Zhao, X.H., Chen, Y.B., 2023. Spatial Agglomeration and Diffusion of Population Based on a Regional Density Function Approach: A Case Study of Shandong Province in China. Journal of Geographical Research. 6(3): 61-80. DOI: https://doi.org/10.30564/jgr.v6i3.5826

# 1. Introduction

Population is the most dynamic and active element in the process of urban development, and its spatial distribution in cities has always been an important part of urban geography research [1-3]. The spatial structure of a population refers to the tendency of the population to agglomerate or diffuse within a given region, which can, to a certain extent, reveal the strength or weakness of the region's socioeconomic activities [4]. With the increasingly significant spatial reconfiguration of the inner city, studying population distribution within the city has become increasingly vital [5]. Population spatial structures have far-reaching implications for regional transport planning [6], risk assessment and policy decisions [5], public safety, and crisis management [7]. Therefore, this study helps understand the characteristics of the regional spatial structure and its evolutionary trends, thus providing a reference for regional spatial organization and restructuring.

Researchers have a long history of studying regional spatial structures from the perspective of population spatial distributions. In 1951, Clark pioneered the Distance Decay Model, which suggests that population density tends to decrease with increasing distance from urban centers [8]. Since then, population density functions have been used as effective tools to characterize urban spatial structures. On this basis, scholars such as Tanner, Sherratt, McDonald, Suits, Mason and others have proposed various models of population density in monocentric cities [9], which have resulted in significant achievements in the study of urban population spatial structures. However, these studies only depicted population distribution at the city level. Parr highlighted in the mid-1980s that the decaying characteristics of population density with distance in suburban and rural areas outside cities did not conform to a negative exponential model but were closer to a Pareto function. He also proposed a unified functional form to describe the characteristics of population density across regions [10]. Later, Barkley [11], Wang [4], and others applied different forms of monocentric regional population density models to explore the fitting of the regional population density distribution and analyze the regional spatial structure and its evolutionary characteristics. However, compared to urban population density models, the research results are still relatively limited. With the innovation of information technology, restructuring of economic space, and development of transport infrastructure, the trend toward urban polycentricity is becoming increasingly evident. The existence of multiple centers with specialized economic, social, and cultural functions, as well as the interaction between the centers, makes monocentric models no longer suitable for describing contemporary urban structures [12]. Therefore, scholars have questioned the application of monocentric models [13] and have begun to apply polycentric regional density functions to explain the spatial structural characteristics and evolutionary trends of regional population density. Heikkila et al. [14] proposed three models of population density distribution in polycentric urban areas, followed by Small and Song [15], Bontjie [1], McMillen, McDonald [16] and Joseph [17] who applied polycentric regional density functions to Los Angeles, Western Europe, Chicago, and Port-au-Prince.

Research into population density models in China began in the late 1990s. This research focused on fitting regional optimal population density models based on census data and summarizing the characteristics of regional spatial structure evolution. Zhou Chunshan and Xu Xueqiang were the first to apply a monocentric city population density model to illustrate the urban population density development process in Guangzhou [18]. Later, Wang and Zhou [19] and Luo and Wei [20] simulated the population density distribution in Beijing and Nanjing, respectively, under monocentric conditions. Along with rapid urbanization and industrialization in China, the spatial variation in population density has taken on new characteristics, and the regional spatial structure has gradually changed to a complex polycentric structure. Consequently, scholars have begun to explore the spatial structure of polycentric cities and population spatial distribution. Wang and Meng [21] used Shenyang as the study object and were the first to investigate the polycentric population density distribution structure in Chinese cities. Feng Jian and Zhou Zhouxing conducted a systematic study on the multi-core population density model in Beijing [22]. Wu Wenyu and Ma Xiya used Shanghai as the study object to analyze the characteristics of the polycentric structure of population distribution from 1990 to 2000 [23]. Jiang Li and Wu Shoulong measured the change in population spatial distribution in Guangzhou [24], and the results demonstrated a good fit for the polycentric model. Subsequently, the analysis of polycentric structures gradually expanded to regional areas, including the Beijing-Tianjin-Hebei metropolitan area [25], Yangtze River Delta urban agglomeration [26] and Huanghuaihai Plain [27]. In terms of research regions, most studies focused on more economically developed large cities or hotspot regions. There has been less exploration of regions than cities in terms of the volume of literature. In contrast to Western scholars' systematic analysis of population density models and improved testing of model applications, the analysis of population density models in the Chinese geographical circle primarily uses the existing population density model to conduct empirical research on a specific region, with few theoretical innovations. Moreover, Chinese scholars mostly base their calculations on the Euclidean distance. The Euclidean distance characterizes the straight-line distance, which differs from the actual distance in reality and does not accurately reflect a real situation. When applying the regional density function, the shortest vehicular route between two places, provided by Amap (https://www.amap.com/), was adopted to describe the distance, which is more relevant to a real situation than the Euclidean distance.

In terms of population and economic output, Shandong is one of the largest provinces in China and is characterized by an uneven level of development within the region. In previous studies, scholars have discussed the population distribution in Shandong Province, starting from the structure index [28,29], population gravity center [28,29], shift-share analysis [28] and spatial autocorrelation analysis [29,30]; however, few studies have used regional density functions for analysis. Population density patterns are important features of regional economies and societies [31]. The optimization of the spatial distribution of the population can have a significant impact on the structure and layout of various factors, such as the economy, culture, and industry, helping to promote regional economic development and improve people's quality of life. Viewing the growing importance of the population spatial structure and rapid urbanization and continuous economic restructuring in Shandong Province in recent years, it is particularly essential to utilize the regional density function to study its population distribution and spatial structure, evolution pattern and regional spatial structure's variation trend.

In summary, this study analyzed the population density characteristics of Shandong Province from 2000 to 2020 based on county data. It used the Inverse Distance Weighted method to clarify the spatial relationship of population distribution. Subsequently, the spatial structure of Shandong Province and its evolutionary characteristics were shown by applying monocentric and polycentric regional density functions, respectively. The spatial agglomeration and diffusion of the population in Shandong Province were discussed in depth based on the population growth rate and hot and cold spot analysis. Analyzing the spatial structure of Shandong Province from the standpoint of the regional density function provides a new perspective on the study of spatial structure, which can be compared with the results obtained from other methods. Simultaneously, the evolutionary characteristics and development trend of Shandong Province's population spatial structure can be examined, as well as the problems that hamper its long-term development process and the law of urban agglomeration development can be better understood. This can provide a basis for urban planners to rationally guide regional population distribution, optimize resource allocation, make scientific spatial planning decisions, and serve as a reference for other urban agglomerations in China.

## 2. Materials and methods

### 2.1 Study area

Shandong Province is located in the economically developed eastern coastal region of China, downstream of the Yellow River, the second-longest river in China, and between the two state-level urban agglomerations: the Beijing-Tianjin-Hebei region, and the Yangtze River Delta urban agglomerations. To the east, it is separated from the Korean Peninsula and Japan by the sea. Its eastern part is dominated by hills, while the central part has many mountains, and the southwest and northwest are mostly plains (**Figure 1**), with a total land area of 156,700 km$^2$. According to data from the 7th National Census, the number of people living in Shandong Province exceeded 100 million, ranking second in China in terms of total population. Simultaneously, the gross national product of Shandong Province is expected to reach 728 million yuan in 2020, ranking third in China. Shandong Province is veritable in terms of its population and economy. As an uncommon province in China where a province is developed as an urban agglomeration, the Shandong Peninsula Urban Agglomeration is one of the important urban agglomerations proposed in the National 14th Five-Year Plan for development and growth and is also the core of the national strategy to promote new urbanization and economic development [32]. To respond positively to the national planning objectives, Shandong Province specified in the "Outline of the 14th Five-Year Plan for National Economic and Social Development of Shandong Province and Vision 2035" that the institutional mechanism for the coordinated development of the whole region should be promoted in an integrated manner. Optimizing and improving the regional spatial structure is the key to achieving coordinated regional development [33], which must be based on an in-depth understanding of the spatial structure of population density and its evolutionary characteristics in Shandong Province.

### 2.2 Methods

The regional density function is an important means to study the spatial structure of the regional population and its evolution trend. Since its introduction, many scholars have extended its application and supplemented its amendments, achieving rich research results. Given that the acquisition of population data is relatively convenient and reliable and the mathematical form of the regional density function is quite simple, this study also chose this method to model the population agglomeration and diffusion characteristics of Shandong Province.

