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Unveiling the Impact of Transportation Infrastructure Construction on Rurality: A Case Study from Guangdong, China

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Abstract: Rurality is an important indicator to reflect the development of villages and reveal internal differences in rural areas. The unbalanced development of transportation infrastructure in the current period of rapid urbanization has become one of the principal elements triggering spatial differences in rurality and changes in rural territorial characteristics. However, there are few studies on the impact of transportation infrastructure accessibility on the multidimensional characteristics of rurality from the perspective of heterogeneity. This paper analyzed the spatio-temporal characteristics of transport accessibility (TA) and the county rurality index (CRI) in Guangdong in 2005, 2010, 2015 and 2020 using an accessibility model and the rurality index and explored the clustering characteristics and interactions of TA and the CRI through exploratory spatial data analysis (ESDA) and geographic weighted regression (GWR) modeling. The findings showed that (1) TA and the CRI in Guangdong were significantly unbalanced in terms of space. The CRI showed a weakening trend in general, forming a distribution pattern of "high in the north and low in the south, high in the west and low in the east", while TA was on the rise, maintaining a stable pattern of "high in the middle and low in the periphery". (2) Both TA and the CRI in Guangdong had a Moran's I value greater than 0.6 during the study period, exhibiting strong spatial agglomeration, while the two showed a significant spatial negative correlation. (3) The influence of TA on the CRI in different dimensions showed dynamic changes in stages, with TA having a higher intensity of effect on society rurality and land rurality in 2005, while on society rurality and industry rurality in 2020. (4) This paper grouped 77 counties in Guangdong into four types of policy zonings—coordination types, lagged types of accessibility, lagged types of rurality and double lagged types—and put forward corresponding development recommendations. The study conducted in this paper contributes to an in-depth understanding of the impact of transportation infrastructure development on the multidimensional characteristics of rurality and provides a basis for policy formulation for coordinated urban–rural development and sustainable rural development.

Keywords: rurality; transportation accessibility; geographically weighted regression; rural sustainability; China

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1. Introduction

1.1. Background

Rurality is an important concept that reflects the level of rural development and depicts the geographical differences in rural areas and is of great significance for the identification and optimization of urban and rural spaces [1,2]. Rurality, as an important indicator measuring the state of rural development and portraying its level, essentially reveals the extent of the developmental differences between different rural areas and profoundly reflects the intrinsic connections and influence processes within the rural development space, with regions with a lower level of rurality usually having a better development, while those at a higher level are poorly developed [2–4]. Since the beginning of the twenty-first century, China's urban–rural development pattern has gradually transitioned from a separated state to a new stage of coordinated and integrated urban–rural development with the rapid development of industrialization and urbanization [5]. However, cities, as the mainstay of regional development, have gathered most of the development resources, making them significantly superior to rural areas in terms of social and economic development, urban environment construction and supporting service facilities [6]. In addition, the siphoning effect of urbanization has led to a continuous loss of the rural population and intensified the gap between urban and rural areas, resulting in a sharp contrast between the rapid development of urban areas and the decline in rural areas [7,8]. However, rural areas have been a crucial support for urban and regional development and are a key and indispensable component of coordinated urban–rural development, playing a vital role in ensuring national food security, ecological safety and social stability [9]. As a result, rural sustainability is receiving more attention, and rurality is also becoming a hot topic among scholars.

As a basic service facility for the coordinated development of urban and rural areas, transportation is the direct medium that drives the flow of development factors, such as population and economy, between urban and rural areas, as well as the evolution of rural regional characteristics [10]. The construction of rural transportation infrastructure is of great significance in promoting organic connections between rural transportation, resource development and industrial development, thereby realizing transportation-led rural poverty alleviation and sustainable development [11,12]. The UN 2030 Agenda for Sustainable Development released in 2015 also emphasizes the need to strengthen transportation infrastructure to promote rural sustainability [13]. The continuous improvement of transportation infrastructure in regional development has strengthened the economic development of rural areas and the interaction between urban and rural areas and improved the quality of life of rural residents [14]. However, the imbalance of transportation infrastructure construction is also one of the major causes of geographical differences in the pattern of rurality [15,16], and the spatio-temporal compression effect brought about by transportation may further exacerbate the imbalance between urban and rural development [17,18]. It is not yet clear to what extent the construction of comprehensive transportation infrastructure in rural areas has affected the spatial characteristics of both comprehensive and multidimensional rurality and what differences there are in its impact on different dimensions of rurality. Therefore, discussion of the impact of transportation infrastructure on rurality in the context of the current coordinated urban–rural development and rural sustainability is helpful to reveal the connection between transportation infrastructure construction and the multidimensional characteristics of rurality, providing a theoretical basis and practical guidance for the formulation of more scientific and reasonable transportation planning and rural development policies.

1.2. Literature Review

1.2.1. Evaluation of Rurality and Its Influence Mechanism

Rurality is a multidimensional concept that covers production and life, development level and the regional characteristics of rural areas [19,20]. At present, the focus of rurality research is mainly on the construction of a rurality indicator system [14,15,21] and the evaluation of rural characteristics [3]. Early in 1977, Clock constructed a system covering 16 rurality indicators for the first time, including population structure, population density, employment structure and transportation patterns, to evaluate rurality and geographic types in England and Wales [22–24]. As rural studies have progressed, scholars have continued to refine and supplement the indicator system for rurality [25,26]. For example, Waldorf added the human development index [27]; Harrington et al. added demographic indicators and rural structure indicators [28]; Li et al. added industrial structure and urban–rural linkage indicators [4]; Woods [19] and Hidle [29] further incorporated spiritual culture and rural resource advantage indicators; Johansen et al. refined the rurality evaluation indicators accordingly based on rural planning and policy makers [30]; Li et al. included population aging, education, agricultural employment and other indicators to consider; and in Ref. [31]. Wang and Li constructed more detailed evaluation indicators, such as per capita area of agricultural land, the number of non-agricultural industries, housing quality, infrastructure (schools, hospitals, etc.) and ecology [32,33]. With the continuous progress of economy and science and technology, innovation factors, technical level, Internet coverage, logistics services and other innovation and information indicators have gradually been incorporated into the rurality evaluation system [34–37]. This indicates that the rural index focuses on traditional rural characteristics and gradually incorporates the needs of modern social development to adapt to a constantly changing rural social and economic environment. In terms of rurality evaluation methods, Shcherbak et al. evaluated the sustainable development of rural areas using factor analysis and cluster analysis [38]; Ma et al. evaluated the rurality of counties in intertwined agricultural and pastoral zones in northern China using exploratory spatial data analysis and k-mean clustering and classified the types of rural development [39]; Yang and Cheng revealed the spatial differences in rurality using a coupling and coordination model [40,41]; Huang et al. evaluated the changes in rural regional characteristics using a fuzzy analytic hierarchy process quality function development method [42]; and Xiao and Li studied the interaction of rurality components based on multi-dimensional continuous measurement of the human development index and a coupled coordination model [18,43].

