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Article

# Variation analysis in historical demographic distribution within urban agglomeration: Experimental evidence from the Wuhan "1+8" City Circle

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**Abstract:** Understanding the spatial distribution of population is crucial in regional research, as it informs the development of effective population policies, long-term regional planning, and the balanced growth of the economy, resources, and environment. This study employs a quantitative approach to construct a research framework using demographic data to elucidate the historical population dynamics within the Wuhan "1+8" City Circle (WCC). The study examines whether the central city and its peripheral cities have experienced coordinated growth or if a town has dominated. The findings reveal several key findings and insights: Wuhan, as the core city of the WCC and the capital of Hubei Province, shows population growth driven not only by natural increases but also by a significant population siphoning effect, with Hongshan of Wuhan experiencing the most pronounced impact; from 2010 to 2020, the WCC's overall population distribution displayed a dispersal trend, while population density continued to concentrate, particularly around Wuhan and its vicinity, thereby establishing Wuhan as a central population hub; Gender distribution within the WCC generally reflects a higher proportion of males than females, with exceptions in Jiang'an of Wuhan and Huangshigang of Huangshi, where females outnumber males. This pattern may result from attracting male labor to industrial parks and female labor to service sectors. In summary, the WCC needs to refine its regional development strategies, especially for crucial siphoning areas such as Hongshan of Wuhan and Wuchang of Wuhan, to foster balanced regional growth. Additionally, policies to encourage childbirth, enhance elderly care services, and implement a comprehensive population data monitoring and forecasting system are crucial for addressing demographic shifts and achieving sustainable development.

**Keywords:** demography; historical dynamical; spatial characteristics; structural trends; county-level scale; Wuhan "1+8" City Circle (WCC)

## 1. Introduction

Nowadays, the multiple pressures of demographic, social, economic, and environmental issues have led to a gradual shift in the development dynamics of Chinese cities from industrial industries to service industries and diversified emerging digital industries [1]. Cities with better economic and industrial structures are better positioned to dominate the allocation of resources and attract talent [2]. These effects are most pronounced in more developed cities, providing residents with more competitive social service policies [3]. With China's working-age population having peaked in 2015, the competition for talent among towns is expected to intensify [4]. Population research not only focuses on characteristics such as total population, density, growth rate, and composition in different regions but also on population movements, migration, and the relationship between population, economy, society, resources, and the environment [5]. As the most dynamic element in urbanization, the population's demographic characteristics, overall scale, and spatial distribution are crucial for sustainable city development [6]. In recent years, as urbanization continues to advance, large numbers of migrants have flocked to cities. While this rapid urban population growth has stimulated economic development, it has also caused significant social and environmental issues, including regional environmental degradation, traffic congestion, insufficient public facilities, and the lagging development of service facilities in densely populated areas, along with the coexistence of over-utilization and inefficient use of land [6,7]. Generally, city development is accompanied by changes in population distribution, with regional overpopulation and underpopulation resulting from the imbalance of natural endowments and socio-economic development, as well as the progress of regional socio-economic development to certain stages [8]. Overpopulation leads to competition for resources and environmental carrying capacity, while underpopulation results in labor shortages and decreased domestic demand [9,10]. Thus, the spatial distribution of the population, which examines the distribution, dispersion, and combination of regional populations at a certain point in time, is the most fundamental manifestation of the man-land relationship, an essential aspect of regional spatial structure, and a key prerequisite for the coordinated allocation of industrial resources [4,11–15].

As a core focus of regional research, the spatial distribution of the population has received unprecedented and widespread attention from the academic and policy communities. Understanding the patterns and dynamics of demographic information is crucial for formulating rational population policies, long-term regional development planning, and the coordinated development of the economy, resources, and the environment [4,5,7,8,16,17]. (1) In terms of regional scope, scholars have explored the spatial distribution of populations in different historical periods at the national administrative scale in countries such as Spain [18,19], China [20], Jordan [21], and Tanzania [22] using demographic grids, censuses, or area statistics. Additionally, some researchers have monitored and analyzed designated town areas [23], specific demarcation lines [24], and metropolitan areas [25] by employing numerical tools and multiple sources of demographic data to understand demographic dynamics in specific regions. (2) Regarding data characteristics, scholars have identified spatial distribution patterns of populations during specific historical periods by categorizing basic population attributes, including the female population [26], the elderly population [27], the rural population [28], and different ethnic groups [29–31]. Other researchers have revealed the spatial distribution characteristics of specific populations by dividing various population attributes, such as employed population [32], higher education levels [33], mobile populations [34], border populations [35], and potential populations [36]. (3) In the realm of population prediction and simulation, scholars have based their analyses on data reflecting population locations, such as remote sensing image data [37], nighttime lighting information [38,39], cell phone positioning information [40], and traffic dynamics data [41]. Predictive modeling methods, including spatial statistical measurement [42,43], geospatial modeling [44], localized spatial three-dimensional modeling [45], and machine learning algorithms [46–49], have been employed to simulate and estimate the spatial distribution of urban populations.

In addition, some scholars use the spatial distribution of the population as an essential variable indicator for research: (1) to comprehensively explore the relationship between the spatial distribution of the population and various vital elements of cities and towns, such as spatial structure [50], population mobility [51,52], economic structure [53,54], transportation system [55,56], terrain conditions [57,58], and land use [59]; (2) to examine its relationship with the distribution of various service facilities [60], such as medical institutions [61], housing space [62], commercial facilities [63], and shelters [64]; and (3) to investigate its relationship with potential risk prevention, such as climate change [65,66], epidemic or disease transmission [67], and crime risk [68,69]. Therefore, the population's spatial distribution is a critical factor affecting regional socio-economic vitality, infrastructure construction, public service allocation, and urban transportation, housing, and ecological issues. Acquiring and understanding information on the urban population's spatial distribution provides an essential scientific basis for formulating regional long-term development policies and urban management measures.

