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Spatiotemporal Dynamics and Driving Forces of Land Urbanization in the Yangtze River Delta Urban Agglomeration

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Abstract: Land urbanization is a comprehensive mapping of the relationship between urban production, life and ecology in urban space and a spatial carrier for promoting the modernization of cities. Based on the remote sensing monitoring data of the land use status of the Yangtze River Delta urban agglomeration collected in 2010 and 2020, the spatial differentiation characteristics and influencing factors of land urbanization in the area were analyzed comprehensively using hot spot analysis, kernel density estimation, the multi-scale geographically weighted regression (MGWR) model and other methods. The results indicated the following: (1) From 2010 to 2020, the average annual growth rate of land urbanization in the Yangtze River Delta urban agglomeration was 0.50%, and nearly 64.28% of the counties had an average annual growth rate that lagged behind the overall growth rate. It exhibited dynamic convergence characteristics. (2) The differentiation pattern of land urbanization in the Yangtze River Delta urban agglomeration was obvious from the southeast to the northwest. The hot spots of land urbanization were consistently concentrated in the southeastern coastal areas and showed a trend of spreading, while the cold spots were concentrated in the northwest of Anhui Province, showing a shrinking trend. (3) Compared with the GWR model and the OLS model, the MGWR model has a better fitting effect and is more suitable for studying the influencing factors of land urbanization. In addition, there were significant spatial differences in the scale and degree of influence of different influencing factors. Analyzing and revealing the spatiotemporal characteristics and driving mechanism of land urbanization in the Yangtze River Delta urban agglomeration has important theoretical value and practical significance for the scientific understanding of new-type urbanization and the implementation of regional integration and rural revitalization strategies.

Keywords: land urbanization; new-type urbanization; rural revitalization; multi-scale geographically weighted regression (MGWR); Yangtze River Delta urban agglomeration

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Citation: Zhu, H.; Ou, X.; Yang, Z.; Yang, Y.; Ren, H.; Tang, L. Spatiotemporal Dynamics and Driving Forces of Land Urbanization in the Yangtze River Delta Urban Agglomeration. *Land* **2022**, *11*, 1365. https://doi.org/10.3390/land11081365

Academic Editors: Wei Sun, Zhaoyuan Yu, Kun Yu, Weiyang Zhang and Jiawei Wu

Received: 14 July 2022
Accepted: 18 August 2022
Published: 21 August 2022

1. Introduction

Urbanization is a product of the industrialization era, including major changes in economic structure, production methods, lifestyles and land use methods. It is also the result of the long-term accumulation of population aggregation and urban construction [1–5]. Unlike the urbanization development of developed countries in Europe and America, China's urbanization realized the 200-year development process experienced by developed countries in Europe and America in more than 40 years [6,7]. China's urbanization is based on the top-level design under the growth model. Especially after entering the 1990s, due to the expectation of China's rapid development and the eagerness to achieve success in the actual command process, the decision-making level often excessively promoted urbanization, with a focus on the digital and physical dimensions of economic growth and spatial expansion [6,8,9]. The urban built-up area caused by the rapid expansion of urban space will become larger and larger, leading to incurable urban diseases, and some "empty cities" and "ghost towns" are likely to appear in the future. Urban planning should gradually shift from expansionary planning to limiting urban development boundaries and optimize the planning of the space structure [8,9]. Land urbanization, as the concrete manifestation of urbanization in space, is mainly manifested in the transformation of agricultural land into urban construction land, which has become the focus of both scholars and the government [10–12]. According to the statistics of the *China Urban Construction Statistical Yearbook*, from 2010 to 2020, the area of urban construction land in China increased from 39,758.4 km^2 to 58,355.3 km^2, an increase of 46.77%. However, the rapid development of urbanization and the disorderly spread of urban land have been criticized, and they have been repeatedly banned in various places. As a result, the conflict between urban production space (it is a specific functional area where people engage in production activities), living space (it is the space for people's daily life activities) and ecological space (it is a regional space with an ecological protection function that can provide ecological products and ecological services) [13] has become increasingly intensified, posing a threat to the sustainable development of cities [14–16]. China's urbanization problem is more complicated. On the one hand, the leverage force caused by the difference in land rent makes the relatively low suburban prices the main attraction of urban spatial development, which leads to the disorderly extension of urban boundaries without an effective control mechanism [17]. On the other hand, the deep reasons are the financial decentralization and the performance appraisal system aiming at economic growth under China's long-term urban–rural dual system [18]. Under the influence of multiple internal and external factors, the long-term unequal exchange of capital, land, labor and other elements between urban and rural areas makes the urban land expansion rate ahead of the urban population growth rate a common disease in most cities [19]. In November 2019, the General Office of the Central Committee and the General Office of the State Council issued the "Guiding Opinions on the Overall Delineation and Implementation of Three Control Lines in National Land and Spatial Planning", which clearly stated that the three control lines of urban development boundaries, permanent basic farmland and ecological protection red lines should be adjusting the economic structure, planning the development of the industry and promoting the insurmountable red line of urbanization [20]. Under the strong control of the three major land and space red lines, the urban development path that traditionally relies on the disorderly expansion of extension space will be well controlled [21].

With the advent of the era of global cities, the development of each city does not exist in isolation. The flow of people, logistics, information and capital connects different cities in the process of spatial flow [22]. Urban agglomeration has become the main form of urbanization development, with a high level of land urbanization [23,24]. Scholars from home and abroad have conducted much research on the pattern of land use change in urban agglomerations and metropolitan areas. Bosch et al. [25] explored the spatial and temporal patterns of land use change in three Swiss urban agglomerations through landscape indicators and growth patterns; Wu et al. [26] performed a comparative analysis of the metropolitan regions of Phoenix and Las Vegas and revealed that, throughout the twentieth century, the two agglomerations showed a strikingly similar trend towards a landscape that is more diverse in land use, fragmented in structure and complex in shape; Dutta et al. [27] used geospatial indices to explore the dynamics of urban expansion in the English Bazar Urban Agglomeration, revealing that the northwest and southwest parts of the English Bazar UA are experiencing a rapid increase in sprawl. Li et al. [28] used mathematical statistics and spatial analysis methods to analyze the change process of urbanization, coupling co-scheduling and ecological risk response pattern in the Yangtze River Delta, and found that the coupling coordination degree of population, land and economic urbanization in the Yangtze River Delta is increasing, and the ecological risk is weakening. Niu et al. [29] studied the evolution of the interactive relationship between urbanization and land use transformation in the Yangtze River Delta and found that rapid urbanization exacerbates the trend of land fragmentation, promotes the rapid expansion of construction land and hinders the further development of urbanization. The Yangtze River Delta urban agglomeration is one of the regions with the most active economic development, the highest level of urbanization and the greatest degree of land development in China. It has consistently been a major focus among academics both domestically and internationally [30,31]. Revealing the spatial and temporal evolution patterns and influencing factors of land urbanization in the Yangtze River Delta urban agglomeration is of great significance in guiding the healthy development of urbanization in other urban agglomerations and similar regions in China and the world and in promoting the sustainable development and utilization of urban land resources.

Among the relevant research progress at home and abroad, scholars' attention and discussion regarding land urbanization mainly focus on three aspects. The first aspect is the concept definition and measurement evaluation of the land urbanization level. Scholars have interpreted the concept of land urbanization from the perspectives of land use form transformation [32] and the nature of rights [33]. Li et al. [34] pointed out that the definition of the connotation of land urbanization should serve the coordination and matching relationship between land urbanization and population urbanization. For the calculation of the level of land urbanization, the single index method (the proportion of construction land or built-up area to the total area) [35,36] and the other composite index method (the quality of land urbanization) [37] are widely used. Some scholars also measured the process of land urbanization from the aspects of land structure, input and output [29,38,39]. The second aspect is the research on the coordination relationship between land urbanization and population urbanization and its regional differences [40]. There is a consensus that land urbanization is ahead of population urbanization on a national scale, but this unbalanced relationship appears in different regions or cities [41]. Some scholars found that the coupling relationship between land and population urbanization has periodic characteristics [42,43]. In recent years, the imbalance between the two has eased, and some areas have even developed land. Urbanization lags behind the trend of population urbanization [44]. The third aspect is research on the driving mechanism of land urbanization. China's specific fiscal decentralization and dual urban–rural land management system are recognized as the fundamental driving forces of land urbanization [45,46]. However, from the perspective of "human–land coordination", factors such as natural geographical conditions (including terrain conditions and annual precipitation) and social and economic development (including economic development and social basic conditions) [47] can also explain the changes in the spatial pattern of land urbanization to a certain extent. Zhou et al. [48] addressed the impact of population, economy, social public services and space on rural in situ urbanization in the Beijing–Tianjin–Hebei region. Gao et al. [49] revealed the impact of six major influencing factors, foreign direct investment (FDI), labor force, government competition, system, population and the employment housing relationship, on urban land expansion in the Yangtze River Delta. Traditional correlation analysis [50], multiple regression analysis [51] and principal component analysis [52] have often been used in the study of driving factors, but they ignore the regional differences between research units, and it is difficult to characterize the spatiality of the data fully.