Besides expanding the index system and the research methods for rurality, a few studies have also explored the factors driving its evolution. For example, Han et al. qualitatively analyzed the main driving factors behind the evolution of rural characteristics in rapidly industrializing areas in terms of urban development, economic transformation, location and transportation and human resources by induction [44]; Shi et al. analyzed the impact of economic development, technological progress, industrialization and rural marketization on the overall sustainable development level of rural China using Tobit regression [37]; Wei et al. explored multifaceted influences on the changing patterns of rurality using the spatial Durbin model, such as rural greening, healthcare, elderly services, transportation accessibility, cultural atmosphere and fixed asset investment [45]; and Dong et al. quantitatively analyzed the driving factors behind the divergence in rurality in the Yangtze River Economic Belt in terms of the natural environment, locational conditions, technological and policy support and capital and market factors [46]. However, the complexity of the component of rurality and its many influencing factors have kept the above research in its infancy, necessitating a broader and deeper exploration of the mechanisms behind it.

1.2.2. Impact of Transportation Infrastructure on Rurality

The term infrastructure is mostly used in the field of construction engineering, covering transportation, bridges, water conservancy and other fundamental facilities. Transportation infrastructure, including roads, bridges and railroads, is particularly emphasized in the study of regional development and rural infrastructure construction, as it is directly related to intra- and extra-regional connectivity and influences the flow of people, materials and information [11,47,48]. The construction of transportation infrastructure is an important component and support for the rural territorial system and also a driving factor for socio-economic development and changes in rural areas [12,49,50]. Therefore, scholars have also turned their attention to the interaction between the construction of transportation infrastructure and the evolution of rurality, mainly from two dimensions. First, they incorporate the relevant indicators for transportation infrastructure construction into the rurality evaluation system, making it an important reference for measuring the pattern of rurality; second, they analyze the role of transportation infrastructure in relation to rurality and explore the way that the construction of transportation infrastructure affects changes in rural characteristics. In the first case, the relevant indicators include road network density, traffic patterns, traffic quality, traffic convenience and accessibility [24,32–34,51–53]. In the second case, Li et al. revealed that transportation conditions have a significant supportive role in the evolution and development of rural industrial characteristics according to quantitative value evaluation [54]; Panagiotopoulos et al. investigated the connection between rural accessibility and rural spatial inequality in remote areas of Greece by building a geographic remoteness index and pointed out that rural spatial inequality in remote areas with undeveloped transportation is prominent [55]; Caschili et al. explored the relationship between accessibility and rurality at the urban level using a double constraint spatial interaction model and came to the conclusion that areas with high rurality usually have poor accessibility [56]; Vaishar et al. studied the impact of integrated transportation systems on the accessibility of basic services in rural settlements and found that the accessibility of services in villages with good access to transportation is significantly higher than that in peripheral areas [57]; in their study, Sánchez-Mateos and Neumeier presented the differential impact of rural accessibility levels on public policy and infrastructure decisions [58]; Yao and Kaiser's study showed that rural transportation infrastructure plays a crucial role in improving the well-being of rural residents and that villages with a weak transportation network base have a more pronounced rural character, i.e., a higher level of rurality [59,60]; Lu et al. found, by analyzing the connection between transportation infrastructure and the urban–rural income gap, that national roads, as well as provincial and municipal roads, have played a positive role in promoting rural labor mobility, narrowing the urban–rural income gap and lowering the level of rurality [61]; Qin et al. pointed out that rural transportation infrastructure plays a positive role in improving the quality of life of the poor and alleviating poverty by promoting the growth of the tertiary industry, thereby indirectly reducing rurality [53]; Zhang et al. pointed out that transportation infrastructure has made a significant contribution to rural industrial integration, but different regions have different needs and influences on transportation facilities at different stages of rural industrial integration development [62]; Sasmal and Chotia further pointed out that rural transportation infrastructure stimulates economic growth by increasing productivity, which, in turn, increases income and reduce poverty [63,64].

The current research as a whole focuses on the exploration of the impact of transportation infrastructure on rural characteristics such as rural industry, spatial equality, service facility accessibility, urban–rural disparity and rural poverty, revealing the key role of transportation infrastructure in the evaluation of rurality. These findings provide valuable data support and a theoretical basis for studying transportation infrastructure development and rurality, as well as rural sustainability. However, from the perspective of the research content, the existing studies only involve the connection between transportation infrastructure and rurality according to a certain aspect, and there are not many studies focusing on their multidimensional characteristics. Most of the existing studies have methodologically used classical linear regression models, resulting in a significant lack of discussion on spatial heterogeneity. For example, Li et al. analyzed the spatial relationship between rural functional types and influencing factors based on correlation [54]; Panagiotopoulos et al. used a spatial regression model to reveal the impact of rural accessibility on development inequality in Greece [55]; and Zhang et al. studied the impact of transportation infrastructure on rural industrial integration using a spatial panel autoregressive model [62].