After a comprehensive literature review of existing studies on the spatial distribution of the population, it is found that, as a focal issue of regional research, there has been abundant progress and various approaches in the academic community. Among them, Chinese academics have conducted the most extensive research, but there remains a gap, specifically in studies related to population distribution patterns from the perspective of urban agglomerations. China's urbanization is advancing rapidly and on a large scale, yet existing studies on the population distribution of urban agglomerations typically focus on coastal regions such as the Yangtze River Delta, the Pearl River Delta, and Beijing-Tianjin-Hebei, with fewer studies on inland urban agglomerations [70,71]. Uneven population distribution at the macro level not only leads to social problems such as widening regional development gaps but also exacerbates imbalances in the development of education, healthcare, and elderly care, resulting in the wastage of social resources [10,72]. Therefore, this study takes the Wuhan "1+8" City Circle (WCC) as the case study area, using 2010 and 2020 as historical reference points. The study focuses on the population distribution pattern within the urban agglomerations, exploring the general and structural characteristics of population distribution in inland urban agglomerations, and explains the internal patterns of population in the process of urban agglomeration development. The study results show that analyzing the changes in the population distribution pattern of the WCC helps to determine the population's spatial development trend, thereby providing insights into historical demographic problems and their logical relationships within the region. This has empirical value and significance for regional coordinated development and the rational allocation of resources.

## 2. Materials and methods

### 2.1. Description of the study area

Urban agglomeration refers to a vast urbanized area comprising several regions that are spatially adjacent and functionally interconnected [73]. The WCC, also known as the Wuhan Urban Agglomeration (WUA) [74]. Located in Hubei Province, China (**Figure 1**), the WCC includes the prefecture-level administrative units of Wuhan, Huangshi, Ezhou, Xiaogan, Huanggang, Xianning and the special county-level administrative units of Xiantao, Tianmen, and Qianjiang, with Wuhan at its center [75]. According to China's Compendium of Administrative Divisions, the administrative hierarchy below the prefecture-level units is county-level units, which generally encompass city districts, county-level cities, and counties [76].

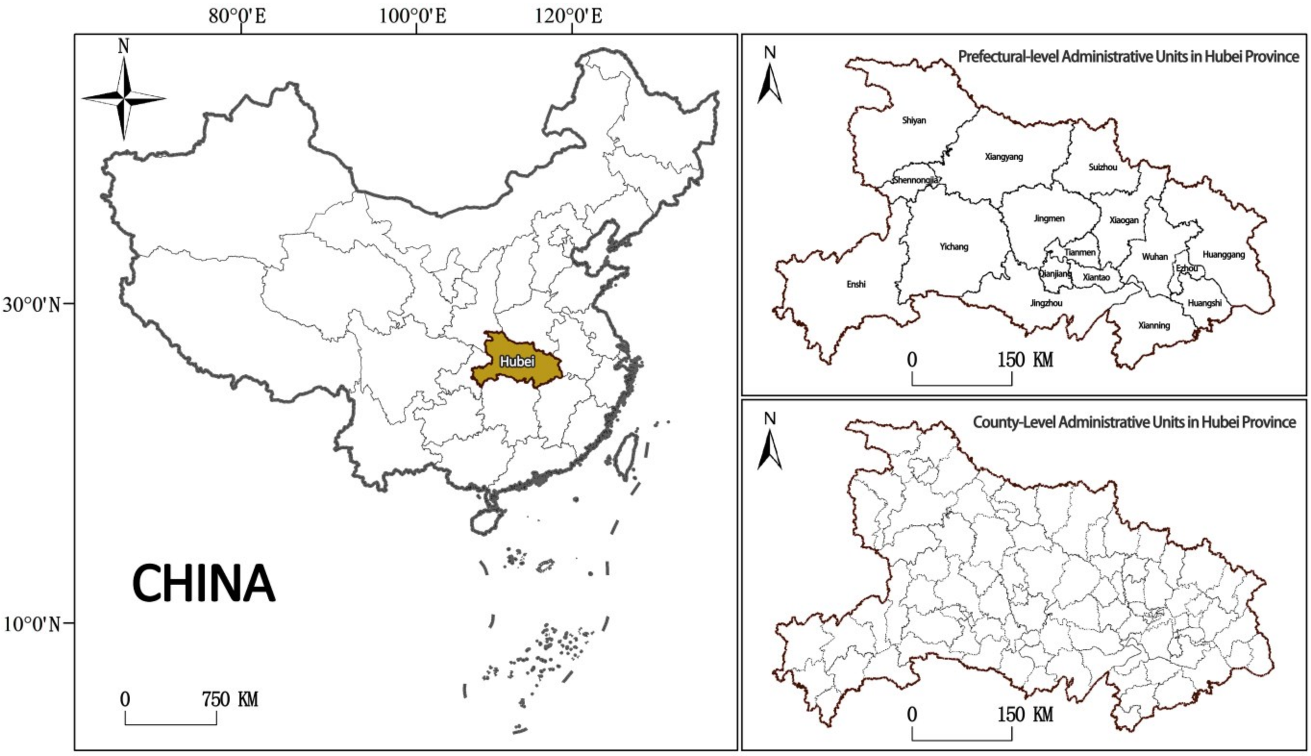



**Figure 1.** Geographical location and distribution range of administrative units in Hubei Province, China.

[Note: The base map is based on the Chinese standard map with the approval number GS (2020) 4619].

## 2.2. Data collection

Population census data from the Hubei Provincial Statistics Bureau's website (http://tjj.hubei.gov.cn/) was utilized. The data includes the 2010 census (sixth nationwide population census) and the 2020 census (seventh nationwide population census) for the county-level administrative units within the WCC. The research focuses on the county-level administrative units under the jurisdiction of the prefecture-level units within the WCC. Consequently, 48 county-level units within the nine prefecture-level units of the WCC were selected for the study (**Figure 2**). These data were collected and organized by national and regional census leading groups collaborating with local authorities over nearly three years, ensuring comprehensive coverage without missing values in the county-level administrative units.