(i) Monocentric regional density function

The regional density function is used to describe how population density varies with distance from the central city, and is an effective tool for studying the characteristics of population agglomeration and diffusion [13]. Following Alperovich, the following four forms of monocentric area density functions (**Table 1**) were validated by some scholars [4]:

The monocentric regional density function as-

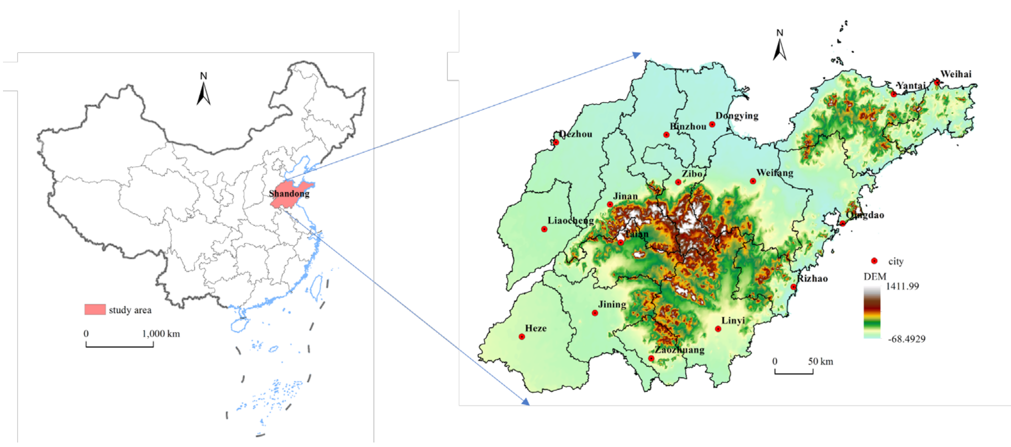


**Figure 1.** Location and topography of Shandong Province.

**Table 1.** Monocentric regional density functions and the parameters.

| Models | Function used in regression | Original function | X variable | Y variable | Restrictions | Meanings of parameters |
|---|---|---|---|---|---|---|
| Linear | $D_r = a + br$ | Same | r | $D_r$ | None | $r$ is the distance between the area and the regional center, $D_r$ is the population density at distance $r$ from the regional center, and $a$ and $b$ are parameters to be estimated. |
| Logarithmic | $D_r = a + b\ln r$ | Same | $\ln r$ | ${}_D$r | $r \neq 0$ | |
| Power | $\ln D_r = a + b\ln r$ | $D_r = ar^b$ | $\ln r$ | $\ln D_r$ | $r \neq 0$ and $D_r \neq 0$ | |
| Exponential | $\ln(D_r) = a + br$ | $D_r = ae^{br}$ | r | $\ln D_r$ | $D_r \neq 0$ | |

sumes that there is only one central city in the region. Therefore, when discussing the form of the monocentric regional density function, it is first necessary to divide Shandong Province into a number of monocentric metropolitan areas. In this study, we referred to Wang Fahui's approach for delineating urban influence ranges [4] and used the urban areas of the central cities in the region as the core to delineate their zones of influence. The delineation of the zone of influence was based on the gravity model:

$$I_i = C_i \ / \ r_{ij}^{\beta} \tag{1}$$

where $C_i$ is the population size of city $i$; $r_{ij}$ is the distance between regional unit $j$ and city $i$; $I_{ij}$ indicates the degree to which regional unit $j$ is influenced or radiated by city $i$; and $\beta$ is the distance friction coefficient, where the empirical value of $\beta = 2.1$ is taken from the gravity model used by Yang Qi in his study of inter-regional passenger flows in China [34]. A central city is an attributed city of regional unit $j$ if its radiation or influence on regional unit $j$ is the greatest among all central cities.

(ii) Polycentric regional density function

The monocentric regional density function only considers the influence of a single central city when analyzing the regional population distribution [25]. It is believed that the population density at the same distance from the center is the same, regardless of the direction [17], which has some limitations when analyzing the trend of population density changes in polycentric regions. Therefore, it is essential to consider the impact of multiple centers in the region on the population distribution to more accurately interpret the characteristics of regional population agglomeration and dispersion. The polycentric regional density function was used to reveal the distribution and trend of regional population density under the combined effect and influence of multiple centers. Heikkila et al. argued that if multiple centers are in competition and division of labor with each other, and there is both substitutability and complementarity, then the polycentric density function may formally take the form of a merger of multiple monocentric density functions. Based on this, they proposed three models for the distribution of population density in polycentric urban areas [14]. Assumptions regarding the impact of multiple centers on population distribution range from full substitution to full complementation. Given the fact that most scholars deem the impact of each center in the region to be between complete substitution and complementation [38] and the actual situation in Shandong Province, this study selected the exponential model to test Shandong Province. Its functional form is:

$$D_r = \sum_{i=1}^{n} a_i e^{b_i r_i} \tag{2}$$

where $D_r$ is the population density at distance $r$ from the regional center, $n$ represents the number of regional centers, $r_i$ is the distance from the region to each center, and $a_i$ and $b_i$ are parameters specific to regional center $i$.

(iii) Inverse Distance Weighted (IDW) Interpolation

To clearly reflect the spatial relationship of the population distribution in Shandong Province, this study applied the IDW method to analyze the regional population density distribution. The IDW is one of the most commonly used methods for interpolating spatial information. It is based on the "first law of geography", which assumes that the parameter values of observations closer to the prediction point are more similar than those further away from the prediction point [36]. Therefore, the IDW method assigns more weight to observations that are closer to the predicted points [37]. The equation for this method is as follows:

$$Z = \sum_{i=1}^{n} \frac{Z_i}{d_i^p} / \sum_{i}^{n} d_i^p \tag{3}$$

where $Z$ is the estimated value, $Z_i$ is the $i$ ($i = 1,...,n$) sample value, $d_i$ represents the distance, and $p$ is the power of the distance, which was chosen based on the minimum mean absolute error criterion. The default setting is $p = 2$, at which point the corresponding method is called inverse distance squared interpolation [38].

(iv) Cold and hotspot analysis

Cold and hotspot analysis is one of the methods used for global aggregation testing. It identifies high- and low-value clusters of regional elements at different spatial locations by calculating the Getis-Ord $G_i^*$ statistics for each element in the dataset. That is, it identifies the spatial distribution pattern of cold and hot spots in the study area [39]. The equation [40] is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} W_{ij} x_j}{\sum_{j=1, j \neq i}^{n} x_j} \tag{4}$$

where $G_i^*$ is the Getis-Ord $G_i^*$ statistic. $x_j$ is the elemental attribute value at location $j$; $n$ is the total number of districts and counties; and $W$ is the spatial weighting matrix. When the $G_i^*$ value is positive and significant, it indicates that the values around the detected points are relatively high and belong to the high-value spatial agglomeration (hot spot area); a negative and significant $G_i^*$ value indicates that the values around the detected points are relatively low and belong to the low-value spatial agglomeration (cold spot area); a $G_i^*$ value of zero indicates that the result was randomly generated and not statistically significant. A significance test was performed on the obtained $G_i^*$ values to identify cold and hot spots at the confidence intervals.

### 2.3 Data sources

In this study, resident population data for 2000, 2010, and 2020 were selected as the population data. Compared to the household population indicator, the resident population indicator more accurately reflects the total number of people residing in a region over a certain time period and can more accurately indicate the true size of a region's population [41]. Resident population figures for 2000, 2010, and 2020 were obtained from the fifth, sixth, and seventh national census bulletins, respectively, published by each municipality.

For the administrative division data, the land area data of the county administrative area were used to calculate the regional population density, and the data were derived from the Baidu Encyclopedia of the corresponding county. The administrative divisions of Shandong Province underwent adjustments and changes during the study period. To ensure continuity and comparability of the data, this study used the 2020 administrative divisions as the standard and matched the statistics for 2000 and 2010. This included correction and matching of the names used in 2020 for county-level administrative units that had been renamed and adjusted, adjustment of the zoning of newly established districts and counties according to the streets and towns under their jurisdiction in 2020, and merging or splitting of county-level units with boundary adjustments and changes according to boundary changes. In addition, non-administrative areas, such as high-tech zones and economic and technological development zones in each municipality were consolidated according to the area in which they were located.

Data used to measure the distance between the two regions were obtained from Amap (https://www.amap.com/). This study selected the shortest vehicle route between the county or municipal government of the two administrative regions to represent the distance between each region.