1.3. Aim and Question

This paper studied Guangdong province in China from 2005 to 2020 with county as the basic research unit. It constructed the county rurality index (CRI) to show the rurality characteristics; calculated transportation accessibility (TA) to reveal the transportation infrastructure construction characteristics; analyzed the spatial distribution, aggregation and correlation characteristics of the CRI and TA according to spatial cluster and exploratory spatial data analyses; and further analyzed the impact of TA on the CRI and its spatial heterogeneity through geographically weighted regression. Therefore, this paper focuses on the following questions: (1) What are the changing patterns of the spatial distribution and spatial aggregation of the CRI in Guangdong? (2) What are the changing patterns of spatial distribution and spatial aggregation of TA in Guangdong? (3) What changes do the spatial correlations of the CRI and TA present? (4) What are the changes in the impact of TA on the CRI and its spatial heterogeneity? This paper attempts to address the above issues to reveal the spatial changes in rurality and transportation infrastructure construction in counties, discern the driving mechanism of the influence of transportation facilities on changes in rurality and put forward suggestions for the differentiated development of villages in different counties, with a view to providing references for the central and local governments to promote rural revitalization.

2. Materials and Methods

2.1. Research Area

Guangdong, one of the most economically active and rapidly urbanizing regions in China, is located in South China and borders the Hong Kong and Macau Special Administrative Regions. It has experienced rapid development since reform and opening up, with its GDP increasing from 0.9 trillion yuan in 2000 to 11.1 trillion yuan in 2020, its industrial structure adjusted from 10.4:51.1:38.4 to 4.3:39.2:56.5 and urbanization growing from 47% to 74%. In addition, primary industry contributed to its GDP growth up to 13.6% in 2020 from −2.9% in 2000, with the disposable income of rural residents growing from 3.6 thousand yuan to 20.1 thousand yuan [65]. However, despite greatly improved rural industry and farmers' incomes, the province is plagued by rural development gaps in different areas due to differences in resource endowment conditions and provincial and municipal development policies. For example, in 2020, the highest added value of primary industry in Gaozhou (17.044 billion yuan) was 337 times higher than that in Chancheng, with the lowest (50 million yuan), and the highest disposable income of farmers in Shunde (61,500 yuan) was 5 times higher than that in Jiexi, with the lowest (13,300 yuan) [66]. Featuring significant differences in rural development during rapid urbanization, Guangdong is a good representative place to explore the impact of county transportation infrastructure construction on rurality. It has 124 counties under its jurisdiction, and this paper focuses on 77 counties, excluding 47 nearly fully urbanized counties with no obvious rural characteristics (Figure 1).

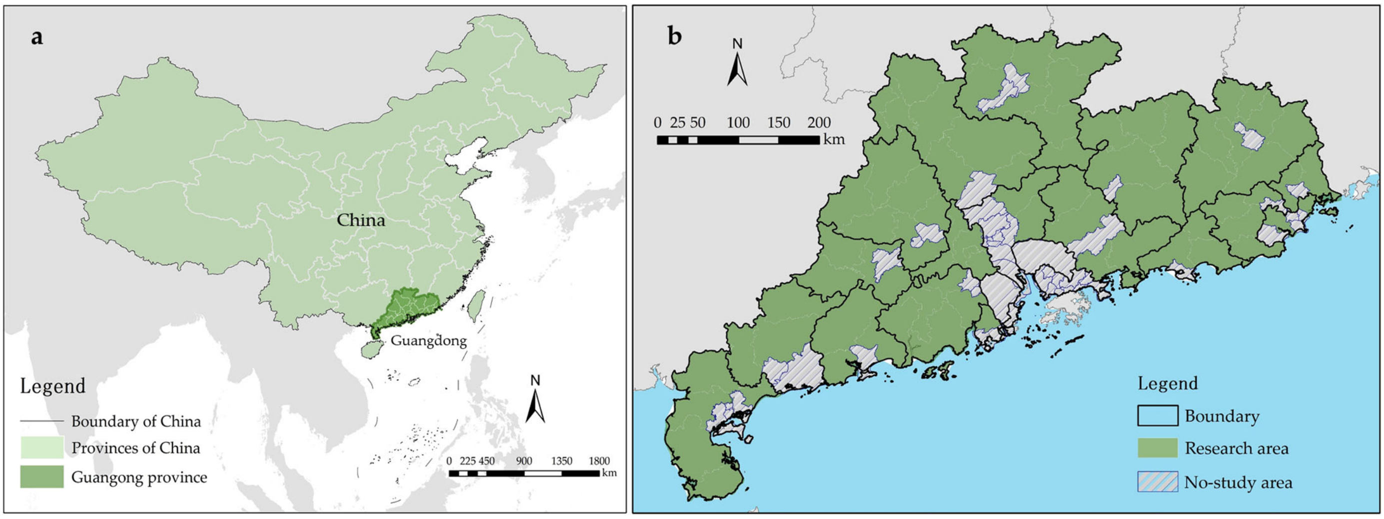

Figure 1. Study area. (**a**) Study area in China; (**b**) study area in Guangdong. All the maps are depicted by Arcgis 10.2, which is developed by Esri China (Hong Kong) Ltd., Hong Kong, China, the same below.

2.2. Research Methods

2.2.1. The County Rurality Index

Population mobility and urban–rural integration in the process of urbanization have led to changes in the rural population structure [67], while a large amount of agricultural land has been converted into urban construction land [68]; therefore, the current evaluation indicators for rurality are mainly related to population, industry and land. However, with the diversification of the rural economic structure, its social culture and lifestyle have also undergone significant changes [69], and the level of social living has become an important indicator representing rurality. Therefore, in this paper, we focus the rurality indicator on four elements that have a fundamental impact on long-term rural development, population, land, industry and society, so as to comprehensively analyze the spatial development pattern of the county rural index (CRI) in Guangdong (Table 1).

Table 1. Evaluation indicators of county rurality index.

Type	Indicator	Calculation	Direction
population	Rural population change rate	(End stage rural population—initial rural population)/initial rural population	Positive
	The proportion of employees in the primary industry	Number in primary industry labor force/total number in rural labor force	Positive
land	Change rate of planting area	(End stage planting area—initial planting area)/initial planting area	Positive
	Per capita planting area	Planting area at the end of the year/total rural population	Positive
society	Income level of rural population	Per capita disposable income in rural areas	Negative
industry	The proportion of primary industry	Primary industry output value/total output value	Positive
	Labor productivity in the primary industry	Output value of primary industry/number in labor force in primary industry	Negative
	Agricultural land productivity	Total agricultural output value/agricultural planting area at the end of the year	Negative
	Per capita crop production	Total output of planting industry/total rural population	Positive

Note: Positive indicator means the larger the value, the stronger the rurality; negative indicator means the smaller the value, the stronger the rurality.