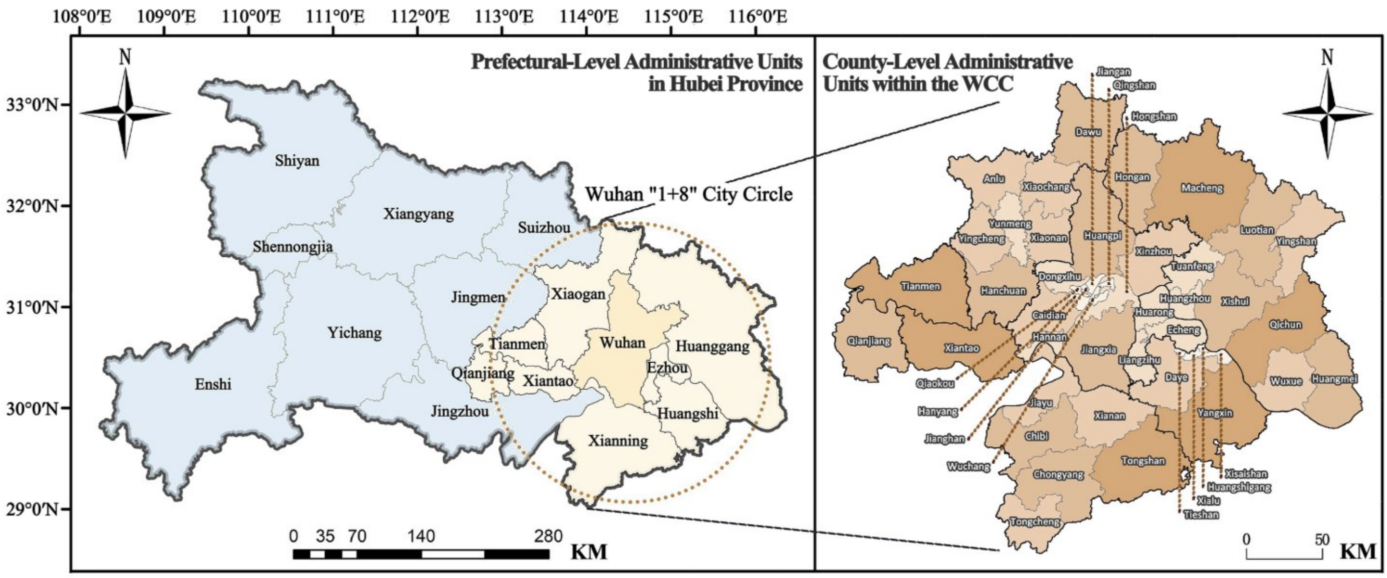



**Figure 2.** Location and scope of the Wuhan "1+8" City Circle, China.

[Note: Projection Coordinate System: WGS 1984 UTM Zone 49N].

The study further prepared and examined various population data types, including total population numbers, population density, population gender ratio, and population age structure. These metrics were analyzed using manual visual methods and data statistics management to ensure accuracy and reliability. In addition, four administrative units—Honghu of Jingzhou, Jingshan of Jingmen, Guangshui of Suizhou, and Jianli of Jingzhou—were excluded as they were observers and not officially part of the WCC.

## 2.3. Design of the study

The study began with computer-aided spatial visualization, which used geographic analysis software to differentiate data at different color levels (symbol system visualization) on a regional scale. The spatial differentiation of color levels reflected the differences in values and distribution of various statistics [77]. After visualizing the demographic data information, this study reveals the pattern of the spatial distribution of the population by using a weighted mean center and standard deviation ellipse.

The formula for calculating the weighted mean center is as follows [78].

$$\bar{X} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \bar{Y} = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

where, $\bar{X}$ and $\bar{Y}$ are the coordinates of the weighted mean center for the feature $i$; $w_i$ is the weight at feature $i$.

The formula for calculating the standard deviation ellipse is as follows [78].

$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{n}}, SDE_y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{Y})^2}{n}} \tag{2}$$

$$\tan\theta = \frac{\left(\sum_{i=1}^{n}\tilde{x}_i^2 - \sum_{i=1}^{n}\tilde{y}_i^2\right) + \sqrt{\left(\sum_{i=1}^{n}\tilde{x}_i^2 - \sum_{i=1}^{n}\tilde{y}_i^2\right)^2 + 4\left(\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i\right)^2}}{2\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i} \tag{3}$$

$$\sigma_x = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}(\tilde{x}_i\cos\,\theta - \tilde{y}_i\sin\,\theta)^2}{n}}, \sigma_y = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{n}(\tilde{x}_i\sin\,\theta + \tilde{y}_i\cos\,\theta)^2}{n}} \quad (4)$$

where, $SDE_x$ and $SDE_y$ denote the form of the standard deviation ellipse; $\tan\theta$ denotes the direction angle when the ellipse is rotated, with the $x$-axis as the base and the noon direction as 0 degrees, clockwise rotation; $\sigma_x$ and $\sigma_y$ denote the standard deviation of the $x$-axis and $y$-axis; $n$ is the total number of the feature $i$; $x_i$ and $y_i$ are the coordinates of the feature $i$; $\tilde{x}_i$ and $\tilde{y}_i$ are the deviations of the $x_i$ and $y_i$ from the weighted mean center.

The study then examined the spatial correlation of the population spatiotemporal data through the Moran's I index. The results were used to identify the relationship between the overall distribution of the population within the WCC in 2010 and 2020. The Moran's I used to provide feedback on the overall correlation between the data elements and determined each spatial element's dependence [79,80]. Moran's I greater than 0 indicated that the spatial elements were positively correlated, with larger values representing more significant overall spatial clustering dynamics; Moran's I less than 0 indicated that the spatial elements were negatively correlated, with smaller values representing more significant overall spatial dispersion dynamics; Moran's I equal to 0 meant that the spatial elements were randomly distributed [81]. The Moran's I is calculated as the following formulation [78].

$$I = \frac{n}{S_0}\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}w_{i,j}z_iz_j}{\sum_{i=1}^{n}z_i^2} \quad (5)$$

$$S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n}w_{i,j} \quad (6)$$

where, $w_{i,j}$ is the spatial weight between element $i$ and $j$; $z_i$ is the deviation of an attribute for element $i$ from its mean $x_i - \bar{X}$; $z_j$ is the deviation of an attribute for element $j$ from its mean $x_j - \bar{X}$; $n$ is equal to the total number of elements; $S_0$ is the aggregate of all the spatial weights.

## 3. Results and discussion

### 3.1. Dynamic variation of population number characteristics

#### 3.1.1. Spatiotemporal trends in the distribution of the population number

Through data collation and statistical analysis, this study revealed that the population of Wuhan increased by 2,541,100 between 2010 and 2020, whereas the population of the WCC only increased by 1,623,400 during the same period. This indicates that the eight prefecture-level units other than Wuhan lost 917,700 people. This loss accounted for 36.11% of Wuhan's new population and 56.53% of the new population in the WCC. These variations suggest that Wuhan's population growth was driven not only by the natural population growth rate but also by the advantages brought by its regional development level, which had a significant siphoning effect on the surrounding population.