Academic research has expanded the multi-dimensional perspective of land urbanization analysis, which is of great significance for profoundly understanding the pattern of land urbanization and its driving forces and then optimizing the pattern of urban and rural land use [53–55]. Most of the existing studies established global models based on statistical data and failed to consider the spatial heterogeneity and non-stationarity within the study area [47,56,57]. Furthermore, the spatial variation characteristics and spatial distribution rules of the research objects cannot be reflected, resulting in strong universality and insufficient pertinence of the policy recommendations proposed by the research. Urban agglomerations are the main body of urbanization [58]. They play an important role in optimizing the urban spatial structure, promoting the construction of new urbanization and promoting the development of regional integration [59,60]. However, according to the current research progress, the systematic research on the development dynamics, spatial pattern and formation mechanism of land urbanization in urban agglomerations is still insufficient [36,48,49]. The 19th National Congress of the Communist Party of China also clearly proposed that the urban agglomeration should be the main body with which to build an urban pattern of coordinated development for large, medium and small cities and small towns [61]. Therefore, based on the remote sensing monitoring data of China's land use status, this paper quantitatively analyzes the spatiotemporal characteristics and formation mechanism of land urbanization in the Yangtze River Delta urban agglomeration in order to deepen the theoretical research on rural geography and land use and to promote urban–rural integration and provide a new scientific basis for strategic decisions such as those regarding urbanization.

This study aims to reveal the spatiotemporal dynamics of land urbanization in the Yangtze River Delta urban agglomeration and explore its driving mechanism. This article is divided into five sections. Section 2 presents the study area, study methodology and data sources. The Section 3 introduces the spatiotemporal dynamics of land urbanization in the Yangtze River Delta urban agglomeration from 2010 to 2020, and the Section 4 discusses the multi-scale effects and spatial heterogeneity of different influencing factors based on the MGWR model. Section 5 compares key findings with previous research, makes policy recommendations and provides a brief conclusion.

2. Materials and Methods

2.1. Study Area

The Yangtze River Delta urban agglomeration is an important intersection between the "Belt and Road" and the Yangtze River Economic Belt. It has a pivotal strategic position in the overall situation of China's national modernization and development. It is an important platform allowing China to participate in international competition, an important engine for economic and social development. The center of the Yangtze River Economic Belt is also one of the regions with the best urbanization foundation in China. The study area falls within the scope of the central area delineated by the "Outline of the Yangtze River Delta Regional Integrated Development Plan" issued by the Central Committee of the Communist Party of China and the State Council in December 2019, including 9 cities in Jiangsu Province (Nanjing, Suzhou, Wuxi, Changzhou, Zhenjiang, Yancheng, Nantong, Yangzhou, Taizhou), 9 cities in Zhejiang Province (Hangzhou, Jiaxing, Shaoxing, Ningbo, Jinhua, Huzhou, Zhoushan, Taizhou, Wenzhou), 8 cities in Anhui Province (Hefei, Maanshan, Wuhu, Tongling, Anqing, Chuzhou, Xuancheng and Chizhou) and Shanghai. The Yangtze River Delta urban agglomeration has a total area of 223,800 km^2 and a population of approximately 225 million. The topographic features of the Yangtze River Delta urban agglomeration are high in the southwest and low in the northeast, with an elevation range of −83.31~1736.98 m (Figure 1), including a total of 127 counties. Due to the incompleteness of the land use remote sensing monitoring data of Shengsi County, it was omitted from the study, and the study area thus included 126 counties.

2.2. Data Sources

The research used the urban and rural construction land (including towns, industrial and mining areas, rural settlements, transportation and other construction land) in the remote sensing monitoring data of China's land use status collected in 2010 and 2020, mainly from the Resource and Environment Data Center of the Chinese Academy of Sciences, covering 30 m across the country. We constructed a spatial distribution map of land use types with high resolution. The socioeconomic data required for the analysis of influencing factors came from the 2011 and 2021 *China Counties Statistical Yearbook* (County and Cities volume). The population density data came from the WorldPop population dataset (https://www.worldpop.org/ accessed on 10 January 2022); the average annual precipitation, DEM and other data were also from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn accessed on 10 January 2022), and density of roads data came from OpenStreetMap.

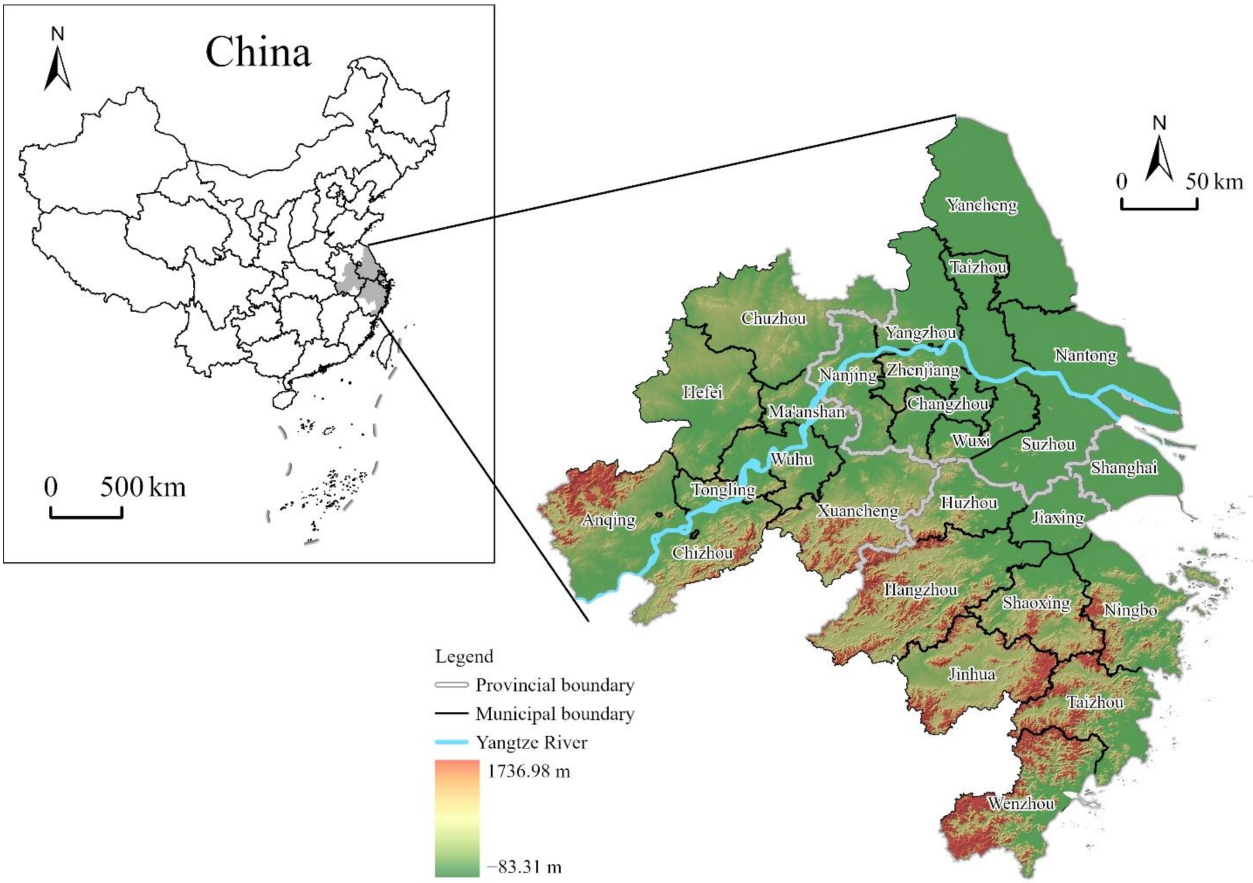

Figure 1. Location of the study area.