(1) Population indicator: Population is the core of rural development, and the rate of rural population change directly reflects dynamic change in the rural population and the evolution of the labor force structure [70]. The proportion of primary industry employees presents the population employment structure and agricultural dependence in rural areas [2]. Therefore, in this paper, the change in the rural population and the proportion employed in the primary industry are used to show the rurality characteristics of the population.

(2) Land indicator: The relationship between man and land has always been one of the core focus points of geographical research [71]. Rural land is mainly used for living and production, and indicators related to productive land use better reveal the structure and nature of rural land use, providing important information for understanding land use and agricultural production [40,68]. Therefore, according to the studies available [2–4], change in planting area is added to the per capita planting area to further represent the rurality of the land.

(3) Social indicator: The economic level is a key indicator of social development, and current studies generally reflect the living standard of rural residents using per capita net income [72]. However, per capita disposable income in rural areas is a truer reflection of the actual living conditions of rural residents, and its growth is often closely related to the improvement of their social living standards [73]. Therefore, per capita disposable income in rural areas is used to reflect the level of social development in rural areas.

(4) Industrial indicator: The development of rural industries is a reflection of the industrial structure of rural areas. In view of the fact that most of the rural industries are dominated by the primary industry, key indicators such as the proportion of added value of the primary industry, labor productivity in the primary industry and agricultural land productivity are selected in this paper, based on existing studies [56,74], to reflect the industrial composition and development level of villages. In addition, an indicator of per capita planting output is introduced to provide a more realistic measure of the level of agricultural development and the efficiency of resource utilization in terms of the productive capacity of rural plantations [18,75].

The range method is used to standardize the indicators to eliminate the impact of dimensions, and factor analysis is relied upon to calculate the weight of indicators in the above table. The CRI for each year is calculated based on standardized values and indicator weights as follows:

$$x'_{ij} = \begin{cases} \frac{x_{ij}-x_{j,min}}{x_{j,max}-x_{j,min}} & (Positive\ indicator) \\ \frac{x_{jmax}-x_{ij}}{x_{j,max}-x_{j,min}} & (Negative\ indicator) \end{cases} \tag{1}$$

$$CRI_i = \sum_{i=1}^{n} w_j \times x'_{ij} \tag{2}$$

where CRI_i is the county rural index of the ith county, w_j is the weight of the jth indicator, x'_{ij} is the standardized value of the jth indicator of the ith county and n is the number of j indicators. A larger value of CRI_i indicates a stronger rural character and attribute of the county, accompanied by a lower level of rural development, and vice versa.

2.2.2. Transport Accessibility

Transport accessibility (TA) was first used to describe how easy it is for a traveler to reach a certain destination within a given transportation system [76]. The concept of TA in common use today is derived from Hansen's definition in 1959—"the probability of interaction between nodes in a traffic network" [77]. With deepening of the research, the concept of transport accessibility continues to expand and deepen, from Hansen's emphasis on the location and spatial attributes of TA to the four components of TA proposed by Geurs et al. (opportunity, spatial impedance, individual attributes and time constraints) [78]. TA is also widely used to evaluate the convenience and location advantages and disadvantages of public facilities, commercial facilities and transportation stations. In the calculation of regional TA, the Geographic Information System (GIS) has created important research directions for urban and rural TA [79]. This paper presents the accessibility of counties in Guangdong to other counties through GIS technology based on the average of the shortest travel time from each county to other counties. The calculation is as follows:

$$TA_{ij} = \sum_{j=1}^{n} T_{ij}, \quad TA_i = \frac{1}{n} TA_{ij} \tag{3}$$

where T_{ij} is the travel time from town i to town j, TA_{ij} is the total travel time from town i to town j, n is the total number of towns except town i and TA_i is the transport accessibility of location i. A larger value of A_i indicates lower transport accessibility, and vice versa.

2.2.3. Exploratory Spatial Data Analysis

Exploratory spatial data analysis (ESDA) is a method of exploring data patterns using a GIS and spatial statistics to discover the spatial patterns, trends and anomalies behind the data [80]. ESDA contains a variety of tools, such as global Moran's I, univariate local Moran's I and bivariate local Moran's I. In this paper, global Moran's I is used to explore the spatial aggregation of TA and the CRI, local Moran's I is used to identify localized spatial agglomeration or dispersion in the study area and the bivariate local Moran's I index is further used to show the localized spatial correlation between the two metrics, the CRI and TA [81], calculated as below:

(1) Global Moran's I:

$$I_g = \frac{n}{s_0} \times \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2}, \quad s_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \tag{4}$$

where I_g is *global Moran's* I; x_i and x_j are TA or the CRI values for county i and county j, respectively, with i,j = 1, 2, 3, . . ., n and n being the total number of counties, here 77; $\overline{x}$ is the average TA or CRI for all counties; w_{ij} is the spatial weight matrix, with 1 for spatial adjacency and 0 for spatial dispersion, and s_0 is the sum of all the w_{ij} values. The value of *global Moran's* I is $[-1, 1]$. A positive value indicates more prominent spatial aggregation, a negative value indicates more prominent spatial dispersion, and a larger absolute value indicates more pronounced aggregation or dispersion.

(2) Local Moran's I:

$$I_l = \frac{(x_i - \overline{x})\sum_{j=1}^{n} w_{ij}(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{5}$$

where I_l is *local Moran's* I; x_i and x_j are TA or the CRI values for county i and county j, respectively, with i,j = 1, 2, 3, . . ., n and n being the total number of counties, here 77; $\overline{x}$ is the average TA or CRI for all counties; and w_{ij} is the spatial weight matrix. Local spatial autocorrelation analysis can be used to identify similarities or differences between TA or the CRI in different counties and their surrounding areas.