Analyzing the spatial distribution of population numbers in 2010 and 2020, an overall east-west oval deviation was observed in both years, indicating that population numbers were more significant in the east-west direction than in the north-south direction. The weighted average center of population was in Hongshan of Wuhan (**Figure 3**). The fastest growth in total population numbers occurred in Hongshan, where the population was 1,390,300 in 2010 and increased by 1,394,900 between 2010 and 2020, more than doubling over the ten years (**Figure 4**). This rapid growth suggests a pronounced population siphoning effect in Hongshan [82]. Conversely, one of the fast decline unit in total population was observed in Xishui of Huanggang, known on the internet as “a large working county [83].”

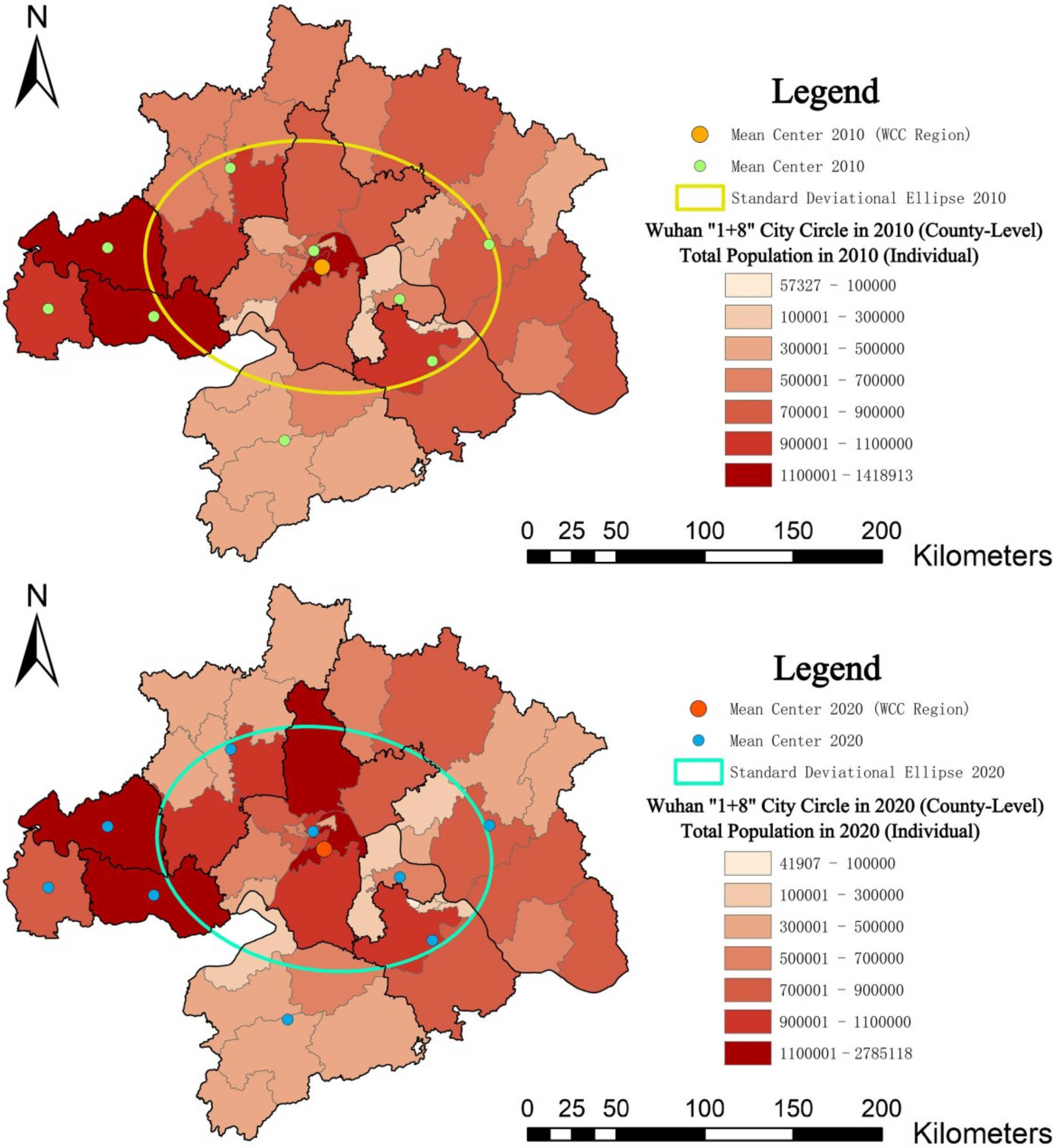



**Figure 3.** Population number distribution of the Wuhan “1+8” City Circle in 2010 and 2020.

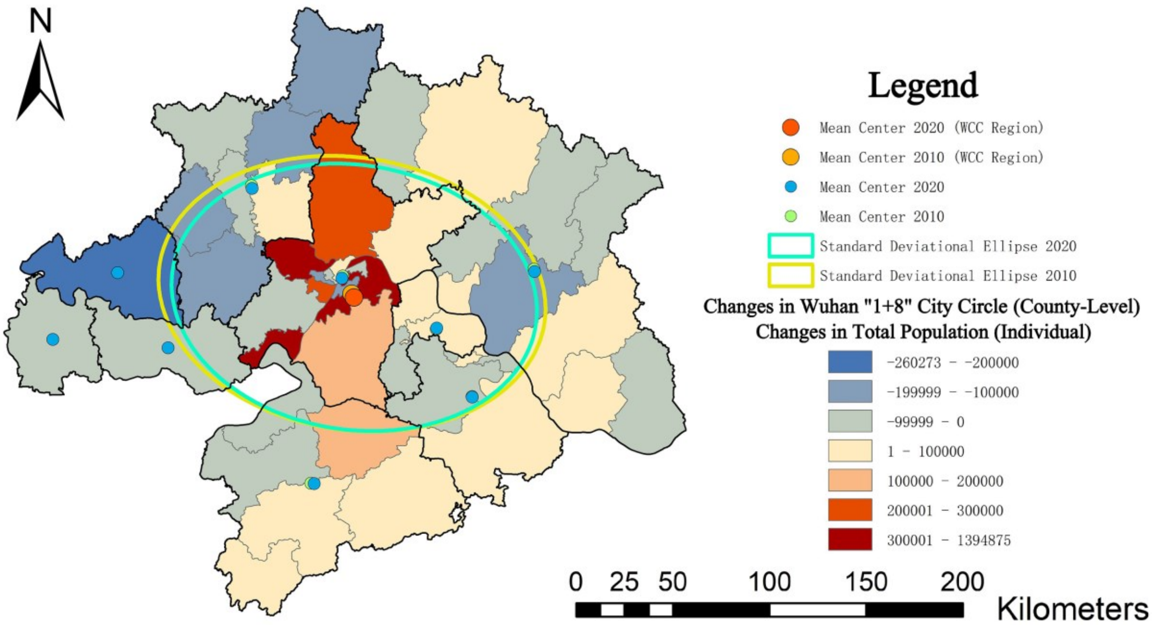
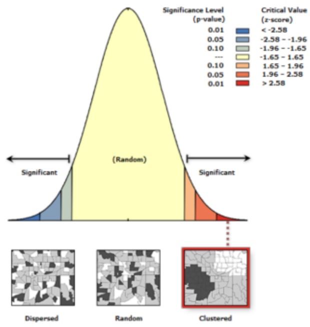
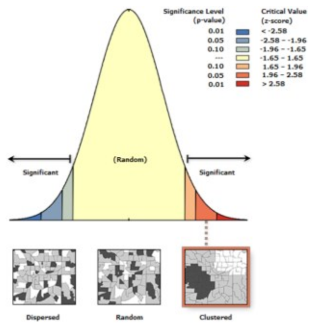



**Figure 4.** Population number variation of the Wuhan "1+8" City Circle from 2010 to 2020.

### 3.1.2. Spatial relations of population number in the county units of regions

The spatial autocorrelation results based on geospatial analysis yielded the following conclusions. The Moran's I value decreased from 0.349 to 0.187, with the *p*-value and *z*-value remaining within the 95% confidence interval of the statistical test (**Table 1**). This suggests that the overall regional distribution of the total population in 2010 and 2020 exhibited a clustering pattern, although the significance of this clustering has diminished over time. This significant decrease indicates an expanding dispersion of population numbers in the WCC over the past ten years.

**Table 1.** Moran's I result for the population number of the Wuhan "1+8" City Circle.

| Year | Moran's *I* | *E*-Value | Variance | *Z*-Value | *P*-Value | Spatial relation |
|---|---|---|---|---|---|---|
| 2010 | 0.349049 | -0.021277 | 0.011145 | 3.507840 | 0.000452 |  |
| 2020 | 0.187402 | -0.021277 | 0.008330 | 2.286385 | 0.022232 |  |

## 3.2. Dynamic variation of population density characteristics

### 3.2.1. Spatiotemporal trends in the distribution of the population density

The spatial distribution of population density in 2010 and 2020 showed an overall east-west elliptical deviation in both years (**Figure 5**), indicating that population density was more significant in the east-west direction than in the north-south direction. Population density changes revealed that Hongshan of Wuhan and Hanyang of Wuhan experienced the fastest growth in population density (**Figure 6**). These areas reflected rapid changes due to the siphoning effect of population migration in addition to natural population growth. Conversely, Jianghan of Wuhan, Qiaokou of Wuhan, and Wuchang of Wuhan were regions with the fastest decreasing population density. Additionally, some areas in the western and eastern parts of the WCC experienced varying degrees of population density reduction, while certain northern and southern regions showed increases in population density.