2.3. Methods

(1) Land Urbanization Evaluation Index

With reference to the land non-agriculturalization index [62] and the quality of land urbanization [37], the index of land urbanization rate (LUR) in the counties of the Yangtze River Delta urban agglomeration was constructed, i.e., the ratio of urban industrial and mining land and transportation land to the total scale of urban and rural construction land. The indicators not only describe the level of land urbanization, but also reflect the changes in the land use structure in the process of county urbanization [57]. The formula is as follows:

$$LUR = \frac{ul + il + tl}{ul + il + tl + rl} \quad (1)$$

where ul is the scale of urban land, il is the scale of industrial and mining land, tl is the scale of transportation land and rl is the scale of rural residential land. Based on the spatial analysis function of ArcGIS Pro 2.8 software (https://www.esri.com/zh-cn/arcgis/products/arcgis-pro/trial (accessed on 10 January 2022)), the land urbanization pattern of each county in the Yangtze River Delta urban agglomeration from 2010 to 2020 was visualized.

(2) Spatial Autocorrelation Analysis

Spatial autocorrelation analysis can reveal the spatial distribution of a single attribute of the research object and quantitatively measure its correlation degree [63]. The global spatial autocorrelation, which uses Moran's I index [64], was used to identify whether the spatial distribution of land urbanization in the Yangtze River Delta urban agglomeration had spatial agglomeration; the local correlation analysis used the "local Getis-Ord's index" [65]. The cold spots and hot spots of land urbanization in the Yangtze River Delta urban agglomeration were identified, and the conceptualization of spatial relationships was set with CONTIGUITY_EDGES_CORNERS.

(3) Kernel density estimation

Kernel density estimation is a non-parametric estimation method [66,67] that uses continuous density function curves to describe the distribution of random variables. Kernel density estimation uses a smooth peak function to fit the sample data and uses a continuous density curve to describe the distribution of random variables, which has the advantages of weak model dependence and strong robustness. In this study, epanechnikov was selected as the kernel function, and the bandwidth was 0.0749.

(4) Index selection and model construction of influencing factors

Considering the particularity of land urbanization in the Yangtze River Delta urban agglomeration in the process of development and the availability of data, LUR was used as a dependent variable, and the population size, economic level, social basic conditions and natural environment were analyzed separately. We selected variables to build a model to explore the main influencing factors of land urbanization in the counties of the Yangtze River Delta urban agglomeration (Table 1, Figure 2). The selection of variables was mainly based on the following assumptions. ① Economic development can effectively increase the income of urban residents, improve urban living conditions and stimulate the transfer of agricultural populations to urban areas, thereby increasing the demand for urban residential, industrial, transportation and other construction land and increasing the demand for land urbanization. It leads to positive promotion [68,69]. ② Social basic conditions, the soft infrastructure of urbanization, are closely related to the lives of urban residents. Social public service mainly guides the development of urban land space by attracting the population, thereby promoting the expansion of urban residential land [48,70]. ③ Population growth in counties is the main source of demand for urban land [71,72], and the larger the population scale, the higher the level of land urbanization [49,71–73]. ④ A good natural environment should be able to better meet the expansion needs of urban construction land and contribute to the process of land urbanization [74,75]. Due to the stability of the model and the difficulty of data collection, the year 2020, with better timeliness, was used to study the influencing factors of land urbanization.

Table 1. Indicators to analyze the driving factors of LUR.

Type	Symbol	Variable	Definition
Economy	X1	Per capita GDP	Gross domestic production (GDP)/permanent population
	X2	Proportion of secondary and tertiary industry in GDP	The proportional relationship to indicate the industrial structure of a region
	X3	Fiscal revenue	Budget revenue/GDP
Social basic conditions	X4	Number of healthcare beds	An indicator to indicate the medical level of a region
	X5	Density of roads	Total road mileage/area of district or county
Population	X6	Population density	Permanent population/area of district or county
Natural environment	X7	Topographic relief	Stemming from Feng et al. [76]
	X8	Annual precipitation	In this study, it was believed that the higher the annual average precipitation, the better the natural environment

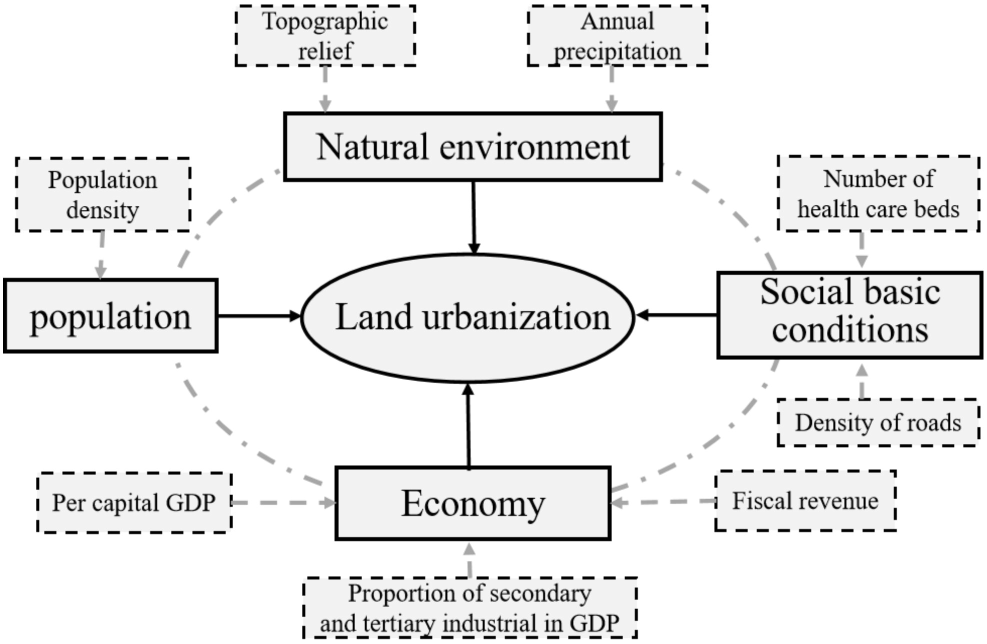

Figure 2. Analysis framework of land urbanization in Yangtze River Delta urban agglomeration.

All independent variables were standardized and tested for multicollinearity using the variance inflation factor (VIF) before running the MGWR model. The larger the VIF value, the greater the multicollinearity [77]. It is generally believed that if the VIF value is greater than 7.5 or the tolerance (the reciprocal of VIF) is closer to 0, it indicates that the multicollinearity is stronger. The VIF value of each index was less than 7.5 (Table 2), indicating no multicollinearity problem among the selected indexes.

Table 2. Influencing factors multicollinearity test.

Variable	X1	X2	X3	X4	X5	X6	X7	X8
VIF	4.776	1.892	2.552	1.704	4.210	4.817	1.110	1.189
Tolerance	0.209	0.529	0.392	0.587	0.238	0.208	0.901	0.841

The greatest difference between the MGWR model and the classical GWR model is the heterogeneity of bandwidth. This improvement is achieved by redefining GWR as in the definition of the generalized additive model (GAM) [78]. Compared with the GWR model, the MGWR model allows each variable to have different spatial smoothing levels. This model is expressed as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{n} \beta_{bwj}(u_i, v_i)x_{ij} + \varepsilon_i \quad (2)$$

where y_i is the LUR of i county, x_{ij} is the nth predictor variable, β_{bwj} is the optimal bandwidth used by the nth variable regression coefficient, (u_i, v_i) is the geographic coordinate of the ith spatial unit centroid, $\beta_0(u_i, v_i)$ is the intercept of the model at i, $\beta_j(u_{i,} v_i)$ is the regression coefficient corresponding to the jth variable of the i space unit, ε_i is the random error term and k is the number of units. The kernel function and bandwidth selection criteria of the MGWR model use the Gaussian function and AICc, respectively, and GAM uses a backward-fitting algorithm to fit each smooth term. We used SOC-f [79] as a convergence criterion with a convergence threshold of 1×10^{-5}.