# 3. Results and discussions

## 3.1 Population distribution characteristics of Shandong Province

### *Statistical characteristics of the population distribution*

An analysis of regional population density can reveal the basic characteristics of regional population distribution and reflect regional differences in population distribution [27]. According to the population density distribution map of Shandong Province from 2000 to 2020 (**Figure 2**), the population of Shandong Province was spatially unevenly distributed, with obvious differences between districts and counties. Areas with high population densities were more dispersed, with multiple densely populated circles in local areas. In contrast, areas with low population densities were characterized by faceted contiguity. Specifically, the population density was lower in the northern part of Shandong Province and higher in the eastern coastal, central, and southern regions. Peak population density areas were concentrated in the urban areas of the cities, with the northern and southern districts of Qingdao having extremely high population densities, forming two polarized centers with population densities of over 10,000 persons per square kilometer in all years. The other regions with higher population densities (Lixia District in Jinan, Zhangdian District in Zibo, Licang District in Qingdao and Zhifu District in Yantai) were almost all between 5,000 and 10,000 persons per square kilometer, a far cry from the two districts in Qingdao. There were sharp differences in population density between urban areas and districts and counties outside urban areas, presenting a clear decay from urban areas to the periphery of the city. Most population densities in the districts and counties outside the city are less than 1,000 persons per square kilometer. In addition, the population density varied significantly between districts and counties in Shandong Province (**Table 2**). For example, in 2000, the minimum population density was only 97 persons/square kilometer, whereas the maximum reached 14,918 persons/square kilometer, a difference of nearly 150 times. Specifically, in terms of spatial changes in population distribution, with the exception of Heze City and the peripheral districts and counties of Qingdao City, where there was a widespread increase in population density, there was little change in the distribution of all classes of population density over the study pe-

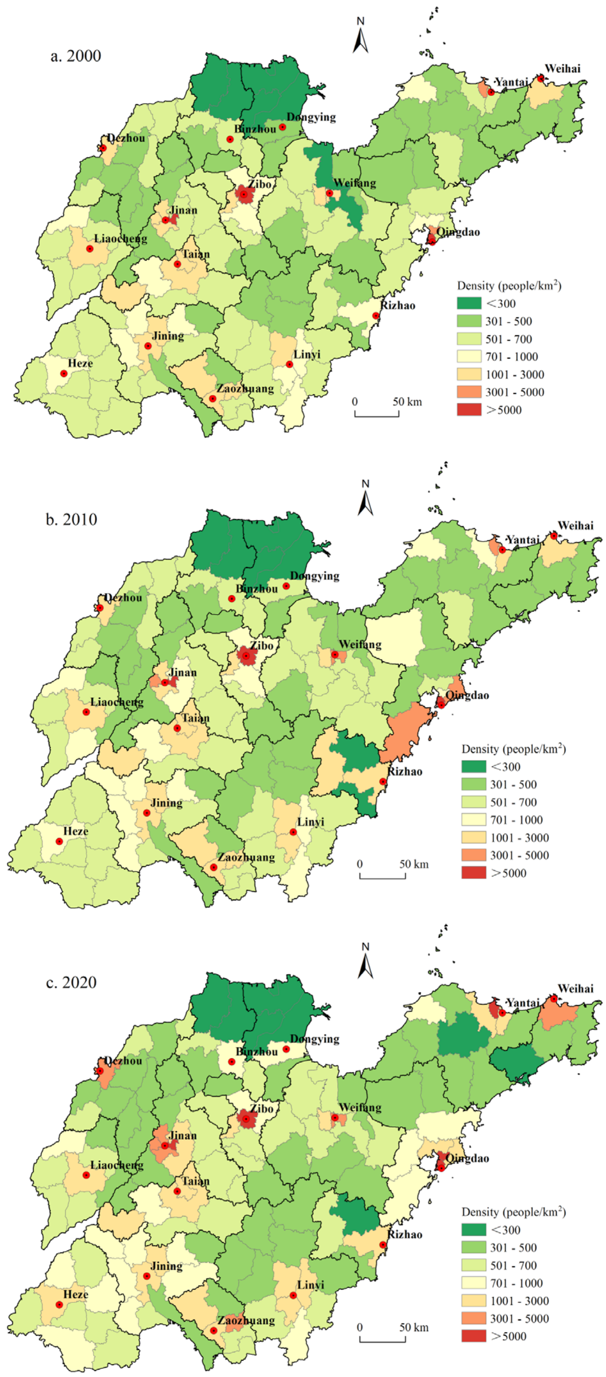


**Figure 2.** Population density distribution map of Shandong Province.

**Table 2.** The descriptive statistics of population density in Shandong Province.

| **Year** | **Population density (person/km$^2$)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | Maximum | | Minimum | | Average | | Standard deviation |
| 2000 | 14918 | | 97 | | 1010 | | 1889 |
| 2010 | 18162 | | 109 | | 1168 | | 2246 |
| 2020 | 17411 | | 108 | | 1280 | | 2337 |
| **Year** | **Number of counties by population density(person/km$^2$)** | | | | | | |
| | **< 300** | **300-500** | **500-700** | **700-1000** | **1000-3000** | **3000-5000** | **> 5000** |
| 2000 | 7 | 38 | 52 | 15 | 18 | 2 | 4 |
| 2010 | 7 | 36 | 45 | 19 | 20 | 5 | 4 |
| 2020 | 8 | 41 | 34 | 20 | 21 | 6 | 6 |

riod, and the pattern of population distribution was relatively stable.

From the perspective of temporal changes in population density, both the mean and standard deviation of population density in Shandong Province showed an increasing trend (**Table 2**). This indicates that the population density of Shandong Province has grown over the past 20 years, and regional differences have increased. This is demonstrated by the minimum population density in Shandong Province (Hekou District, Dongying City) increasing from 97 persons/km$^2$ in 2000 to 108 persons/km$^2$ in 2020; the average population density increasing from 1010 to 1280 persons per square kilometer over a period of 20 years; and the number of areas with a population density greater than 1,000 persons per square kilometer rising from 24 in 2000 to 33 (**Table 2**), with new areas including Licheng District in Jinan, Laoshan District in Qingdao, Laishan District in Yantai, Donggang District in Rizhao, Luozhuang District, and Hedong District in Linyi. There was a marked change in the districts and counties with population density values between 500 and 700 persons/km$^2$, with several of them having increased to 700-1000 persons/km$^2$ in 2020.

In summary, the densely populated areas of Shandong Province are concentrated in economically developed areas with superior natural geography. Economically developed areas with accelerating levels of urbanization are attracting growing population concentrations from outlying districts and counties, making the local population density significantly higher than that of other districts and counties. The influence of the natural geographical environment on population distribution can be observed in the topography of the terrain. The flatter terrain favors the growth of local crops, which in turn leads to higher population densities [42]. In the south-central region of Shandong Province, mountainous and hilly terrain is widespread, transportation is inconvenient, and economic development is relatively slow, making the population more dispersed [43]. The Yellow River Delta region of Dongying and Binzhou, although located on the plain, is plagued by seawater erosion and serious land salinization, making reclamation and renovation difficult; therefore, it is sparsely populated. The topography of the Jiaodong Peninsula is predominantly hilly and complex; thus, the population is mostly concentrated in gently sloping coastal areas [28]. Coupled with the advantageous geographical location of the Shandong Peninsula urban agglomeration, convenient waterway transportation, earlier development, and higher levels of economic development and urbanization than in inland areas, this has led to the movement of the surrounding population to coastal areas, resulting in significant differences between the surrounding districts and counties [44]. In addition, the areas along the axes of the main railway lines (Jiaoji, Beijing-Shanghai, Beijing-Kowloon and Xinshi lines) are also areas of high population density.

### *Spatial characteristics of population distribution*

The IDW results (**Figure 3**) demonstrated that,

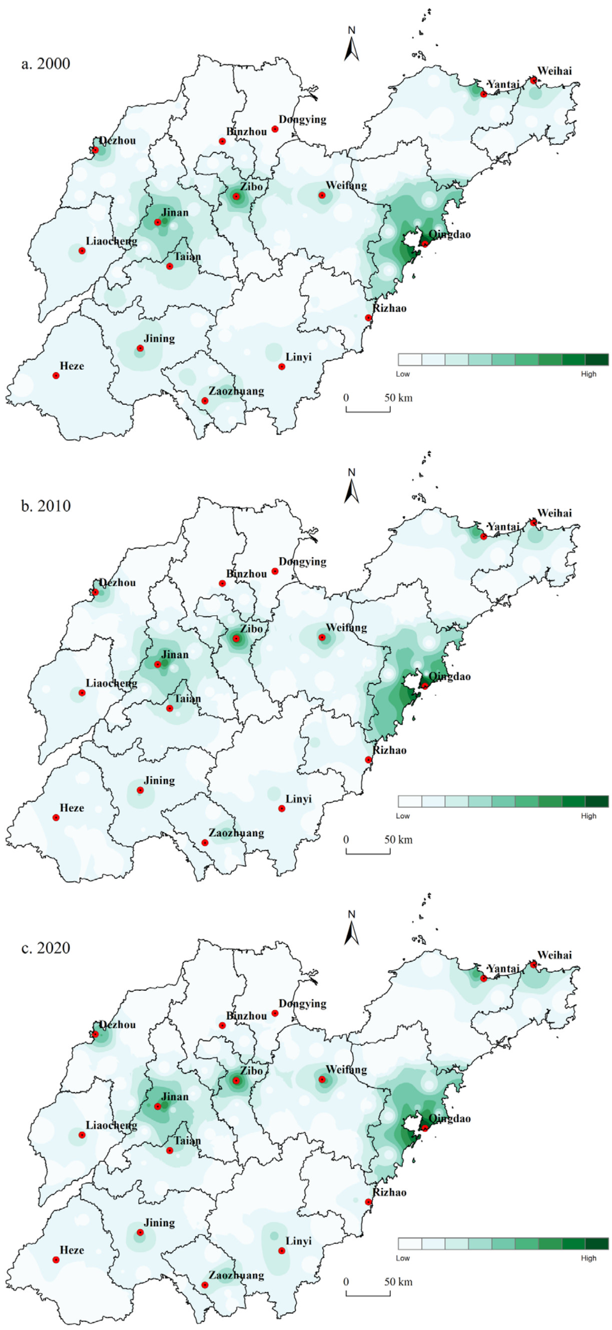


**Figure 3.** Population density distribution map of Shandong Province based on IDW.

in general, the areas with high and low values did not vary significantly during the study period. The divergence in population density was evident, showing a trend of local concentration in high-value areas and a contiguous distribution in low-value areas. A spatial distribution pattern was formed, with Jinan, Qingdao, Zibo, Weifang, Yantai, and Dezhou as local high-value areas, whereas other areas were low-value areas for a long time. Meanwhile, several high-value areas tended to diffuse from the center to the periphery, presenting a certain circular structure. Moreover, degradation of the high- and low-value areas occurred in almost all outer districts of the city during the study period. This could indicate a developmental tendency of the population to concentrate on the central city.