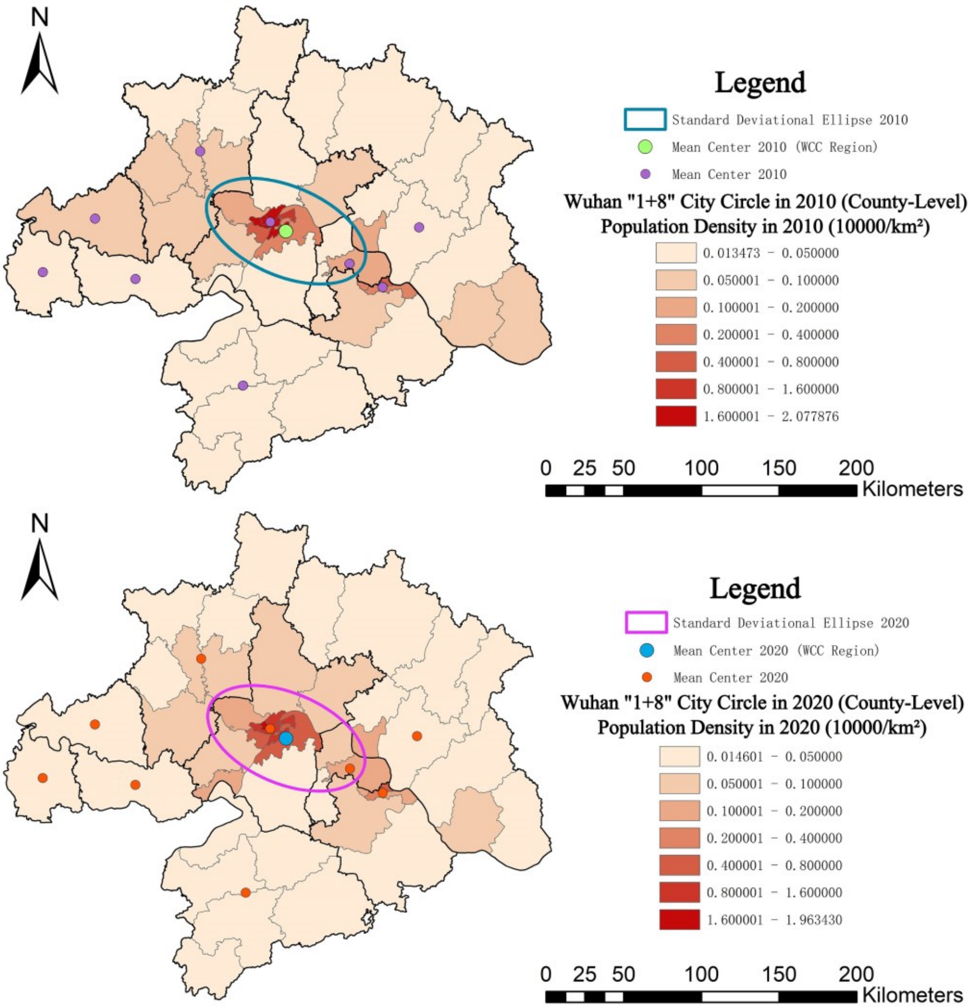



**Figure 5.** Population density distribution of the Wuhan "1+8" City Circle in 2010 and 2020.

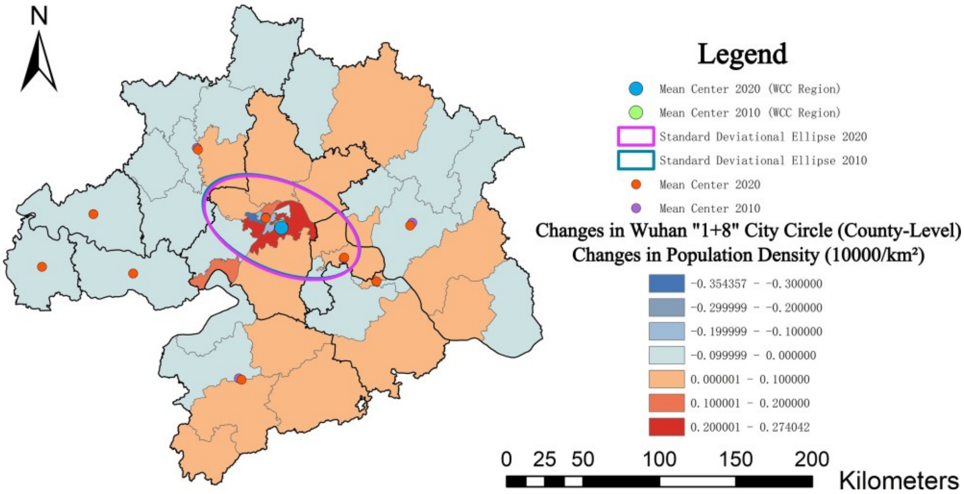
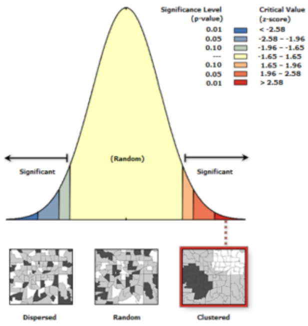
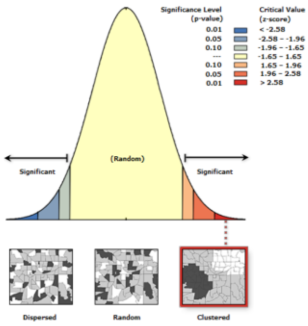



**Figure 6.** Population density variation of the Wuhan "1+8" City Circle from 2010 to 2020.

#### 3.2.2. Spatial relations of population density in the county units of regions

The spatial autocorrelation results for population density revealed continuous changes over the past decade. Moran's I increased from 0.502 to 0.569, with the p-value and z-value within the 99% confidence interval of the statistical test (**Table 2**). This indicates that the overall regional distribution of population density in 2010 and 2020 showed a general clustering trend, with the significance of this clustering increasing over time. This suggests that Wuhan has developed a more regular and centered high-value density clustered, attracting populations from other nearby regions within the WCC.

**Table 2.** Moran's I result for the population density of the Wuhan "1+8" City Circle.

| Year | Moran's I | *E*-value | Variance | *Z*-value | *P*-value | Spatial relation |
|---|---|---|---|---|---|---|
| 2010 | 0.502251 | −0.021277 | 0.009699 | 5.315880 | 0.000000 |  |
| 2020 | 0.568892 | −0.021277 | 0.009961 | 5.913225 | 0.000000 |  |

### 3.3. Dynamics variation of population structure characteristics

#### 3.3.1. Spatiotemporal trends in the distribution of the gender structure

The spatial distribution of the population gender structure in 2010 and 2020 showed that all regions within the WCC had a higher proportion of males than females, except for Jiang'an of Wuhan and Huangshigang of Huangshi, where the proportion of females was higher (**Figure 7**). The overall change in population gender structure from 2010 to 2020 exhibited a north-south elliptical deviation (**Figure 8**), indicating that changes were more significant in the north-south direction than in the east-west direction.