(3) Bivariate local Moran's I:

$$I_b = z_i \sum_{j=1}^{n} w_{ij} z_j \tag{6}$$

where I_b is *bivariate local Moran's* I; z_i and z_j are the variance-standardized values of TA or the CRI for county i and county j, respectively; n is the total number of study units; and w_{ij} is the spatial weight matrix. Both local Moran's I and bivariate local Moran's I can provide a visual representation of the clustering and divergence characteristics of the independent variables or the independent variables and the dependent variable in a local area through local indications of spatial association (LISA). Common clustering patterns include HH, HL, LH, LL and not significant.

2.2.4. Geographically Weighted Regression

Geographically weighted regression (GWR) is a regression method used to deal with spatial heterogeneity which can capture local variation and heterogeneity in geographic space more effectively [82,83]. In this paper, GWR is introduced to explore the impact of TA on the multidimensional CRI and spatial heterogeneity in Guangdong. The calculation is as follows:

$$Y_i = \alpha_0(u_i, v_i) + \sum_{k=1}^{m} \alpha_k(u_i, v_i) X_{ik} + \beta_i \tag{7}$$

where Y_i is the CRI for the ith region, $\alpha_0(u_i, v_i)$ is the intercept, X_{ik} is the value of the kth explanatory variable in the ith region, (u_i, v_i) is the spatial coordinates of the ith region, $\alpha_k(u_i, v_i)$ is the regression coefficient of the kth explanatory variable in the ith region, m is the total number of explanatory variables, k is the sequence number of an explanatory variable and β_i is random error. The spatial weight matrix directly determines its regression coefficients in the use of GWR, while the broadband strongly influences the spatial weight matrix. A bi-square weight function and a Gaussian weight function are available for constructing spatial weights, and there are cross-validation criteria (CV) and Akaike information criteria (AICc) available for examination of the broadband selection.

2.3. Data Sources

There are two main types of core data in this paper: the first is CRI assessment data, based on socio-economic statistics sourced from Guangdong County Rural Statistical Yearbook and China County Statistical Yearbook; the second is transportation and road network data, including data on railroads (high-speed railroads, inter-city railroads and general-speed railroads), highways and ordinary roads (national roads, provincial roads and county and township roads) in Guangdong Province from 2005, 2010, 2015 and 2020, sourced from OSM, Amap and appropriate open-source websites (Figure 2). The calculation of TA needs to set the driving speed for different types of transportation systems. According to the Technical Standards for Highway Engineering of the People's Republic of China (JTGB01-2020) [84] and the actual conditions in Guangdong, this paper determines the driving speed for different types of roads in different years, as shown in Table 2. This study classifies transportation infrastructure into five classes based on types and the hierarchy of the transportation network services. Specifically, first-class roads are highways, second-class roads are national roads, third-class roads are provincial roads, fourth-class roads are county and township roads and railways include ordinary railways, intercity railways and high-speed railways (Table 2).

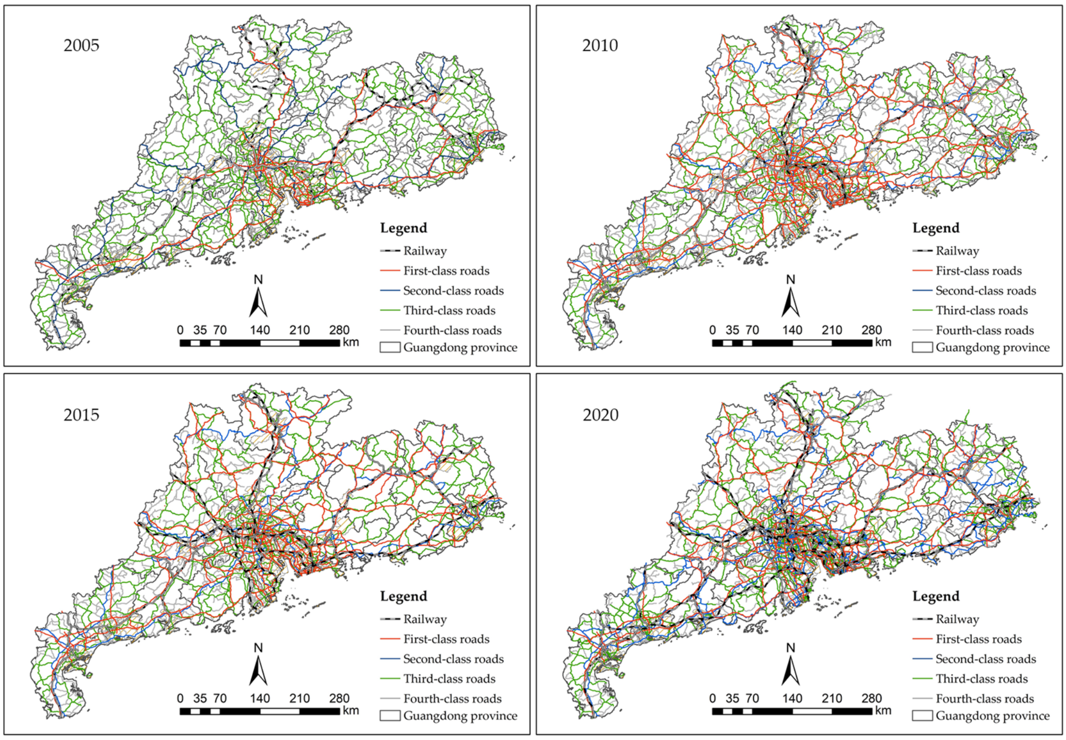

Figure 2. Road network in Guangdong province from 2005 to 2020.

Table 2. Driving speed of different traffic types (km/h).

Year	First-Class Roads	Second-Class Roads	Third-Class Roads	Fourth-Class Roads	Railway		
					Ordinary Railway	Intercity Railway	High-Speed Railway
2005	90	60	50	30	70	\	\
2010	100	80	60	30	90	160	200
2015	100	80	60	40	120	200	300
2020	120	90	70	40	160	200	350

Note: "\" means that the intercity railway or high-speed railway is not open.