Overall, the results based on the IDW revealed the stable existence of six statistically significant high population density areas within Shandong Province, indicating a polycentric spatial structure characteristic of regional population distribution. The six densely populated areas centered on the Jinan, Qingdao, Zibo, Weifang, Yantai, and Dezhou centers can serve as the six population density centers in Shandong Province. This finding provided a basis for the application of the polycentric regional density function to analyze the characteristics of regional population agglomeration and diffusion.

## 3.2 Agglomeration and diffusion of the population in Shandong Province

### *Analysis based on the monocentric regional density functions*

According to the results of the IDW, there are six statistically significant population density centers in Shandong province, namely Jinan center (Lixia District, Shizhong District, Huaiyin District, Tianqiao District, Licheng District), Qingdao center (Shinnan District, Hebei District, Laoshan District, Licang District), Zibo center (Zichuan District, Zhangdian District, Zhoucun District), Yantai center (Zhifu District, Fushan District, Muping District, Leshan District), Weifang center (Weicheng District, Hanting District, Fangzi District, Kuiwen District) and Dezhou center (Decheng District). Considering the need for computation, this study chose the shortest route between the other district and county governments and the regional center government, plus one kilometer as the distance from the regional center; and thus, the impact area was divided. Combined with the results of the influence zone division, this study fits four forms of density functions for the Jinan, Qingdao, Zibo, Yantai, Weifang, and Dezhou centers. The results demonstrated (**Table 3**) that the logarithmic model exhibited high goodness of fit in all six regions. Therefore, a logarithmic model was selected for analysis of the study area.

The intercept *a* and slope *b* of the regional density function represent the estimated population density at the center of the region and the regional population density gradient, respectively. By observing the fitted lines of density functions based on the logarithmic model for the Jinan, Qingdao, Zibo, Yantai, Weifang, and Dezhou centers over the study period (**Figure 4**), the absolute values of the intercept *a* and slope *b* increased in all six regions from 2000 to 2020, and the growth in the Jinan and Dezhou centers was prominent from 2010 to 2020, while the growth in the remaining four population density centers was relatively stable over the two decades, with the Qingdao and Dezhou centers rising particularly rapidly. An increase in the intercept reflects an increase in population density in the urban areas of the central city, while an increase in the slope indicates that population density decreases more rapidly as the distance to the central city increases. This indicates a clear and increasing trend of centripetal agglomeration in the six regions over the 20-year period. Districts closer to the center not only have a higher population density but also a faster growth rate in population density than more distant districts. After analyzing the census data, this study suggests that the rapid increase

**Table 3.** Regression results of monocentric regional density functions.

| Region | Function form | *a* | | | *b* | | | $R^2$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2000 | 2010 | 2020 | 2000 | 2010 | 2020 | 2000 | 2010 | 2020 |
| Jinan | Linear | 786.652 | 919.785 | 1085.737 | –2.793* | –3.767* | –5.605* | 0.226 | 0.235 | 0.238 |
| | Logarithmic | 1310.016 | 1624.713 | 2145.855 | –187.243 | –251.158 | –372.169 | 0.801 | 0.811 | 0.822 |
| | Power | 7.123 | 7.321 | 7.556 | –0.216 | –0.248 | –0.309 | 0.687 | 0.694 | 0.685 |
| | Exponential | 6.517 | 6.619 | 6.676 | –0.003* | –0.004* | –0.005* | 0.190 | 0.193 | 0.179 |
| Qingdao | Linear | 1860.429* | 2478.311* | 3037.079* | –14.989* | –24.340* | –30.040* | 0.409 | 0.443 | 0.502 |
| | Logarithmic | 3163.444 | 4045.571 | 4738.781 | –617.727 | –834.934 | –958.835** | 0.921 | 0.945 | 0.929 |
| | Power | 8.053 | 8.353 | 8.577 | –0.409 | –0.458** | –0.471* | 0.920 | 0.901 | 0.837 |
| | Exponential | 7.261 | 7.598 | 7.900 | –0.011* | –0.016* | –0.018* | 0.511 | 0.575 | 0.683 |
| Zibo | Linear | 1203.035 | 1356.848 | 1469.173 | –13.461 | –16.179 | –18.770* | 0.873 | 0.895 | 0.850 |
| | Logarithmic | 1328.238 | 1533.722 | 1730.581 | –194.064** | –241.313 | –297.126 | 0.780 | 0.856 | 0.917 |
| | Power | 7.264 | 7.419 | 7.546 | –0.242** | –0.271** | –0.310** | 0.655 | 0.718 | 0.768 |
| | Exponential | 7.150 | 7.275 | 7.343 | –0.018 | –0.020 | –0.021 | 0.830 | 0.874 | 0.854 |
| Yantai | Linear | 567.085** | 716.164** | 841.868* | –1.030* | –2.778* | –4.409* | 0.059 | 0.238 | 0.308 |
| | Logarithmic | 629.576** | 813.582** | 988.158** | –36.753* | –81.059* | –126.524* | 0.155 | 0.421 | 0.528 |
| | Power | 6.507 | 6.686 | 6.860 | –0.075* | –0.139* | –0.200* | 0.167 | 0.364 | 0.397 |
| | Exponential | 6.317 | 6.507 | 6.581 | –0.002* | –0.005* | –0.006* | 0.066 | 0.192 | 0.193 |
| Weifang | Linear | 562.077 | 621.762 | 689.244 | –1.242** | –0.937* | –2.967* | 0.283 | 0.041 | 0.307 |
| | Logarithmic | 560.444 | 742.276 | 924.003 | –16.906* | –47.690* | –110.551** | 0.115 | 0.184 | 0.735 |
| | Power | 6.330 | 6.593 | 6.807 | –0.035* | –0.076* | –0.162** | 0.130 | 0.174 | 0.603 |
| | Exponential | 6.328 | 6.398 | 6.463 | –0.002* | –0.001* | –0.004* | 0.294 | 0.038 | 0.251 |
| Dezhou | Linear | 2358.959* | 2904.270* | 4286.715* | –52.823* | –67.412* | –106.679* | 0.937 | 0.942 | 0.939 |
| | Logarithmic | 2383.428** | 2932.550** | 4334.992** | –542.267** | –690.924** | –1094.709** | 0.993 | 0.994 | 0.993 |
| | Power | 7.771 | 7.979 | 8.365 | –0.468** | –0.515** | –0.648** | 0.986 | 0.988 | 0.985 |
| | Exponential | 7.745 | 7.956 | 8.325** | –0.045* | –0.050* | –0.063* | 0.924 | 0.933 | 0.919 |

Note: The significance level of parameter estimates without labeling is p = 0.001; * indicates that the parameter estimates are not significant, and ** indicates that the significance level of parameter estimates is p = 0.01.

in population density in the centers of Jinan and Qingdao is mainly due to the large influx of people from other areas. The population of the urban area in Jinan is large, and the growth of its population density is closely related to its special status as the capital city of the province. The population density in the Jinan center rose faster from 2010 to 2020, and this study speculates on the following reasons: In 2017, Shandong Province clarified the strategic concept of the conversion of old and new kinetic energy, and Jinan city actively responded to the requirements by developing a number of new industries. The objective demand for economic structure optimization and policy support led to the migration of talent to Jinan. In addition, in 2020, Jinan proposed a "strong provincial capital" strategy and zero-threshold settlement policy, which also contributed to rapid growth in population density. Qingdao, the most developed leading city in the Jiaodong Economic Circle and an important national coastal center city, is well placed in terms of economic output, employment opportunities, social security, and infrastructure. Simultaneously, Qingdao hosted various major events, such as the Shanghai Cooperation Organization summit, and the city's influence increased significantly. The reform of the household registration system and the relaxation of settlement and access conditions also provided conditions for population agglomeration, which undoubtedly attracted the population of the surrounding districts and counties. As far as the other three centers are concerned, Zibo has a long history of industry and is an old industrial area that has developed based on its resources. This, coupled with its emphasis on the transformation and upgrading of traditional industries and its focus on the tertiary sector during its development in recent years, has allowed the region to flourish. Yantai is strategically located and is an important land and sea transportation hub in Northeast Asia and the Circum-Bohai Sea Economic Zone. Relying on its excellent port conditions, the city is actively cultivating and growing its hub economy. Simultaneously, as one of the "three cores" of Shandong Province's comprehensive pilot zone for the conversion of old and new kinetic energy, it is developing well. Weifang ranks among the top cities in Shandong Province in terms of geographical area, population, and total economic scale, and has a strong industrial base as a traditional industrial and agricultural city. It relies on the Weifang Port to actively develop its port economy. In recent years, Weifang has been optimizing and upgrading its industrial system, improving its modern industrial system, and continuously increasing its investment in innovative cities with certain advantages. The transport location and natural conditions provide a good foundation for the development of Dezhou. Relying on its superior transportation location, the Dezhou center has taken the lead in development, driven by the synergistic development of the Beijing-Tianjin-Hebei Region. As a large national transportation hub, Dezhou is developing at a relatively rapid pace. In addition, rich mineral resources exist underground in Decheng District. The Dezhou Power Plant of Huaneng International Power Co., Ltd., the second largest thermal power plant in China, is located in the Decheng District, which also attracts the population of surrounding districts and counties to work there [45]. Although the Zibo, Yantai, Weifang, and Dezhou centers also have a certain floating population, they are inferior to the Jinan and Qingdao centers.