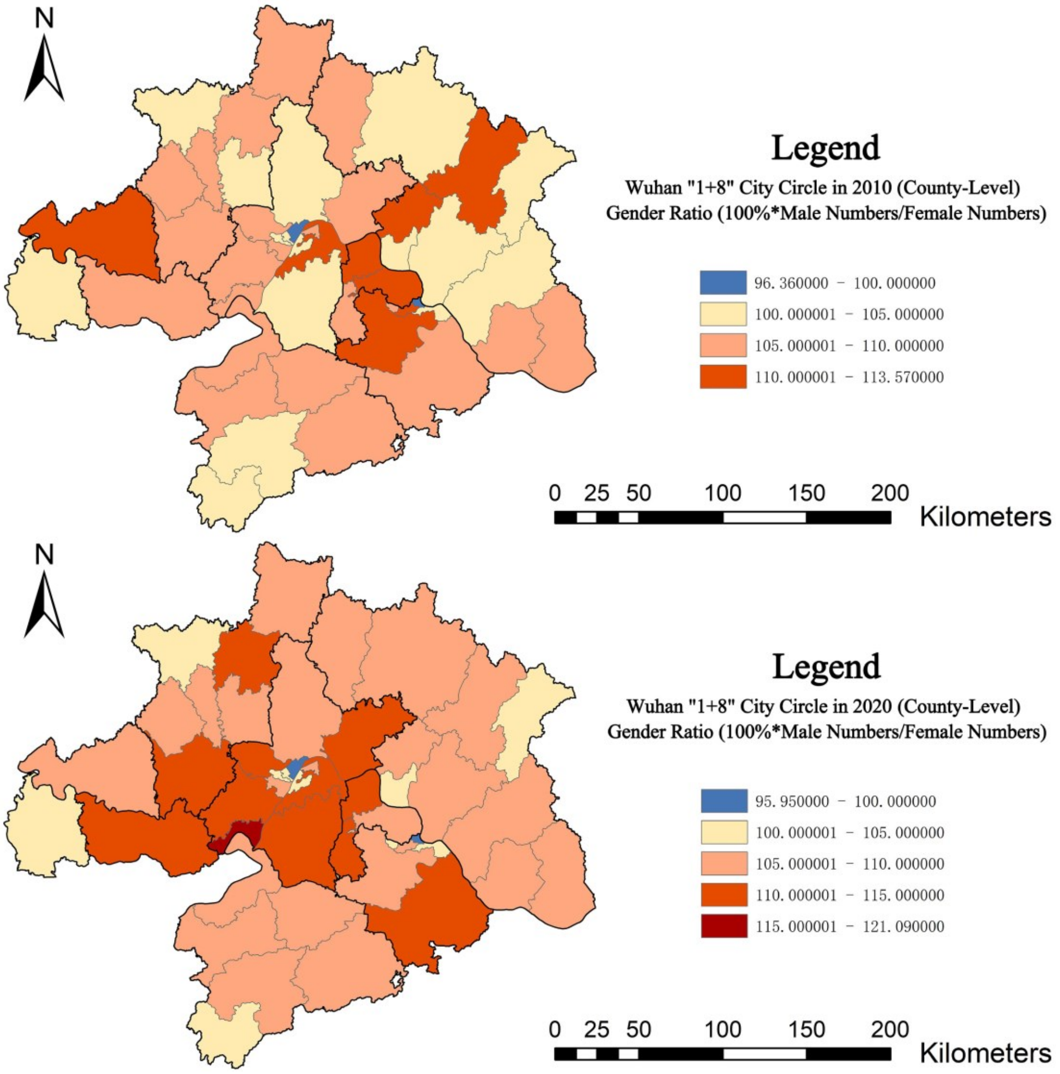



**Figure 7.** Gender structure distribution of the Wuhan "1+8" City Circle in 2010 and 2020.

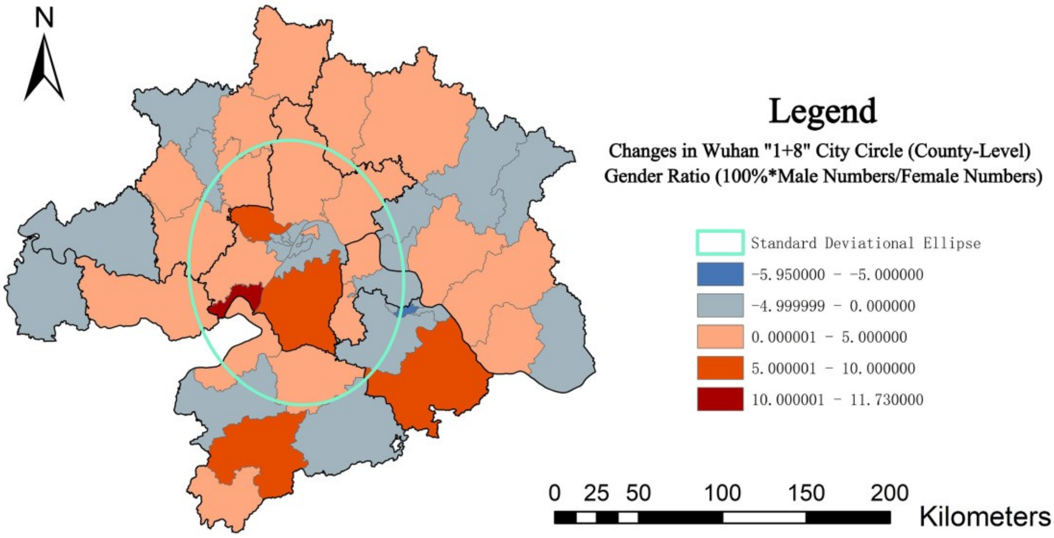



**Figure 8.** Gender structure variation of the Wuhan "1+8" City Circle from 2010 to 2020.

The regions of Dongxihu of Wuhan, Hannan of Wuhan, Jiangxia of Wuhan, Chongyang of Xianning, and Yangxin of Huangshi experienced an overall increase in the proportion of males from 2010 to 2020. This rise in Dongxihu, Hannan, and Jiangxia is likely influenced not by differences in the birth sex ratio but by population movement and migration affecting the gender structure. The presence of many industrial parks in Dongxihu, Hannan, and Jiangxia may have attracted more male laborers from surrounding regions due to labor shortages in these areas. Conversely, Echeng of Ezhou and Luotian of Huanggang showed an increase in the proportion of females. This change is less likely due to natural population growth differences and more likely a result of the loss of the male population due to the siphoning effect of Wuhan. This aligns with the social phenomenon in rural China, where "men would leave their homes to work outside while women remained behind to take care of the household in the past." Therefore, the characteristic changes in the population structure of the WCC were likely to be affected by the regional migration of the labor force caused by the Wuhan siphon effect.

#### 3.3.2. Spatiotemporal trends in the distribution of the age structure

The spatial distribution of the population age structure in 2010 and 2020 indicates that the age weights of the 0–14 and 65+ age groups are increasing, while the age weight of the 14–65 age group is decreasing (**Figure 9**). This suggests a decline in the labor force age group in 2020 compared to 2010. Most regions within the WCC experienced an increase in the 0–14 age group, ranging from 0 to 5 percent, and an increase in the 65+ age group by 5 percent or more from 2010 to 2020. These results highlight a significant aging trend in the WCC population over the decade [84]. The reduction in the proportion of the 65+ age group in Hannan of Wuhan may be attributed to the influx of a large labor force in the area, as it is home to numerous factories and industrial parks that require a substantial number of young and middle-aged workers (**Figure 9i**).