2.4. Research Steps

The study in this paper consists of 4 steps. Step 1 is to raise the research questions, that is, to clarify the shortcomings in the research field of TA and the CRI through an in-depth background analysis and a literature review and point out the key issues that need to be discussed. Step 2 is to provide the index and data, determine the 77 counties in Guangdong as the study units and construct the CRI indicator system, including industry rurality, population rurality, society rurality and land rurality. And the required transportation network data and socio-economic statistics are obtained through statistical almanacs and open-source mapping websites. Step 3 is to introduce the research methods, to calculate the CRI and TA in Guangdong using Excel 2021 and ArcGIS 10.2, to analyze the spatial heterogeneity of TA and the CRI using the clustering tool, to analyze the spatial agglomeration of TA and the CRI using ESDA and to analyze the influence of TA on the CRI using GWR. Step 4 is to carry out the result analysis and discussion, that is, to explore the spatial distribution and agglomeration of TA and the CRI by spatial analysis, aggregation analysis and correlation analysis and the impact of TA on the CRI and its different dimensions (industry rurality, population rurality, society rurality and land rurality) (Figure 3).

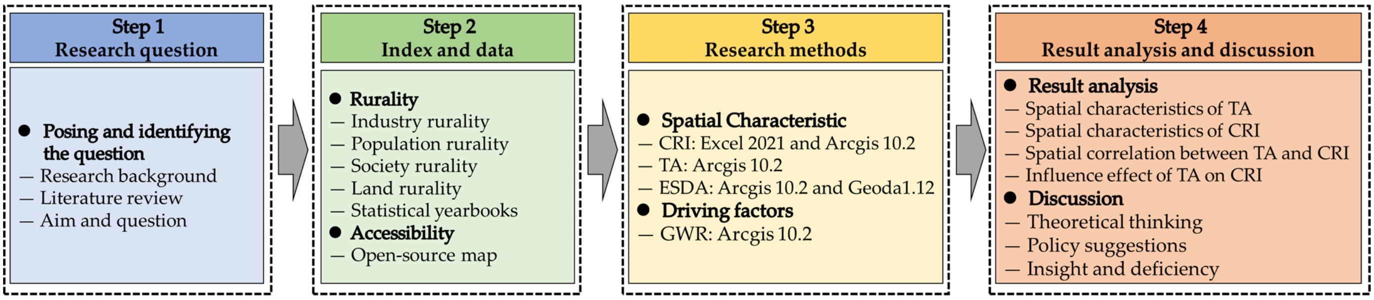

Figure 3. Research steps.

3. Results and Analysis

3.1. Spatial Characteristics of the County Rurality Index

3.1.1. The Spatial Pattern of the County Rurality Index

In this paper, we calculated and visualized the CRI of Guangdong on the ArcGIS 10.2 platform and obtained CRI spatial distribution maps of the 77 counties in 2005, 2010, 2015 and 2020 (Figure 4). In general, Guangdong showed a good development trend, with the CRI on a downward trend, but the development imbalance between counties was prominent. Specifically, areas with high CRI values were concentrated in the north, west and east of Guangdong, while areas with low CRI values were concentrated in the south and west. It should be noted that the changes in the CRI in the south and east were particularly significant. The spatio-temporal analysis showed that in 2005, there were few areas with a low CRI, mainly concentrated in the periphery of well-developed cities in the south, such as Guangzhou, Shenzhen, Dongguan, Zhongshan and Zhuhai, and in the vicinity of the Shantou Special Economic Zone (SZEZ), whereas a high CRI was found in the north, east and west. In 2010, except for a few areas in the west and north, there was a general trend of a decreasing CRI. The CRI decrease was more pronounced after 2010, especially in the central, eastern and southern coastal regions, compared to the western and northern regions, which showed slight CRI changes. These changes indicate that rural development and the quality of life in the central and southern coastal areas of Guangdong are generally higher than in the northern and western areas, further highlighting uneven regional development.