3. Spatial and Temporal Evolution Pattern of Land Urbanization in Yangtze River Delta Urban Agglomeration

3.1. Land Urbanization Pattern of Yangtze River Delta Urban Agglomeration in 2010

In 2010, the land urbanization rate of the Yangtze River Delta urban agglomeration was 50.49%. According to the stage characteristics of population urbanization and the comprehensive measurement results of China's urbanization level [80–82], the land urbanization level can be divided into five types: low (≤0.1), medium low (0.1~0.3), medium (0.3~0.5), medium high (0.5~0.7) and high (>0.7). As shown in Figure 3, most of the counties in the Yangtze River Delta had a land urbanization level of medium or above, accounting for about 76.19%. Specifically, among the 126 counties in the Yangtze River Delta urban agglomeration, less than 20% had a land urbanization rate greater than 0.7; however, there were medium-low-level and low-level counties, accounting for 20.64% and 3.17%, respectively. The counties with a high land urbanization level were mainly distributed in Zhejiang Province and Jiangsu Province, while the land urbanization rate of most counties in Anhui Province was relatively low, showing a pattern of high in the southeast and low in the northwest. Using the spatial analysis module in ArcGIS Pro 2.8 software, the Moran's I index of the land urbanization rate of the Yangtze River Delta urban agglomeration was calculated to be 0.579, and the z-score was 9.95, $p < 0.01$. After passing the significance test, the hot spot analysis tool was further used to analyze the cold and hot spots of the land urbanization of the Yangtze River Delta urban agglomeration. It showed that the land urbanization of the Yangtze River Delta urban agglomeration presented a significant positive spatial correlation feature, and the hot spots were concentrated in the Shanghai metropolitan area. The areas near Hangzhou, Jinhua and Wenzhou had a high land urbanization level and were surrounded by counties with a high land urbanization level. The cold spot areas were concentrated in Hefei, Chuzhou, Wuhu, Tongling, Chizhou and other cities in Anhui Province. These areas had a relatively low land urbanization level and were surrounded by counties with a low land urbanization level.

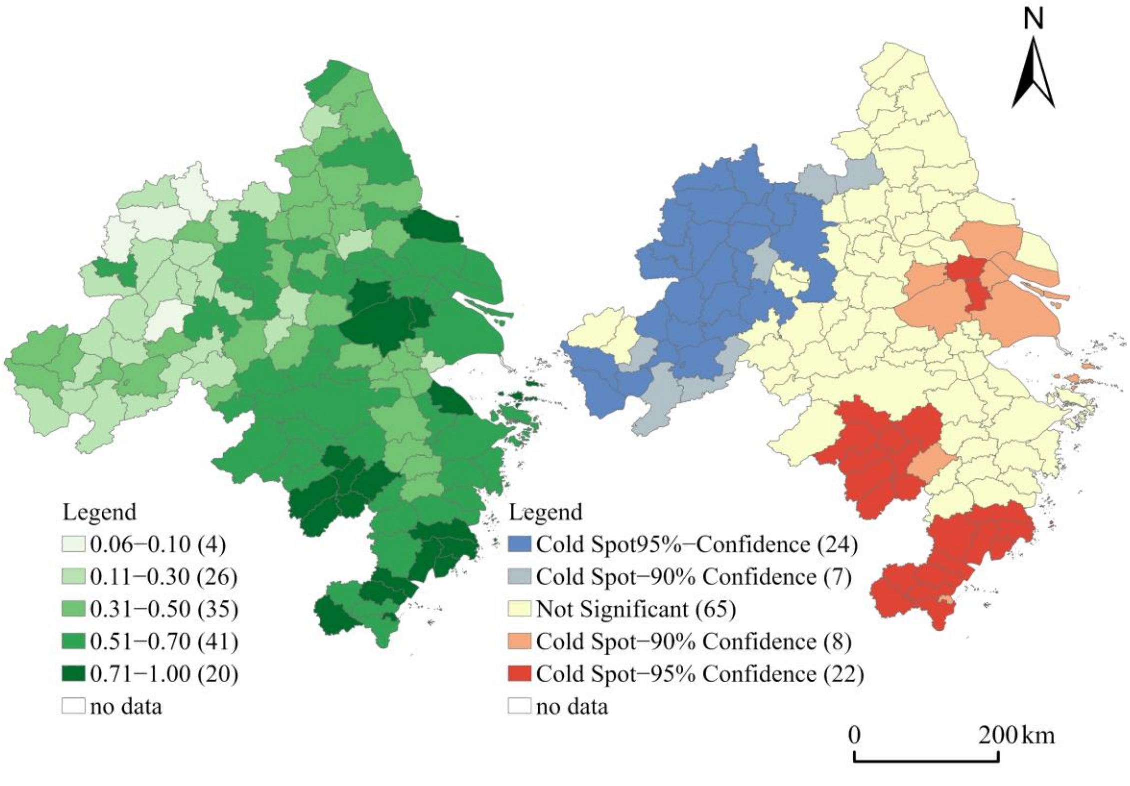

Figure 3. Analysis of land urbanization pattern and hot spots in Yangtze River Delta urban agglomeration in 2010.

3.2. Land Urbanization Pattern of Yangtze River Delta Urban Agglomeration in 2020

In 2020, the land urbanization rate of the Yangtze River Delta urban agglomeration was 55.41%. In 2020, the number of counties with a low or medium low level of land urbanization was reduced from 30 in 2010 to 25; however, the number of counties with a medium or above level reached 81.16%, and those with a land urbanization rate greater than 0.7 accounted for more than 1/4, an increase of 60% compared with 2010 (Figure 4). With the further acceleration of population urbanization, the level of land urbanization also increased correspondingly. Most of the counties in Zhejiang Province and the counties in the south of Jiangsu Province were still high-level areas. The level of land urbanization in some counties in Anhui Province increased significantly, such as in Feixi County, Lujiang County, Anqing City, Chizhou City, Dangtu County and other counties. During this period, for the development of the Yangtze River Delta region, the state proposed a new-type urbanization strategy and regional integration strategy of "coordinating urban and rural development, actively and steadily promoting urbanization", which narrowed the difference in the level of land urbanization between counties to a certain extent. The coefficient of variation for the land urbanization rate dropped from 0.458 in 2010 to 0.423 in 2020. In 2020, Moran's I index was 0.602, and the z-score was 10.32, $p < 0.01$. After passing the significance test and further using the hot spot analysis tool, it was found that the positive spatial correlation characteristics of the urbanization rate of the counties in the Yangtze River Delta urban agglomeration had improved, and the hot spots had further expanded and connected in the southwest of Zhejiang Province; it is worth noting that the hot spots near the Shanghai metropolitan area had reduced, indicating that the land development in this area had gradually become saturated; the number of counties in the cold spot area was reduced from 31 in 2010 to 27 in 2020. The cold spot area in Anhui Province shrank slightly, while Binhai County and Funing County in the north of Jiangsu Province were transformed into cold spots, indicating that the land urbanization rate of these two counties and surrounding counties was growing slowly, lagging behind the land structure adjustment in other regions.