Furthermore, it can be observed from **Figure 4** that the growth rate varied considerably between the different areas in the hinterlands of the Qingdao and Dezhou centers. The growth in population density was very significant in proximity to the Qingdao and Dezhou centers, whereas the growth in areas further away from them was slow. This is in line with the "core growth-hinterland stagnation" pattern of Barkley et al. [11]. In contrast, the growth patterns of the remaining centers were more moderate, and although the areas closer to the center continued to grow faster than those away from it, the difference in growth rates was more moderate than that in the two centers mentioned above. These two growth patterns reflect the difference between the development of the central city and that of its hinterland. Qingdao's economy is large and has an extremely strong agglomeration effect. It has a large development gap

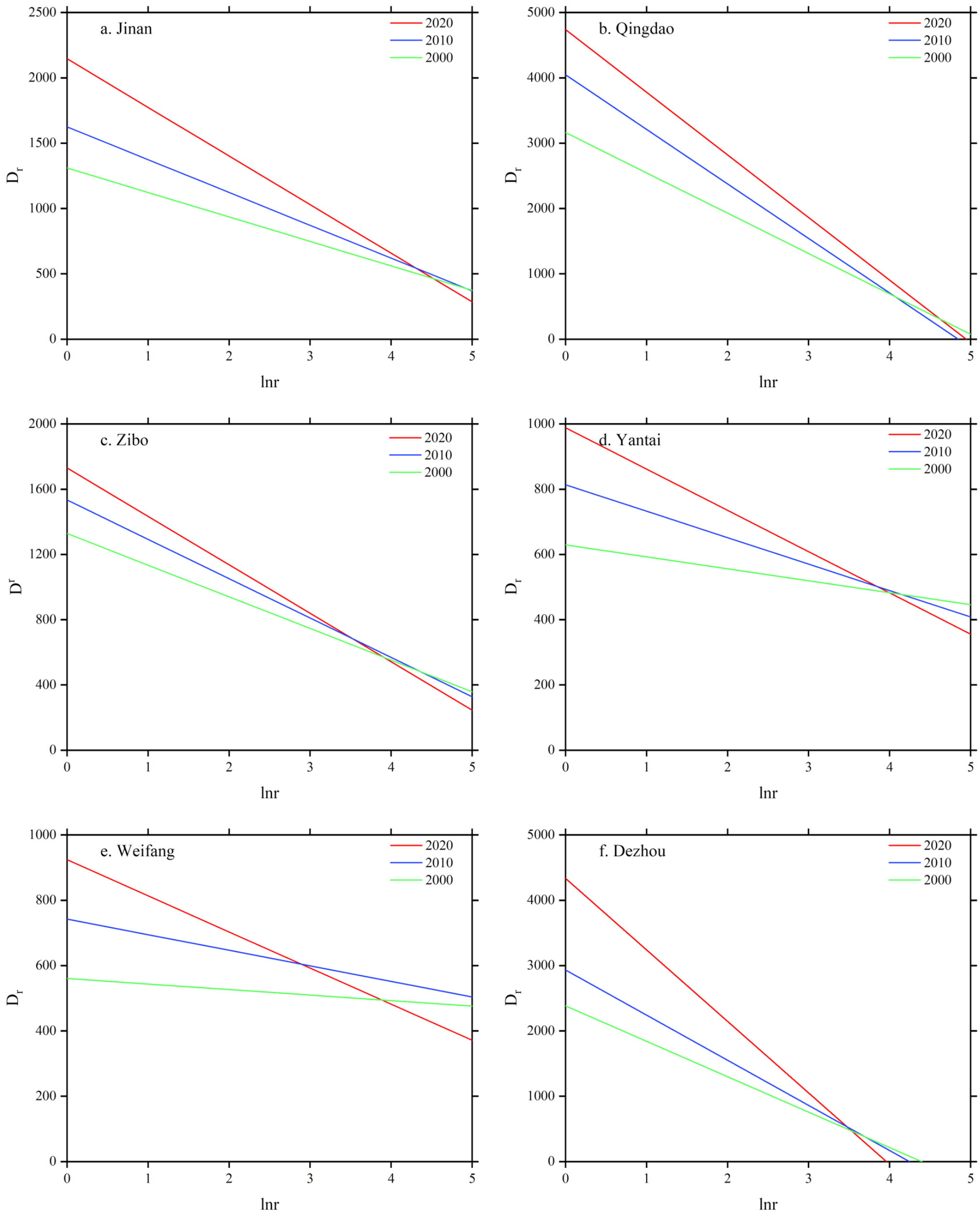


**Figure 4.** Growth patterns in different population density centers.

with the surrounding districts and counties, and the city of Qingdao does not have a strong radiation drive. The lack of large-scale, complete industrial chains and high-level modern industrial enterprises in the Jiaodong Peninsula makes it difficult to stimulate economic development in the hinterland [46]. The stronger polarization effect led to a larger difference in population density between the central area and peripheral districts and counties. The reason for the large difference in population density between the center of Dezhou and the periphery is the low level of economic development in Dezhou as a whole. Compared to other county-level regions, Decheng District has a high degree of development. In Dezhou city, the center has a comparative advantage. In addition, most new infrastructure is concentrated in cities and counties, which increases the development gap [47]. The center of Jinan has a well-developed economy, excellent service facilities and, thanks to the integration construction of the Jinan metropolitan area, Jinan and its neighboring cities have reached the standard of a "one-hour economic circle" with convenient transportation [48]. The diffusion effect has also led to higher population densities in neighboring areas, with stronger spatial correlations between regional units [42]. In addition, **Figure 4** shows that the population density in Jinan center is lower than that in Qingdao center. This study speculates that this is because of the rapid development of Qingdao in recent years, with Jinan, the provincial capital city, being overwhelmed by Qingdao, and the increasing competition gap. Compared to Jinan, the gap between the centers of Zibo, Yantai, and Weifang and the peripheral areas is smaller. The common reason for this is that the economic development of the districts and counties within the sphere of influence of these three centers is at a similar level. The centers do not have a strong population concentration capacity, but their relatively rapid economic development has attracted a certain population from the surrounding districts and counties. Together with the proximity of these three centers to the cities of Jinan and Qingdao, their development is inevitably influenced by the two powerhouses, limiting their polarization and diffusion effects.

### *Analysis based on the polycentric regional density functions*

The determination of regional density centers was based on the above analysis of the characteristics of the population density distribution in Shandong Province. Six population density centers were used for the monocentric regional density function analysis: Jinan, Qingdao, Zibo, Yantai, Weifang, and Dezhou. According to the IDW, the most prominent centers were Jinan, Qingdao, and Zibo. The polycentric regional density function followed the six centers mentioned above, and the models were fitted and compared separately for different numbers of centers. The fit results for the polycentric population density model are presented in **Table 4**.