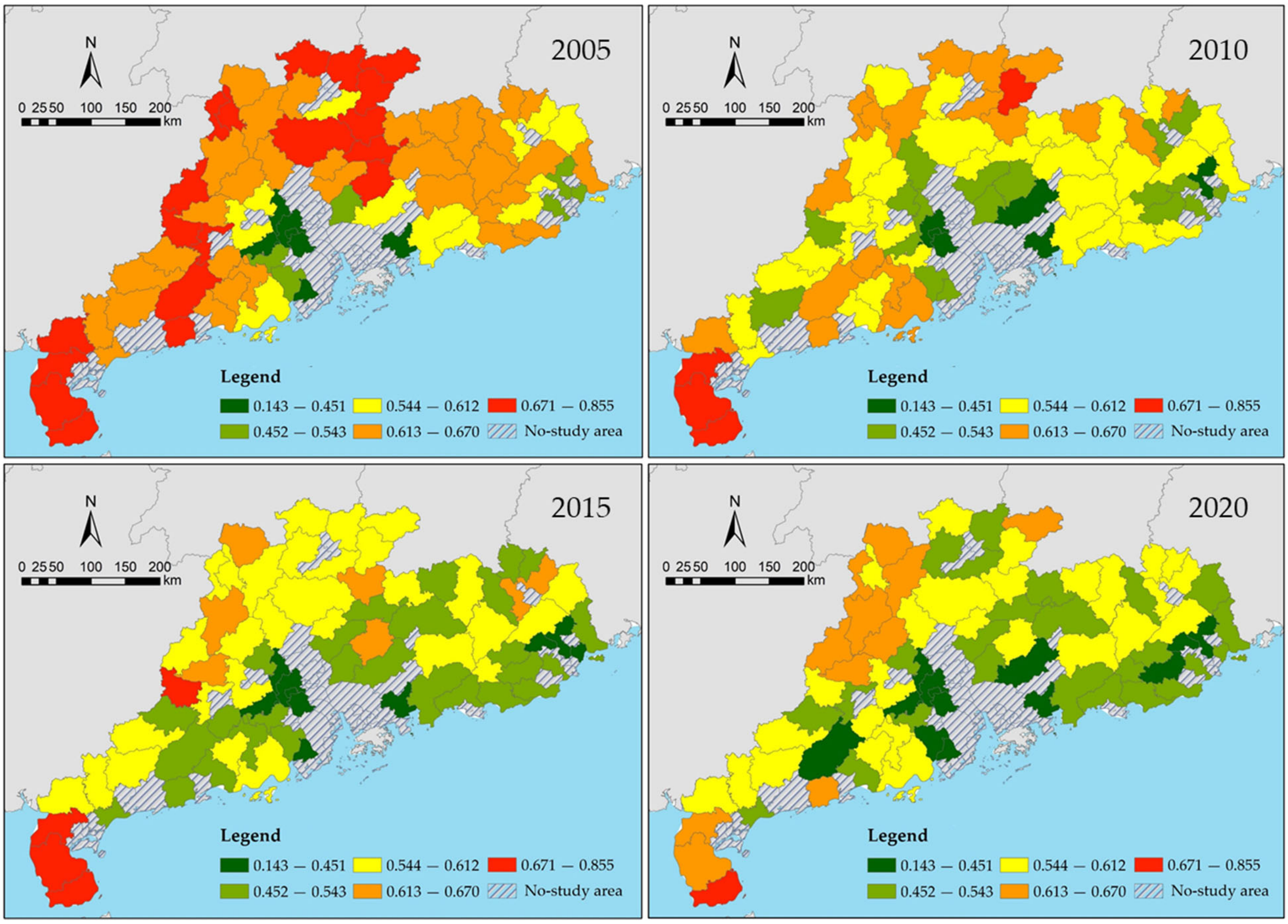

Figure 4. Spatial patterns of CRI in Guangdong Province from 2005 to 2020.

3.1.2. Spatial Aggregation of the County Rurality Index

Based on the characterization of the spatial distribution of the CRIs in Guangdong, this study further explores the aggregation of the CRIs by global and local autocorrelation analysis. Moran's I for the CRI in Guangdong province was positive in 2000, 2010, 2015 and 2020, specifically 0.686, 0.60, 0.667 and 0.624, passing the 1% significance test. This indicates that the CRI is characterized by significant spatial agglomeration. However, the values of Moran's I showed a fluctuating downward trend over time, reflecting that the spatial agglomeration of rurality has gradually weakened. The distribution of the CRI from 2005 to 2020 was mainly dominated by high-value areas (HH aggregation) and low-value areas (LL aggregation), while the mixed aggregation of high-value and low-value regions (HL aggregation and LH aggregation) was rare (see Figure 5). These aggregations were mainly concentrated in central, northern and western Guangdong but were not significant in the east. The CRI HH aggregation areas were mainly in the northern, northwestern and western parts of the province, including Shaoguan, Qingyuan, Zhaoqing and Zhanjiang. Of note, the HH aggregation areas in the north saw a decrease, compared to some increase in the northwest. The LL aggregation areas were mainly concentrated in central regions such as Foshan and Jiangmen.

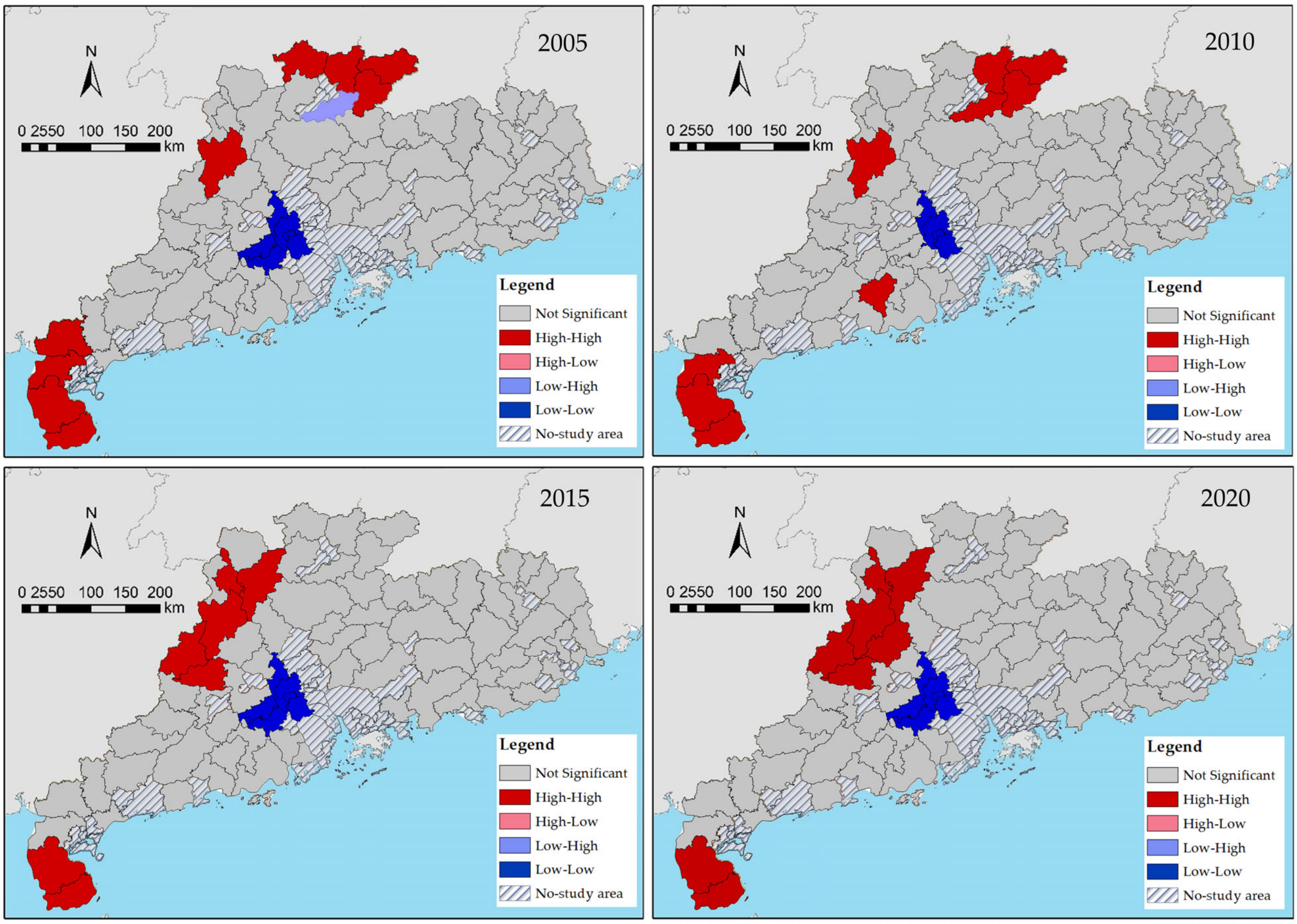

Figure 5. Moran's I for the CRI in Guangdong province from 2005 to 2020.