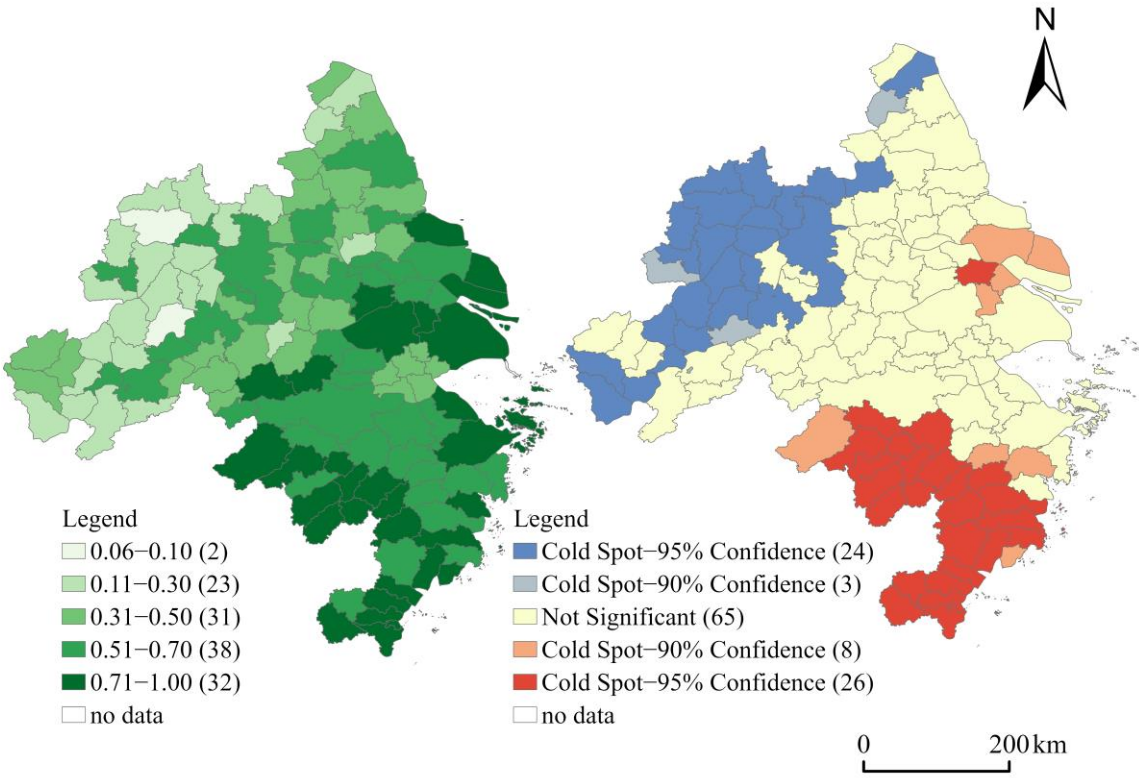

Figure 4. Analysis of land urbanization pattern and hot spots in Yangtze River Delta urban agglomeration in 2020.

3.3. Evolution of Land Urbanization Pattern in Yangtze River Delta Urban Agglomeration

3.3.1. Time Evolution Characteristics

From 2010 to 2020, the overall land urbanization rate of the Yangtze River Delta urban agglomeration increased from 50.49% to 55.41%, with an average annual growth rate of 0.50%. In developed areas, land development takes place earlier than in other, less developed areas, and the potential space for land expansion is limited. Figure 5 is a graph of the urbanization kernel density curve of the Yangtze River Delta urban agglomeration created using the Stata 15 software in order to describe the temporal evolution characteristics of the land urbanization of the Yangtze River Delta urban agglomeration. From the change of the nuclear density curve position, the curve position as a whole shows a trend of rightward migration. From the change of the peak height of the main peak of the curve, it gradually evolves from the broad peak shape to the peak shape; according to the change in the number of peaks in the curve, there is a transition from one main peak and one secondary peak on the left side to a single main peak; according to the curve tailing change, the tailing on the left side and the right side is shortened and raised. A series of changes in the nuclear density curve show that the urbanization rate of urban agglomeration in the Yangtze River Delta showed a continuous upward evolution during the study period; the difference in the level of land urbanization between counties showed a narrowing trend, and the polarization characteristics were weakening. On the whole, the land urbanization rate among the counties of the Yangtze River Delta urban agglomeration was characterized by dynamic convergence.

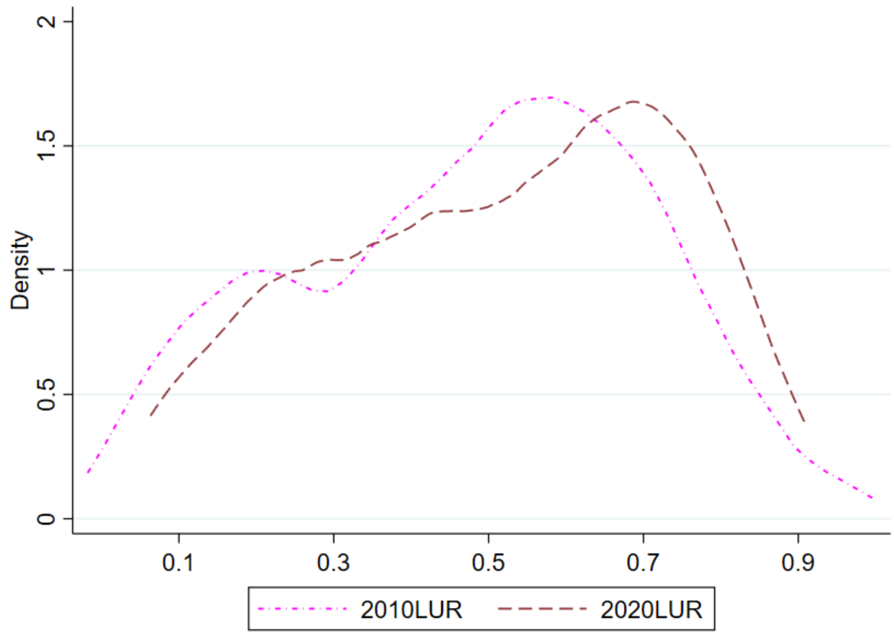

Figure 5. Estimation curve of land urbanization kernel density in Yangtze River Delta urban agglomeration from 2010 to 2020.

3.3.2. Spatial Evolution Characteristics

Referring to the average annual growth of the land urbanization rate in the overall urban agglomeration in the Yangtze River Delta, the growth in the counties was in the range of ≤0, 0~0.5%, 0.5%~1%, 1~2% and >2%. It was divided into five levels of negative growth, low speed, medium speed, high speed and ultra-high speed, and we carried out spatial statistics and Kriging interpolation simulation (Figure 6). The results showed that 64.28% of the counties had an average annual growth rate of land urbanization below 0.5%, which was lower than the regional average growth rate. Among them, the average annual growth rate of 17.46% of the counties was negative. These counties were mainly distributed in Jiangsu Province, and a small number were distributed in the coastal areas of

Zhejiang Province, such as Yuhuan City, Wenling City, etc. The average annual growth rate of land urbanization was between 0.5% and 1% in 18.42% of counties, while only 11.11% of counties had an average annual growth rate of >1%. From the perspective of provincial divisions, the land urbanization rate of counties in Zhejiang Province grew the fastest, with 22 counties with a medium speed and above, followed by Anhui Province, with 20 counties with a medium speed of growth and above. The land urbanization rate of counties in Jiangsu Province grew the slowest, and there were only two counties with a medium speed and above, indicating that the land urbanization in Anhui and Zhejiang Provinces had great potential for development. Specifically, most counties in Anhui Province with a low level of land urbanization grew faster during the study period; Shanghai and the counties near Taizhou City in Zhejiang Province also grew faster, and most of the counties in Jiangsu Province and the counties in the southeast coastal areas of Zhejiang Province had a low average annual growth rate of land urbanization.

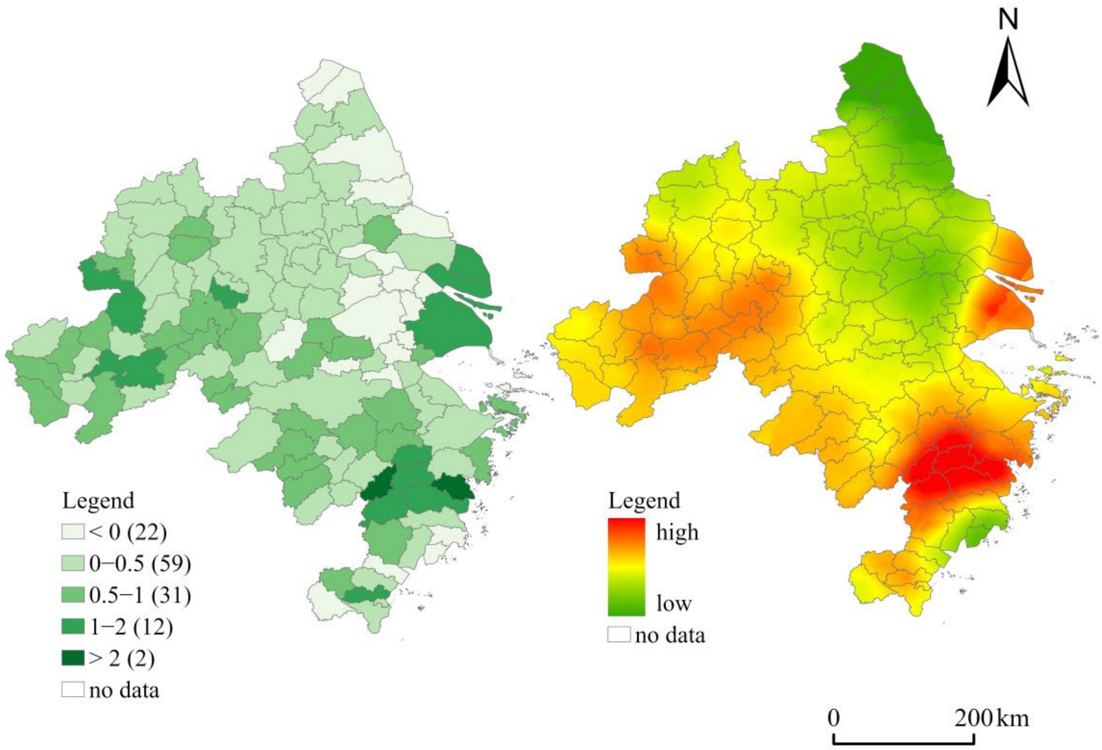

Figure 6. Change in land urbanization growth rate in Yangtze River Delta urban agglomeration from 2010 to 2020.