The polycentric population density model based

**Table 4.** Comparison of the fitting results of the polycentric population density model.

| Center | Year | Model 1 | | Model 2 | | Model 3 | | Model 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | a | b | a | b | a | b | a | b |
| | 2000 | 641.290 | –0.002 | 1538.991 | –0.482 | 1359.701 | –0.356 | 1319.043 | –0.324 |
| Jinan | 2010 | 1020.603 | –0.007 | 1459.236 | –0.114 | 1467.612 | –0.124 | 1444.702 | –0.100 |
| | 2020 | 3223.348 | –0.568 | 2154.727 | –0.111 | 2137.374 | –0.094 | 2138.823 | –0.096 |
| | 2000 | 3216.818 | –0.068 | 3138.012 | –0.080 | 3144.400 | –0.080 | 3144.892 | –0.080 |
| Qingdao | 2010 | 4267.686 | –0.046 | 3932.811 | –0.065 | 3918.105 | –0.066 | 3928.841 | –0.066 |
| | 2020 | 4789.047 | –0.044 | 4551.754 | –0.051 | 4570.155 | –0.051 | 4568.794 | –0.051 |
| | 2000 | 775.341 | –0.050 | 855.579 | –0.044 | 846.112 | –0.045 | 846.598 | –0.045 |
| Zibo | 2010 | 1016.212 | –0.040 | 1053.177 | –0.045 | 1044.845 | –0.047 | 1024.394 | –0.049 |
| | 2020 | 998.269 | –0.006 | 1284.258 | –0.051 | 1267.076 | –0.052 | 1267.173 | –0.052 |
| | 2000 | | | 498.867 | 0.000 | 241.642 | –0.272 | 234.610 | –0.236 |
| Yantai | 2010 | | | 504.216 | 0.000 | 528.988 | 0.000 | 486.983 | –0.268 |
| | 2020 | | | 504.531 | 0.000 | 805.472 | –0.309 | 771.650 | –0.273 |
| | 2000 | | | | | 504.355 | 0.000 | 504.311 | 0.000 |
| Weifang | 2010 | | | | | 486.365 | –0.547 | 568.621 | –0.001 |
| | 2020 | | | | | 538.579 | –0.001 | 534.415 | –0.001 |
| | 2000 | | | | | | | 3972.119 | –0.716 |
| Dezhou | 2010 | | | | | | | 2940.236 | -0.162 |
| | 2020 | | | | | | | 7021.046 | -0.577 |
| | 2000 | 0.887 | | 0.958 | | 0.958 | | 0.968 | |
| $R^2$ | 2010 | 0.888 | | 0.955 | | 0.946 | | 0.962 | |
| | 2020 | 0.920 | | 0.937 | | 0.940 | | 0.961 | |

on the exponential form fits better and is generally more applicable than the monocentric model, with $R^2$ values above 0.9 in all years of the study period. This indicates that the exponential model can better explain the structure of the population density distribution in Shandong Province, which has formed a polycentric population density spatial structure, and the relationship between population density centers is between complete substitution and complementation. Model 1 used three centers, Jinan, Qingdao, and Zibo, all of which had $R^2$ values exceeding 0.88, indicating that these three centers explained, to a large extent, the distribution of population density in Shandong Province. By 2020, the $R^2$ value reached 0.92, indicating that these three centers had an increasingly strong influence on regional population density distribution and could dominate regional population density distribution. Model 2 added the Yantai center, and the $R^2$ value further increased to over 0.93. The explanatory power of the model was further enhanced, indicating that these four centers could fully explain the regional population density distribution. However, between 2000 and 2020, the $R^2$ values showed a decreasing trend, indicating that other population density centers in the region continued to develop and had an increasingly significant impact on the regional population density distribution, while the explanatory power of the Yantai center on the overall regional population density distribution decreased. Models 3 and 4 added the Weifang and Dezhou centers, respectively, and the results demonstrated that the two centers also had an impact on the regional population density distribution; however, there was no significant change in $R^2$ values, indicating that the Weifang and Dezhou centers made a relatively limited contribution to the degree of model interpretation.

Changes in the estimated values of $a$ and $b$ reflect the characteristics of regional population agglomeration and diffusion at different stages. The estimates of regional population density $a$ showed that all six centers had an upward trend in their population density estimates. This reflected the overall trend of population concentration in Shandong Province toward urban areas. In terms of changes in $b$ value of the population density gradient, both the Jinan and Qingdao centers exhibited a decrease in the $b$ value during the study period, demonstrating continuous outward population diffusion. This reflected the spatially evolving characteristics of the population structure of the center's growth-based diffusion pattern, where the center's population density increased while the population density gradient decreased. This indicated that Jinan and Qingdao grew stronger as centers while driving the development of other districts and counties within their spheres of influence, with a high degree of center development. The Zibo, Yantai, and Weifang centers displayed a generally weak upward trend, with the population density gradient increasing but not changing significantly. This reflected the centripetal concentration pattern of the population and the fact that the three areas were relatively "weak" centers. The population density gradient in the Dezhou center demonstrated a decline followed by an increase, indicating that the Dezhou center had not yet shown a strong agglomeration ability from 2000 to 2010. The regional population distribution was mainly dominated by centers such as Jinan, Qingdao, and Zibo, while the agglomeration effect gradually emerged after 2010, displaying a trend of population agglomeration toward the center.

### 3.3 Further discussion on population agglomeration and diffusion

To further explore the spatial variation pattern of population dispersion in Shandong Province, we first visualized the population growth rate during the study period using ArcGIS, and the results are shown in **Figure 5**. Overall, there were significantly more areas with positive population growth rates from 2000 to 2010 than from 2010 to 2020, and the areas with higher population growth rates were broadly concentrated in the central districts and counties of the cities. Specifically, from 2000 to 2010, the population growth rate in the western region of Shandong Province was higher than that in the eastern region, with a contiguous positive regional distribution of

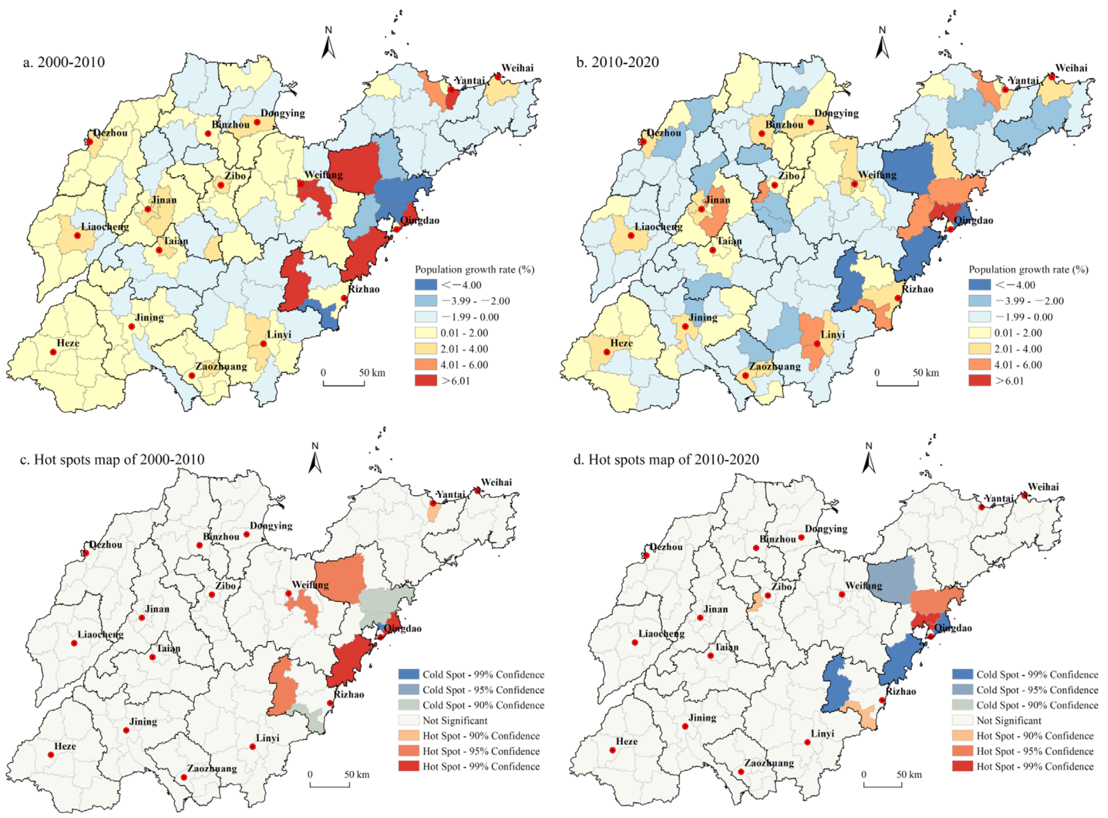


**Figure 5.** Population growth rate map and distribution map of hot and cold spots in Shandong Province.

growth rates. However, the eastern regions of Pingdu City, Kuiwen District, Fangzi District, Laoshan District, Huangdao District, Laishan District and Ju County had the highest population growth rates. The regions with the lowest population growth rates, namely Jimo, Chengyang, Licang, and Lanshan, were also located in the eastern part of Shandong Province. This indicated that the population growth rate varied more among districts and counties in the eastern region and less among districts and counties in the western region. For the period 2010-2020, regions with negative population growth rates constituted the majority. The population growth rate between city center districts and peripheral districts increased further. This reflected a further strengthening of population agglomeration and a more pronounced polarization effect of the centers. It is worth noting that most of the regions with the highest growth rates in the period 2000-2010 had growth rates of less than –4% in the period 2010-2020. In contrast, the regions with the lowest growth rates in the period 2000-2010 almost all saw their growth rates increase above 4% in the period 2010-2020.