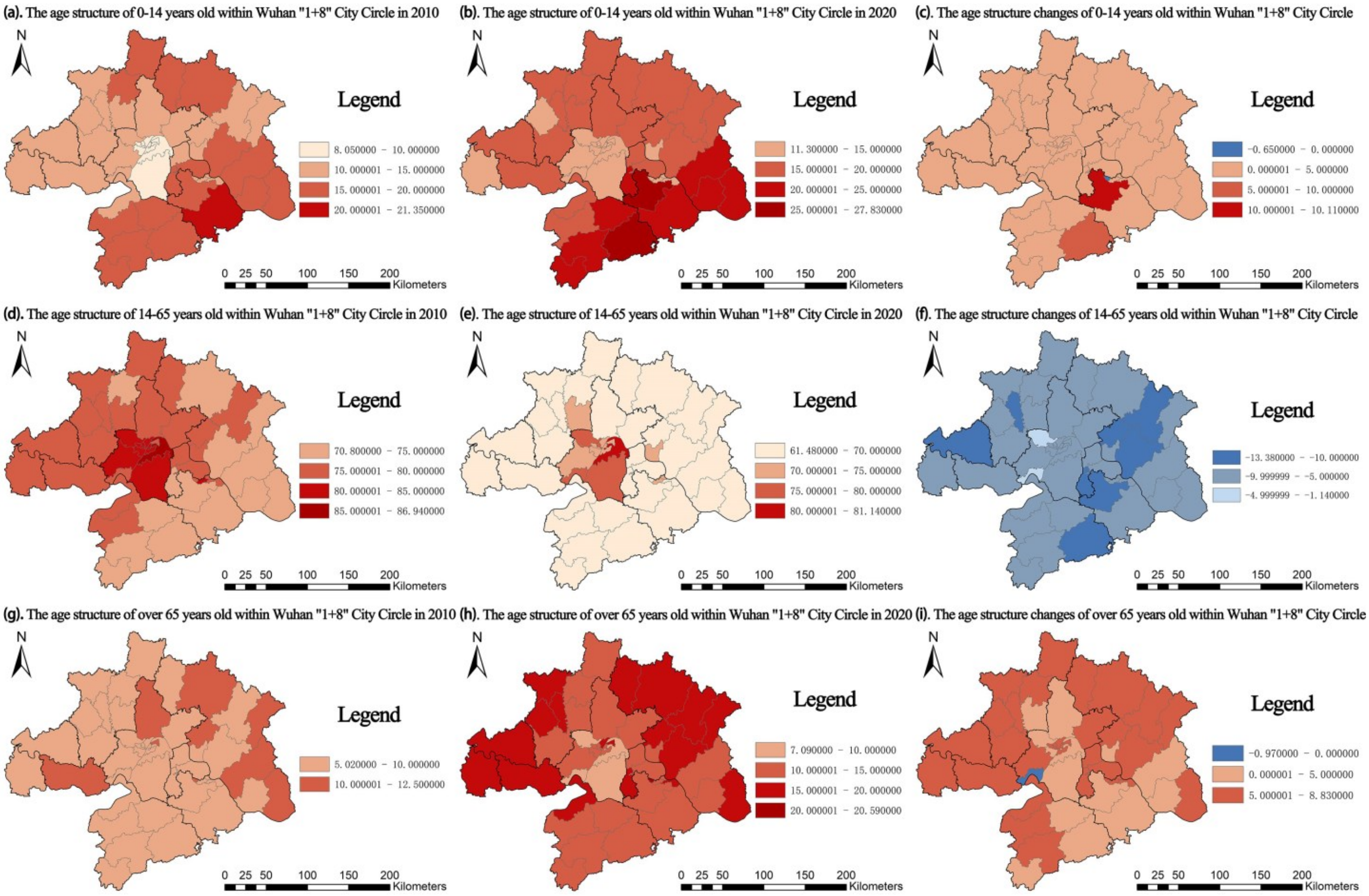



**Figure 9.** Age structure distribution and changes of the Wuhan "1+8" City Circle in 2010 and 2020.

## 4. Conclusion

As the core city of the WCC and the capital of Hubei Province, some units of Wuhan have seen significant population growth driven by natural increases and a pronounced population siphoning effect. Among the WCC's administrative units, Hongshan has experienced the most noticeable siphoning effect. This effect is further supported by the rapid development of the Donghu High-tech Zone in Hongshan, which continues to attract talent. The success of policies such as talent recruitment, the establishment of high-tech industrial parks, and initiatives to retain college graduates have contributed to this trend, enhancing the ability of Hongshan to attract population migration.

The analysis of population and population density from 2010 to 2020 reveals distinct trends. While the total population across the WCC shows a dispersal pattern, the population density has continued to cluster, with this clustering becoming more pronounced over the decade. This indicates that the WCC has evolved into a population magnet centered around Wuhan, with Wuchang and Hongshan emerging as crucial areas influencing this population siphoning effect. Regarding gender distribution, the WCC's overall structure reflects national trends, with a higher proportion of men compared to women. However, Jiang'an and Huangshigang are exceptions, where the proportion of females surpasses that of males. This disparity suggests that industrial parks in more remote areas of Wuhan may attract more male laborers, while the service-oriented industries in Hongshan may draw more female workers.

Looking ahead, the WCC should continue refining and implementing policies to address the challenges posed by the population siphoning effect and ensure sustainable development. To better manage and adapt to evolving demographic trends, the WCC must focus on regional coordinated development, improving the population age structure, and enhancing data monitoring. Specifically, local authorities should optimize development strategies for regions experiencing significant population siphoning, such as Hongshan and Wuchang, and promote balanced regional growth. Policies encouraging childbirth and supporting family-friendly environments are essential to address the declining working-age population. Investment and construction in elderly care services and facilities should be increased to meet the aging population's needs. Finally, establishing a robust system for monitoring and forecasting population trends will enable timely policy adjustments and effective responses to demographic changes.

**Author contributions:** Conceptualization, WL, ZG and JX; methodology, WL, DW and JX; software, WL and DW; validation, ZG and JX; formal analysis, WL and DW; investigation, JX, CZ and YX; resources, CZ and YX; data curation, WL and JX; writing—original draft preparation, WL, ZG, DW and JX; writing—review and editing, WL, ZG, DW and JX; visualization, WL, ZG, DW and JX; supervision, DW and JX; project administration, DW and JX; funding acquisition, JX. All authors have read and agreed to the published version of the manuscript.

**Data availability statement:** All the data for this study is available upon request to the author.

**Conflict of interest:** The authors declare no conflict of interest.

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