4. Influencing Factors of Land Urbanization in the Yangtze River Delta Urban Agglomeration

4.1. Identification of Influencing Factors and the Comparative Analysis of Models

The spatial autocorrelation analysis showed that the land urbanization levels of the counties of the Yangtze River Delta urban agglomeration were not randomly distributed in space but had significant spatial agglomeration characteristics. Therefore, a regression model with spatial effects was used, and the factors affecting land urbanization had different scales in the spatial process. Therefore, this paper used the MGWR model to explore the driving mechanism of land urbanization in the Yangtze River Delta urban agglomeration. The OLS, GWR and MGWR models were used to perform regression analysis on the influencing factors of the land urbanization level of the Yangtze River Delta urban agglomeration. Table 3 shows that the correction coefficient of determination of the MGWR model was higher than that of the OLS and GWR models, and the AICc value and the residual sum of squares were both obviously smaller than those of the GWR and OLS models. The standardized residuals calculated by the MGWR model were tested by

Moran's I and were randomly distributed in the study area, which further indicates that the MGWR model had a better fitting effect. The local R^2 calculated by the MGWR model represented the actual explanatory power of the selected variables in different spaces. The natural fracture method in the ArcGIS Pro 2.8 software was used to classify and visualize the local R^2 (Figure 7). It was found that the goodness of fit was satisfactory. There was an obvious clustering trend, and the local R^2 increased from southeast to northwest in general; all of the values were greater than 0.58, and the fitting effect was good. It can be seen that the eight variables selected in the study had specific explanatory power for the spatial pattern of land urbanization in the Yangtze River Delta urban agglomeration without considering the interference of other factors. In addition to the influencing factors selected in this paper, it also included technological innovation, social culture, policy background, etc. Limited by the difficulty of data acquisition and the model stability, these were not explored in this paper. Because of the different selection of indicators, the conclusions are different.

Table 3. Comparison of OLS, GWR and MGWR fitting results.

Model	OLS	GWR	MGWR
AICc	256.327	226.605	199.571
Adjusted R^2	0.598	0.757	0.801
Residual sum of squares	47.410	0.880	19.508
Moran's I for residual	0.208 ($p < 0.01$)	0.138 ($p < 0.05$)	0.088 ($p > 0.1$)

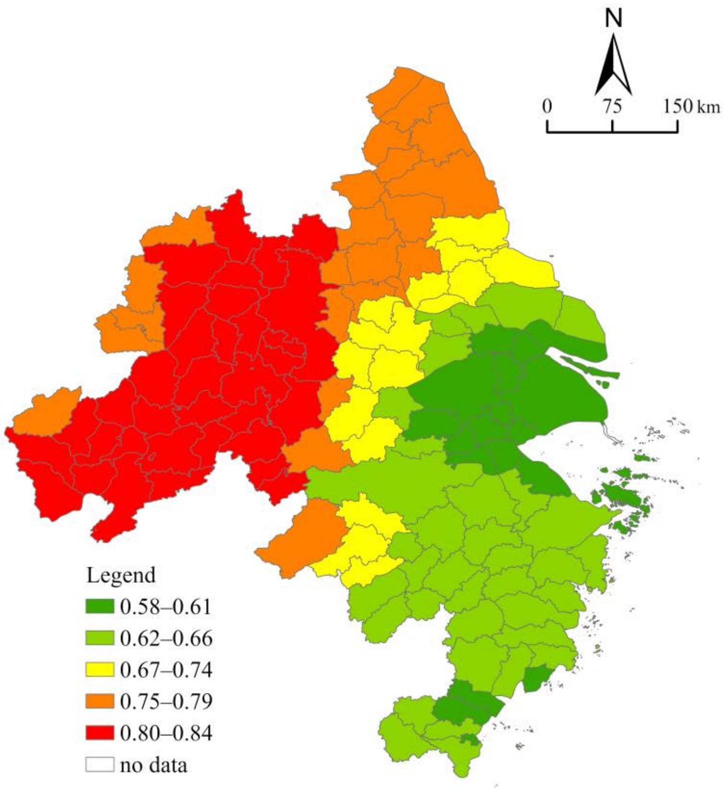

Figure 7. Local R^2 of MGWR model fitting results.

4.2. Scale Analysis of Influencing Factors Based on the MGWR Model

The variable bandwidth calculated in the MGWR model measured the spatial scale of each variable [83], which reflected the difference in the scale of land urbanization in the Yangtze River Delta urban agglomeration caused by different influencing factors. The larger the bandwidth, the larger the effect of the factor on the urbanization of the Yangtze River Delta urban agglomeration, and the smaller the spatial heterogeneity. From Table 4, it can be seen that the bandwidth of each variable in the GWR model was 78, and the optimal bandwidth of each variable was found to be different through the MGWR model. Among them, the proportions of secondary and tertiary industries, density of roads, topographic relief and annual precipitation were 122, 125, 125 and 120, respectively, which are close to the total number of counties and are global variables. In addition, the regression coefficient was relatively more stable in space. The bandwidths of per capita GDP and number of healthcare beds in medical institutions were 95 and 82, respectively, and the regression coefficient varied greatly in space. The bandwidth of fiscal revenue and population density was 43, and the effect scale was the smallest, indicating that land urbanization in the Yangtze River Delta urban agglomeration had a significant impact on fiscal revenue and population density. Moreover, the regression coefficients of these two factors varied the most in space, indicating higher sensitivity.

Table 4. Bandwidth comparison between GWR and MGWR.

Variables	Bandwidth of GWR Model	Bandwidth of MGWR Model
Intercept	78	43
X1	78	95
X2	78	122
X3	78	43
X4	78	82
X5	78	125
X6	78	43
X7	78	125
X8	78	120

4.3. Regression Coefficient Analysis of Influencing Factors Based on the MGWR Model

We used the ArcGIS Pro 2.8 software to display the regression coefficients of each variable calculated by the MGWR model (Figure 8). From the median of the regression coefficients of the influencing factors, per capita GDP > fiscal revenue > density of roads > annual precipitation > population density > number of healthcare beds > topographic relief > proportion of secondary and tertiary industries in GDP, in which the regression coefficients of per capita GDP, fiscal revenue, population density and annual precipitation were all positive values, the regression coefficient of population density was mainly positive and the positive and negative regression coefficients of number of healthcare beds accounted for half, respectively; the regression coefficient of topographic relief was mainly negative, and the regression coefficient of the proportion of secondary and tertiary industries to GDP was negative.