Based on the characteristics of the population growth rate of each county and district in Shandong Province, this study further explored the agglomeration and diffusion characteristics using cold and hot spot analyses. As shown in **Figure 5c**, the spatial variations in the cold and hot spot areas from 2000 to 2010 were small, with more hot spot areas than cold spot areas. Specifically, there are six hotspot areas, mainly in the eastern part of Shandong Province, including Pingdu City, Fangzi District, Laoshan District, Huangdao District, Leshan District, and Juxian County. There are four cold spots: Jimo District, Chengyang District, Licang District, and Lanshan District, which are more concentrated than the hot spots. **Figure 5d** shows that there was some replacement of cold and hot spot zones in 2010-2020 compared with those in 2000-2010. Four cold spot zones—Pingdu City, Laoshan District, Huangdao District, and Ju County—were hot spot zones during the last time period. There are five hotspot zones: the Zhoucun, Lanshan, Jimo, Chengyang, and Licang

Districts. Except for Zhoucun District, the other four districts were cold spots during the last time period.

In summary, the population agglomeration effect in the central districts and counties of Shandong Province was increasing. Variations in population size were more significant along the eastern coastal area than in the inland area, and the phase of population growth rates along the eastern coastal area was more evident over the study period.

# 4. Conclusions and limitations

## 4.1 Conclusions

This study analyzed the distribution of population density in counties in Shandong Province based on data from the 2000, 2010, and 2020 censuses. To directly reflect the spatial relationship of the population distribution, this study used the IDW. On this basis, the monocentric and polycentric regional density functions were applied to study the characteristics of population agglomeration and diffusion in Shandong Province, and the changes in the population growth rate and variations in cold and hot spots were further analyzed over a twenty-year period. The results indicated that the spatial distribution of the population in Shandong Province was uneven, with obvious differences in population size and changes between districts and counties. With urban areas as the center of population concentration, a multi-center spatial structure was formed, and six central cities dominated the spatial distribution trend of regional population density, including Jinan, Qingdao, Zibo, Yantai, Weifang, and Dezhou centers. Methodological and conclusive differences between monocentric and polycentric regional density functions were compared. The polycentric regional density function exhibited a better fit and was more applicable than the monocentric model. The results of the monocentric regional density function analysis showed a clear and increasing trend toward the centripetal agglomeration of regional centers over the study period, but the ability to agglomerate and the difference in the rate of population growth between the center and hinterland differed. Conversely, the polycentric regional density function reflected that some of the centers displayed a spatial trend of diffusing outward, and that different levels of centers exhibited different patterns of population agglomeration and diffusion. The spatial statistical analysis of population density growth further validated the polycentric density function. The multicenter regional density function reflected the trend of population density change more accurately and precisely because of the comprehensive consideration of the influence of multiple centers on the distribution of population density.

## 4.2 Limitations

The study of the characteristics of regional population density distribution is important for identifying the characteristics of regional spatial structure development. In this study, monocentric and polycentric regional density functions were discussed, and the analysis and comparison were relatively complete. However, this study only started with demographic data, as a more diverse range of socioeconomic data was required for a comprehensive analysis of the regional spatial structure. Simultaneously, the distribution of the population density is influenced by economic, social, and natural factors, and further exploration of the mechanisms that influence the spatial structure of the population is needed. In addition, this study was based on county data and did not discuss the spatial structure of the population of Shandong Province in sufficient detail; a more comprehensive study could be conducted in the future using data from smaller-scale geographical units.

# Author Contributions

Conceptualization (Chen YB). Methodology (Chen YB, Zhao XH). Software (Chen YB, Zhao XH). Formal analysis (Zhao XH). Resources (Zhao XH). Data curation (Zhao XH). Writing of the original draft (Zhao XH). Writing, reviewing, and editing (Chen YB). Visualization (Zhao XH). Supervision (Chen YB).

## Conflict of Interest

There is no conflict of interest.

## Funding

This research was funded by the Shandong Provincial Natural Science Foundation (grant number ZR202102240088).

## References

[1] Bontje, M., 2001. Dealing with deconcentration: population deconcentration and planning response in polynucleated urban regions in Northwest Europe. Urban Studies. 38(4), 769-785. DOI: https://doi.org/10.1080/00420980120035330

[2] Salvati, L., Carlucci, M., 2016. In-between stability and subtle changes: Urban growth, population structure, and the city life cycle in Rome. Population Space and Place. 22(3), 216-227. DOI: https://doi.org/10.1002/psp.1877

[3] Kabisch, N., Haase, D., Haase, A., 2012. Urban Population development in Europe, 1991-2008: The examples of Poland and the UK. International Journal of Urban and Regional Research. 36(6), 1326-1348. DOI: https://doi.org/10.1111/j.1468-2427.2012.01114.x

[4] Wang, F.H., 2001. Regional density functions and growth patterns in major plains of China, 1982-1990. Papers in Regional Science. 80(2), 231-240. DOI: https://doi.org/10.1007/PL00013624

[5] Jia, P., Qiu, Y.L., Gaughan, A.E., 2014. A fine-scale spatial population distribution on the high-resolution gridded population surface and application in Alachua County, Florida. Applied Geography. 50, 99-107. DOI: https://doi.org/10.1016/j.apgeog.2014.02.009

[6] Murray, A.T., Davis, R., Stimson, R.J., et al., 1998. Public transportation access. Transportation Research Part D: Transport and Environment. 3(5), 319-328. DOI: https://doi.org/10.1016/S1361-9209(98)00010-8

[7] Li, J.G., Li, J.W., Yuan, Y.Z., et al., 2019. Spatiotemporal distribution characteristics and mechanism analysis of urban population density: A case of Xi'an, Shaanxi, China. Cities. 86, 62-70. DOI: https://doi.org/10.1016/j.cities.2018.12.008

[8] Clark, C., 1951. Urban population densities. Journal of Royal Statistics Society. 114(4), 490-496. DOI: https://doi.org/10.2307/2981088

[9] Cheng, L., 2014. Zhong guo qu yu ren kou mi du mo xing ji jing ji zeng zhang de kong jian mo shi (Chinese) [Regional population density function and spatial patterns of economic growth in China] [Ph.D.'s thesis]. Changchun: Northeast Normal University. p. 8-9.

[10] Parr, J.B., 1985. A population—density approach to regional spatial structure. Urban Studies. 22(4), 289-303. DOI: https://doi.org/10.1080/00420988520080531

[11] Barkley, D.L., Henry, M.S., Bao, S., 1996. Identifying "Spread" versus "Backwash" effects in regional economic areas: A density functions approach. Land Economics. (72), 336-357.

[12] Limtanakool, N., Dijst, M., Schwanen, T., 2007. A theoretical framework and methodology for characterising national urban systems on the basis of flows of people: Empirical evidence for France and Germany. Urban Studies. 44(11), 2123-2145. DOI: https://doi.org/10.1080/00420980701518990

[13] Subasinghe, S., Wang, R., Murayama, Y., 2022. Modelling spatial pattern of population distribution in 50 largest cities in the world: A geospatial approach. IOP Conference Series: Earth and Environmental Science. 1109(1), 012065. DOI: https://doi.org/10.1088/1755-1315/1109/1/012065

[14] Heikkila, E., Gordon, P., Kim, J., et al., 1989. What happened to the CBD—distance gradient? Land values in a polycentric city. Environment and Planningn A. 21(2), 221-232.

[15] Small, K.A., Song, S., 1994. Population and employment densities: Structure and change. Journal of Urban Economics. 36, 292-313.

DOI: https://doi.org/10.1006/juec.1994.1037

[16] McMillen, D.P., McDonald, J.F., 1998. Suburban subcenters and employment density in metropolitan Chicago. Journal of Urban Economics. 43(2), 157-180.
DOI: https://doi.org/10.1006/juec.1997.2038

[17] Joseph, M., Wang, F.H., 2010. Population density patterns in Port-au-Prince, Haiti: A model of Latin American city? Cities. 27(3), 127-136.
DOI: https://doi.org/10.1016/j.cities.2009.12.002

[18] Zhou, Ch.S., Xu, X.Q., 1997. Guang zhou shi ren kou kong jian fen bu te zheng ji yan bian qu shi fen xi (Chinese) [Population distribution and its change in Guangzhou city]. Tropical Geography. 17(1), 53-60.

[19] Wang, F.H., Zhou, Y.X., 1999. Modelling urban population densities in Beijing 1982-90: Suburbanisation and its causes.Urban Studies. 36(2), 271-287.
DOI: https://doi.org/10.1080/0042098993600

[20] Luo, J., Wei, Y.D., 2006. Population distribution and spatial structure in transitional Chinese cities: A study of Nanjing. Eurasian Geography and Economics. 47(5), 585-603.
DOI: https://doi.org/10.2747/1538-7216.47.5.585

[21] Wang, F.H., Meng, Y., 1999. Analyzing urban population change patterns in Shenyang, China 1982-90: Density function and spatial association approaches. Geographic Information Sciences. 5(2), 121-130.
DOI: https://doi.org/10.1080/10824009909480521

[22] Feng, J., Zhou, Y.X., 2003. Jin 20 nian lai bei jing dou shi qu ren kou zeng zhang yu fen bu (Chinese) [The growth and distribution of population in Beijing Metropolitan Area (1982-2000)]. Journal of Geographical Sciences. 58(6), 903-916.
DOI: https://doi.org/10.11821/xb200306014

[23] Wu, W.Y., Ma, X.Y., 2006. Duo zhong xin cheng shi ren kou mo xing ji mo ni: Yi shang hai wei li (Chinese) [Polycentric population density functions and modelling: The case of Shanghai]. Modern Urban Research. 21(12), 39-44.
DOI: https://doi.org/10.3969/j.issn.1009-6000.2006.12.008

[24] Jiang, L., Wu F.L., 2013. Guang zhou ren kou kong jian fen bu bian dong yu duo zhong xin cheng shi kong jian jie gou yan hua ce du (Chinese) [Guangzhou population spatial distribution and polycentricity spatial structure evolution]. Tropical Geography. 33(2), 147-155.
DOI: https://doi.org/10.13284/j.cnki.rddl.002318

[25] Sun, T.Sh., Li, G.P., Lu, M.H., 2009. Jing jin ji dou shi quan ren kou ji ju yu kuo san ji qi ying xiang yin su: Ji yu qu yu mi du han shu de shi zheng yan jiu (Chinese) [Concentration and decentralization of population in the Beijing-Tianjin-Hebei metropolitan region and its determinants: A regional density function approach]. Acta Geographica Sinica. 64(8), 956-966.
DOI: https://doi.org/10.11821/xb200908007

[26] Liu, N.Q., Deng, M., 2018. Duo zhong xin jie gou mo shi yu zhang san jiao cheng shi qun ren kou kong jian fen bu you hua (Chinese) [Urban spatial structure and optimization of population distribution in Yangtze River Delta Region]. Review of Industrial Economics. 27(4), 91-103.
DOI: https://doi.org/10.19313/j.cnki.cn10-1223/f.2018.04.007

[27] Hong, Sh.M., Hao, J.M., 2018. Huang huai hai ping yuan ren kou kong jian jie gou ji qi yan bian te zheng yan jiu (Chinese) [Spatial structure of population and characteristics of evolution in Huang-Huai-Hai Plain]. Resource Development & Market. 34(11), 1526-1532+1557.
DOI: https://doi.org/10.3969/j.issn.1005-8141.2018.11.008

[28] Dong, L.F., Wang, L.L., Shao, J.H., et al., 2012. Jin 20 nian lai shan dong sheng ren kou fen bu kong jian ge ju ji qi yan bian te zheng fen xi (Chinese) [Population spatial distribution pattern and evolution characteristics of Shandong province in recent 20 years]. Territory & Natural Resources Study. 138(3), 11-13.
DOI: https://doi.org/10.16202/j.cnki.tnrs.2012.03.031

[29] Li, W.X., Sun, X.H., 2007. Ji yu GIS de shan dong sheng ren kou zhong xin qian yi yan jiu (Chinese) [Study of the migration of population

gravity center in Shandong Province based on GIS]. Journal of Shandong Normal University. 99(3), 83-86.
DOI: https://doi.org/10.3969/j.issn.1001-4748.2007.03.026

[30] Wang, J., Yang, X.H., Shi, R.X., 2012. Shan dong sheng ren kou kong jian fen bu ge ju de duo chi du fen xi (Chinese) [Spatial distribution of the population in Shandong Province at multi-scales]. Progress in Geography. 31(2), 176-182.
DOI: https://doi.org/10.11820/dlkxjz.2012.02.006

[31] McDonald, J.F., 1989. Econometric studies of urban population density: A survey. Journal of Urban Economics. 26(3), 361-385.
DOI: https://doi.org/10.1016/0094-1190(89)90009-0

[32] Liu, Zh.D., Luo, Sh.F., Lin, Zh.W., et al., 2021. Shan dong sheng ren kou cheng zhen hua de shi kong te zheng ji kong jian xiao ying yan jiu (Chinese) [Study on spatial-temporal characteristics and spatial effects of population urbanization in Shandong Province]. Qu Journal of Qufu Normal University (Natural Science). 47(4), 112-119.

[33] Li, Ch.P., 2015. Xin xi liu shi jiao de shan dong sheng cheng shi wang luo te zheng yan jiu (Chinese) [City network structure of Shandong Province based on information flow]. Journal of Arid Land Resources and Environment. 29(12), 51-56.
DOI: https://doi.org/10.13448/j.cnki.jalre.2015.399

[34] Yang, Q., 1990. Qu yu ke liu fen bu mo xing de yan jiu (Chinese) [A model for interregional trip distribution in China]. Acta Geographica Sinica. 45(3), 264-274.
DOI: https://doi.org/10.11821/xb199003002

[35] Wang, F.H., 2014. Quantitative methods and socio-economic applications in GIS. CRC Press: Boca Raton. pp. 127.

[36] Ohlert, P.L., Bach, M., Breuer, L., 2023. Accuracy assessment of inverse distance weighting interpolation of groundwater nitrate concentrations in Bavaria (Germany). Environmental Science and Pollution Research. 30(4), 9445-9455.
DOI: https://doi.org/10.1007/s11356-022-22670-0

[37] Ghorbani, Z., Sexton, A., Van Loon, L.L., et al., 2023. Biogeochemical prospecting for gold at the Yellowknife City Gold Project, Northwest Territories, Canada: Part 2-Robust statistical analysis. Applied Geochemistry. 149, 105559.
DOI: https://doi.org/10.1016/j.apgeochem.2023.105559

[38] Ashraf, M., Loftis, J.C., Hubbard, K.G., 1997. Application of geostatistics to evaluate partial weather station networks. Agricultural and Forest Meteorology. 84(3), 255-271.
DOI: https://doi.org/10.1016/S0168-1923(96)02358-1

[39] Zhang, K., Wang, Zh.R., 2023. LTPP data-based investigation on asphalt pavement performance using geospatial hot spot analysis and decision tree models. International Journal of Transportation Science and Technology. 12(2), 606-627.
DOI: https://doi.org/10.1016/j.ijtst.2022.06.007

[40] Ord, J.K., Getis, A., 1992. The analysis of spatial association. Geogrphical Analysis. 24(3), 189-206.
DOI: https://doi.org/10.1111/j.1538-4632.1992.tb00261.x

[41] Tan, M.H, Li, X.B., Lu, C.H., et al., 2008. Urban population densities and their policy implications in China. Habitat International. 32(4), 471-484.
DOI: https://doi.org/10.1016/j.habitatint.2008.01.003

[42] Li, P., Xu, Y.T., 2011. Shan dong sheng ren kou kong jian fen bu te zheng fen xi (Chinese) [Characteristic study on the spatial distribution of Shandong Population]. Ludong University Journal (Natural Science Edition). 27(3), 274-278.
DOI: https://doi.org/10.3969/j.issn.1673-8020.2011.03.021

[43] Mao, Q.Zh., Long, Y., Wu, K., 2015. Zhong guo ren kou mi du shi kong yan bian yu cheng zhen hua ge ju chu tan—cong 2000 nian dao 2010 nian (Chinese) [Spatial-temporal changes of population density and exploration on urbanization pattern in China: 2000-2010]. City Planning Review. 39(2), 38-43.

[44] Zhang, P.F., Xu, Y.T., 2019. Ji yu GIS de shan dong sheng ren kou fen bu shi kong ge ju ji ying

xiang yin su fen xi (Chinese) [Spatial temporal pattern and influencing factors of population distribution in Shandong Province based on GIS]. Anhui Agricultural Science Bulletin. 25(9), 158-162.
DOI: https://doi.org/10.3969/j.issn.1007-7731.2019.09.063

[45] Pang, Y., Lian, H., Wang, L., 2019. De zhou shi xian yu cheng zhen hua shui ping ce du ji qi fen yi yan jiu (Chinese) [Study on the measurement and dissimilarity of urbanization level of Dezhou County]. City. 227(2), 53-60.

[46] Zhu, Y., 2021. Ke xue gou jian jiao dong ban dao jing ji quan yi ti hua zhan lue ge ju (Chinese) [Scientifically constructing an integrated strategic pattern of the Jiaodong Peninsula economic circle]. China Journal of Commerce. 830(7), 12-14.
DOI: https://doi.org/10.19699/j.cnki.issn2096-0298.2021.07.012

[47] Gao, Q., 2019. De zhou cheng zhen hua fa zhan bu ping heng bu chong fen wen ti qian xi (Chinese) [Analysis of unbalanced and inadequate urbanization development in Dezhou]. Modern Economic Information. 14, 498.

[48] Cai, Y.J., 2021. Ji yu duo yuan shu ju de ji nan dou shi quan tong cheng hua jin cheng ji qi ying xiang yin su yan jiu (Chinese) [Research on the process and influencing factors of urban integration of Jinan Metropolitan Area based on multi-source data] [Master's thesis]. Jinan: Shandong Normal University. p. 22.