The standardized residual classification standard and natural breakpoint method were used to visually express the regression coefficients of the standardized residual and variables, respectively (Figure 9). The results showed that the range of the standardized residual values was −2.5 to 2.5, and the local regression models of all counties passed the residual test (Figure 9a). From the spatial distribution of the regression coefficient of the influencing factors, the influence degree of the eight independent variables on the land urbanization level of the Yangtze River Delta urban agglomeration showed obvious spatial differences (Figure 9a–i). Among the influencing factors with positive regression coefficients, the per capita GDP, road network density and precipitation showed a pattern of increasing from southeast to northwest, indicating that these three factors had a significant impact on the southeast area of the Yangtze River Delta urban agglomeration. This is because the southeast county of the Yangtze River Delta urban agglomeration was relatively developed, and the land development was early and had superior natural conditions and infrastructure construction level, while the northwest county was relatively backward; therefore, these factors were more likely to promote the urbanization level of the relatively backward counties in the northwest. The proportion of fiscal revenue to GDP was high in the middle and low in the east and west. Moreover, high-value areas were mainly distributed in the vicinity of provincial capital cities and large cities, such as Nanjing, Hangzhou, Hefei, Shanghai and other cities. The general fiscal revenue of the government was closely related to the government's regulation and control ability, which indirectly indicated that cities with high administrative levels play a stronger role in promoting land urbanization. Under China's land use right system, land supply is a powerful tool to intervene in the land market. Land finance is the main source of government financial revenue. The government's revenue from land leasing and land development accounts for a large part of the financial revenue. The macro-control ability of urban governments with high administrative levels is more prominent and has a greater impact on the development of land urbanization; the influence of population density showed that the northern region was larger than the southern region, and the high-value regions were concentrated along the Yangtze River Basin, indicating that the population agglomeration effect of the economic belt along the Yangtze River had an obvious role in promoting land urbanization, and the population scale growth is still the leading factor in promoting the development of land urbanization in developed counties. Only the proportion of secondary and tertiary industries in GDP was negatively affected by the regression coefficient, showing a spatial pattern in which the negative effect on land urbanization in the Yangtze River Delta was weakening from southeast to northwest. This is because, with the increase of the proportion of secondary and tertiary industries, the industrial structure was transformed into non-agricultural and advanced, and the development of service-oriented industries and the improvement of industrial intensification level promoted the improvement of land use efficiency, thus reducing the external expansion of land; however, due to the better industrial base in the southeast region, the effect of industrial structure improvement was better than that in the northwest region. The number of medical beds and the topographic relief had a negative effect on the developed counties in the east and a positive effect on the less developed counties in the west, indicating that these two factors are more conducive to the improvement of the land urbanization level of the less developed counties. This is because the land development degree of the western counties was relatively low, and good natural conditions and perfect public facilities configuration have a certain role in promoting land development; however, the more developed counties in the east shifted from the external expansion of the city to internal renovation and transformation due to the early land development and economic development, and their dependence on natural conditions and public facilities was further weakened.

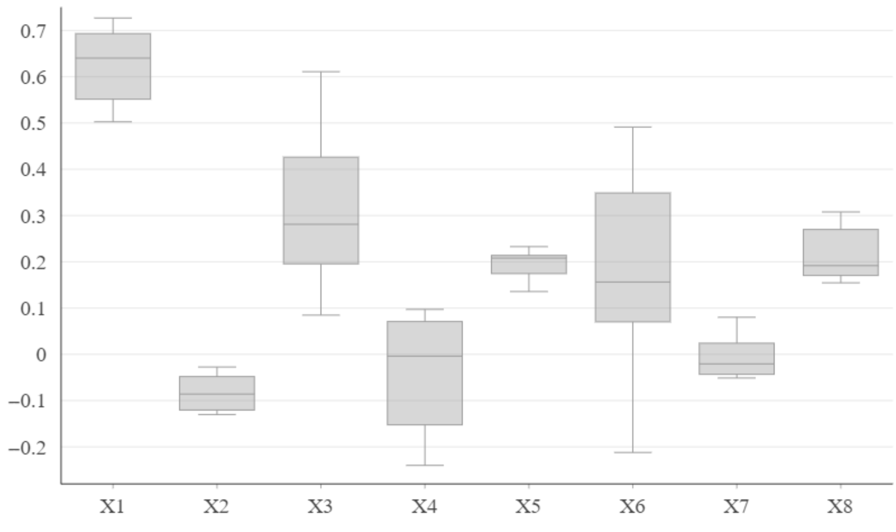

Figure 8. Regression coefficient and significance of spatial distribution of influencing factors of county economic development in Jiangsu Province.

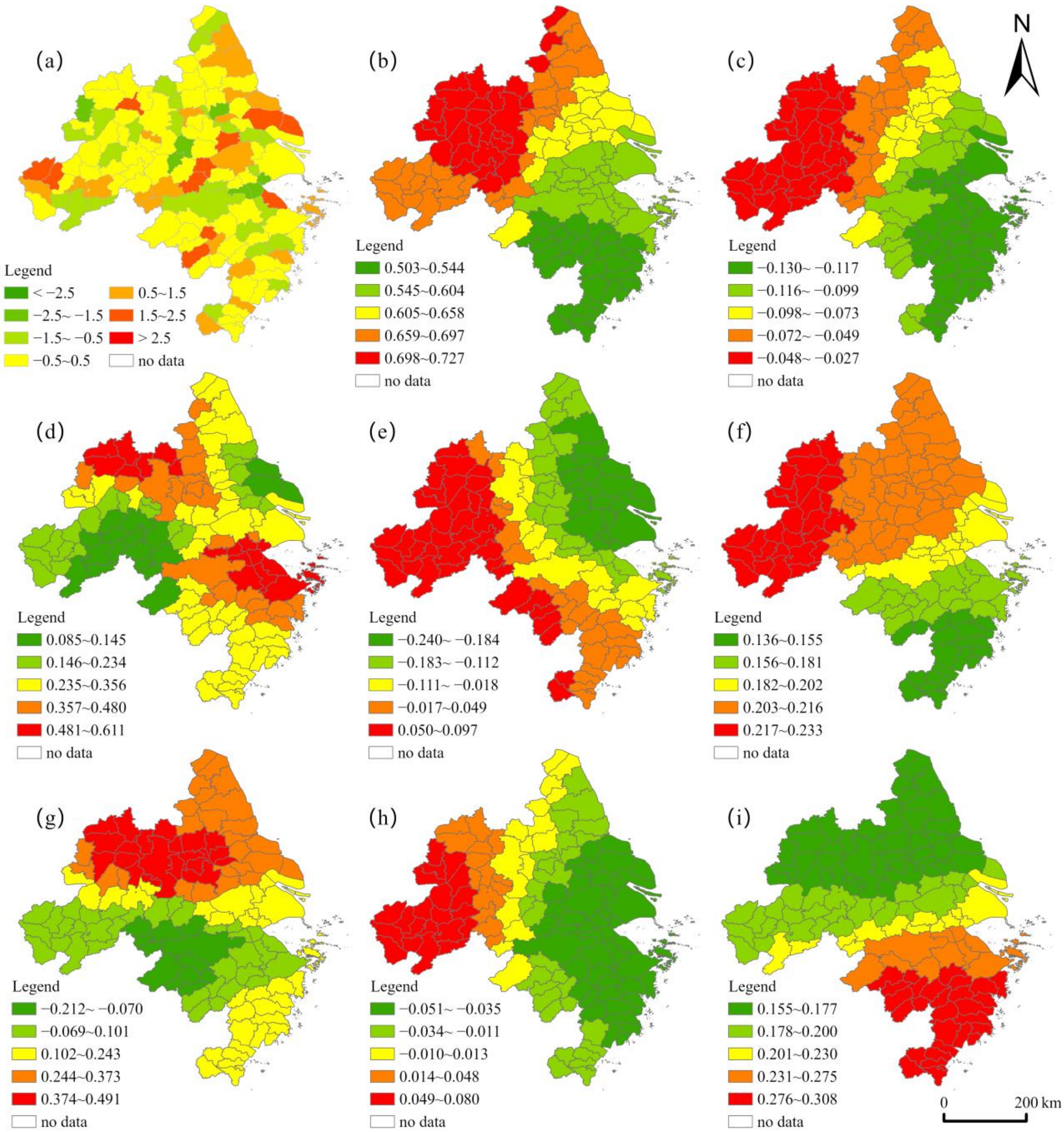

Figure 9. Spatial distribution of standardized residual and regression coefficients of driving factors for LUR based on the MGWR model in the Yangtze River Delta urban agglomeration in 2020. (**a**) Standardized residual; (**b**) per capita GDP; (**c**) proportion of secondary industry in GDP; (**d**) fiscal revenue; (**e**) number of healthcare beds; (**f**) density of roads; (**g**) population density; (**h**) topographic relief; (**i**) annual precipitation.

5. Discussion

5.1. Research Significance

In previous studies, the ratio of urban construction land to total urban area was mostly selected to reflect the urbanization level of urban land. This method is limited by the urban administrative area and cannot reflect changes in urban land use structure. Differing from previous studies, the land urbanization measurement index selected in this study corresponds to the urbanization of the population in a spatial entity through the ratio of urban construction land to urban and rural construction land and reflects the changes in land use in the urbanization process. The Yangtze River Delta urban agglomeration is an important engine for China's economic development and an important platform for its participation in international competition. The urbanization of land has reached a relatively high level, and the growth has been relatively slow in the past ten years. The difference in the level of land urbanization between counties has shown a dynamic convergence. Due to the implementation of the strategies of regional integration and new urbanization in the Yangtze River Delta, the developed counties and regions in the east have been transformed from the incremental expansion stage to the stage of stock renewal. Therefore, these regions need to pursue the improvement of the quality of land urbanization and the high-quality development of urbanization. However, the less developed counties and regions in the west and the counties and regions in the south that are greatly affected by the terrain have a high demand for urban construction land and are still in the stage of rapid improvement of land urbanization; such areas need to avoid the negative effects (such as the imbalance between population urbanization and land urbanization) caused by the rapid expansion of construction land. In the process of promoting urban–rural integration and performing spatial planning of national land, it is necessary to comprehensively consider the differences in the level of land urbanization in different counties. Previous studies have insufficiently explored the influencing factors of land urbanization in urban agglomerations, and the methods used have been relatively simple. The influencing factors are not only different in terms of influence intensity, but also different in spatial scale. The MGWR model used in this paper revealed the difference in the impact intensity and impact scale of different variables on land urbanization. The research results showed that the MGWR model yielded a great improvement in the goodness of fit compared with the GWR and OLS models, and the regression results were more reliable. This provides a theoretical and empirical basis for the further application of the MGWR model in land urbanization.

5.2. Policy Implications

Combined with the spatial and temporal evolution characteristics of land urbanization in the Yangtze River Delta urban agglomeration, we found that the speed of land urbanization in most counties slowed down, and many counties even had negative growth. This shows that, as one of the most economically developed areas in China, the level of land urbanization has entered a mature stage. Against the current background of promoting the urbanization construction with the county as an important carrier, it is particularly important to improve the development level of land urbanization and its coordination with population urbanization in the Yangtze River Delta urban agglomeration. We found that economic development is the main factor in promoting the land urbanization of the Yangtze River Delta urban agglomeration. The macro control of the government also plays a very important role in the process of land urbanization. The higher the administrative level, the stronger the macro-control role of the urban government. Under the land use right system of China, land supply is a powerful tool with which the government can intervene in the land market; the income from land supply contributes greatly to local income and infrastructure construction [84]. In response to the development trend of land urbanization and the challenges of sustainable development in the Yangtze River Delta urban agglomeration, we put forward some policy suggestions. ① First, the existence of regional differences in land urbanization in the Yangtze River Delta urban agglomeration determines that all counties need to be based on the regional perspective in the development and utilization of land resources. The government departments need to comprehensively consider the spatial interaction between the county and neighboring counties, strengthen the linkage control role of cities in land urbanization, continue to reduce the regional differences in land urbanization and promote the coordinated and integrated development of urban agglomeration. ② Second, we need to promote the construction of a people-oriented, new type of urbanization. In urban development, we need to promote people-oriented connotative population urbanization to replace the extensional land urbanization based on urban space expansion, strengthen the tapping of the existing land stock in developed areas led by the Shanghai metropolitan area, focus on the population growth and the improvement of social basic conditions in less developed areas in Anhui Province and promote the coordinated development of population urbanization and land urbanization. ③ Third, we should promote the transformation of kinetic energy of urban development and the transformation and upgrading of industrial structure. The analysis results show that the upgrading of industrial structure and intensive development can promote the renewal of land stock in developed counties in the east and also help to slow down the land expansion in less developed counties in the west and can strengthen the dynamic convergence trend of regional land urbanization level. ④ Fourth, according to the actual development needs of the county, we should implement the differentiated construction land allocation policy, promote the structural reform of the land supply side and release the local fiscal revenue from the real estate market [85], gradually getting rid of the dependence on land finance. The counties with lagging land urbanization should make use of the advanced management technology and development experience of the counties with a high land urbanization level in the east to avoid negative effects in the process of rapid urbanization. ⑤ Finally, it is necessary to give full play to the key role of the market and the government in resource allocation. The government's supervision of land development is aimed at avoiding the destructive impact of externality on the market operation efficiency. In the process of rationally promoting land urbanization, it is necessary to comprehensively consider the coordination and unification of economic benefits, social benefits, ecological benefits and urban space carrying capacity [86] and promote new-type urbanization and rural revitalization through urban–rural integration and rural revitalization strategy.

6. Conclusions

Based on the remote sensing monitoring data of China's land use status, this study calculated the LUR of each county in the Yangtze River Delta urban agglomeration and used spatial autocorrelation and kernel density estimation curves to reveal the spatiotemporal land urbanization of 126 counties in the Yangtze River Delta urban agglomeration from 2010 to 2020. We evaluated the dynamic evolution pattern and further applied the MGWR model to explore the scale effect and spatial heterogeneity of various influencing factors. The main conclusions reached are as follows:

(1) From 2010 to 2020, the overall land urbanization rate of the Yangtze River Delta urban agglomeration increased from 50.49% to 55.41%, with an average annual growth rate of 0.50%. As the region with the most active economic development and the most concentrated cities in the country, its land urbanization gradually increased to create a saturated state. Among the counties, the average annual growth rate of nearly 64.28% lagged behind the overall growth rate, mainly distributed in Jiangsu Province and Zhejiang Province. Overall, the level of land urbanization in each county showed dynamic convergence characteristics;

(2) The differentiation pattern of land urbanization in the Yangtze River Delta urban agglomeration from southeast to northwest was more obvious. The hot spots of land urbanization were consistently mainly distributed in the Shanghai metropolitan area, Hangzhou, Jinhua, Wenzhou and nearby counties and showed a trend of diffusion. The cold spots were concentrated in Hefei, Chuzhou, Wuhu, Tongling, Chizhou and other cities, where there was a shrinking trend;

(3) Compared with the GWR model and the OLS model, the MGWR model has a better fitting effect and is better suited to the study of the influencing factors of land urbanization. On the impact scale, the proportion of secondary and tertiary industries in GDP, density of roads, topographic relief and annual precipitation have larger bandwidths, which are close to global variables, while fiscal revenue and population density have the smallest bandwidths and the strongest spatial heterogeneity. In terms of impact intensity, economic factors have the greatest impact, while natural environment factors have the least impact.

Our empirical research revealed the spatiotemporal dynamics of land urbanization in the Yangtze River Delta urban agglomeration and verified the spatiotemporal heterogeneity effects of the economy, social basic conditions, population and natural environment. These findings are helpful for formulating urban and regional planning for specific regions with different spatial dependencies and the co-evolution of urban expansion. The spatial difference in land urbanization is the result of a combination of factors. In future research, we will compare and analyze the spatiotemporal evolution and driving factors of land urbanization in other urban agglomerations.

Author Contributions: Conceptualization, H.Z. and Z.Y.; methodology, X.O., L.T. and H.Z.; software, H.Z.; validation, Z.Y. and X.O.; formal analysis, Z.Y. and X.O.; investigation, L.T.; data curation, Y.Y., H.R. and H.Z.; writing—original draft preparation, H.Z.; writing—review and editing, X.O., Z.Y., Y.Y., H.R. and L.T.; visualization, H.Z.; supervision, Z.Y. and X.O.; project administration, H.Z. and Z.Y.; funding acquisition, X.O. and H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Project of Philosophy and Social Sciences in Colleges and Universities of Jiangsu Provincial Department of Education (2018SJZDI091), the Social Science Foundation Project of Jiangsu Normal University (20XWRX004), the Jiangsu Graduate Research and Practice Innovation Program (KYCX21_2631), the Jiangsu Graduate Research and Practice Innovation Program (KYCX22_2852) and the Jiangsu Graduate Research and Practice Innovation Program (KYCX22_2790). Priority Academic Program Development of Jiangsu Higher Education Institutions.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the author.

Acknowledgments: The authors are grateful to the editor and reviewers for their valuable comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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