3.2. Spatial Characteristics of Transport Accessibility

3.2.1. The Spatial Pattern of Transport Accessibility

The spatial pattern of TA in the 77 counties was analyzed based on the TA calculation results (Figure 6). From 2005 to 2020, TA in Guangdong was on the rise as a whole and showed a spatial distribution pattern of high in the middle, low in the periphery and higher in the east than in the west, indicating that traffic development in the central and eastern counties was better than that in the western region and the traffic development gap and imbalance between counties were gradually narrowing. In 2005 and 2010, TA was low in Guangdong as a whole and showed a circular distribution of high in the core area and low in the peripheral area. Compared to 2005, the county TA showed an increase in 2010, but there was no significant change in the core region compared to the core periphery and other peripheral regions. After 2010, Guangdong witnessed rapid development of its transportation infrastructure, with TA further enhanced in the core region and generally on the rise in the surrounding counties. In 2020, the development pattern of TA decreasing from the center to the outer periphery in the counties of Guangdong remained unchanged and was further strengthened. Still, there were some counties with low TA levels, especially in the eastern and western regions, suggesting that they should receive more attention and investment in future transportation development.

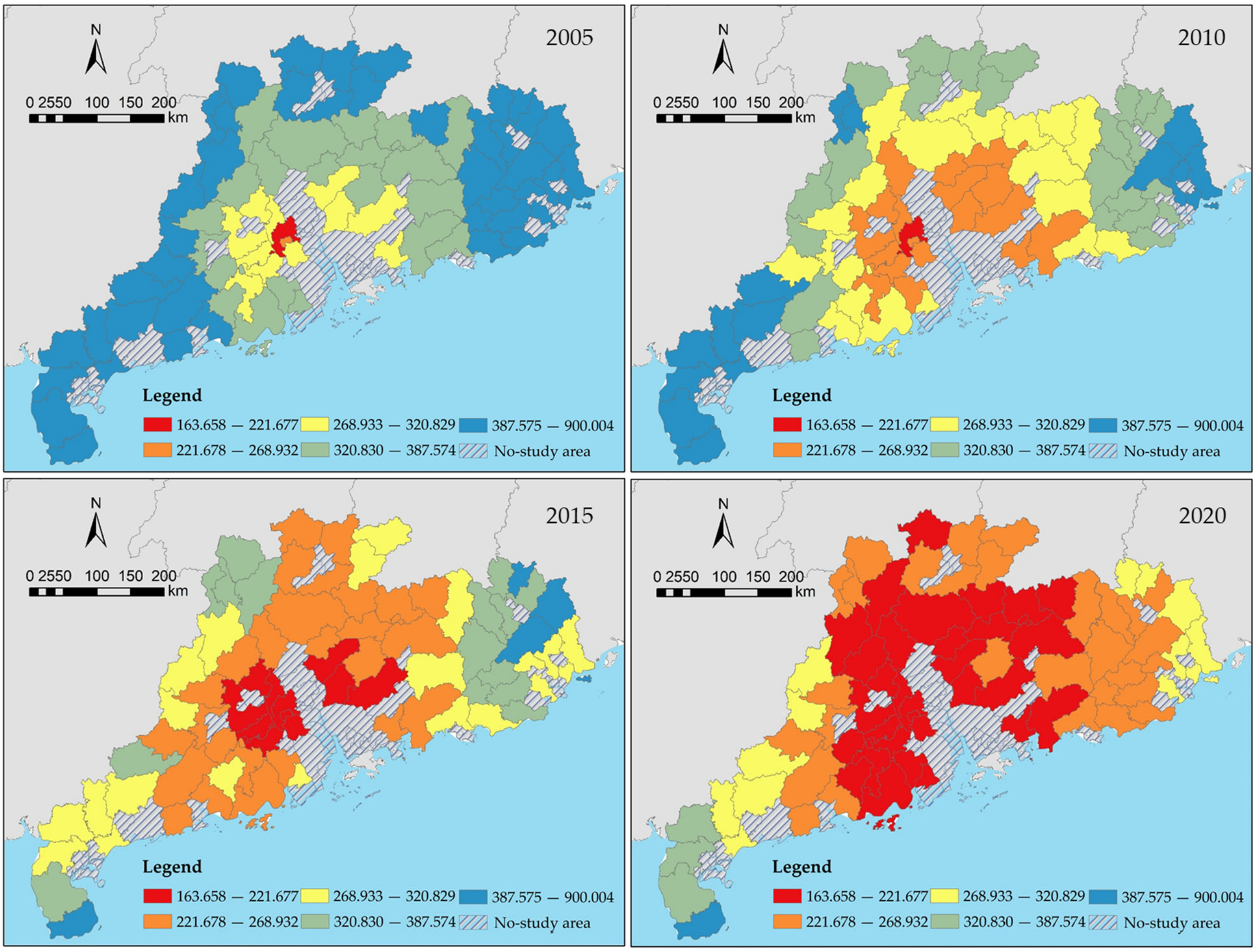

Figure 6. Spatial characteristics of TA in Guangdong province from 2005 to 2020.

3.2.2. Spatial Aggregation of Transport Accessibility

Based on the in-depth analysis of the spatial distribution of TA at the county level in Guangdong, this paper further explores the degree of aggregation of TA in the province by global and local autocorrelation analysis. Globally, Moran's I for the county TA in Guangdong province was significantly positive in 2000, 2010, 2015 and 2020, specifically, 0.855, 0.848, 0.751 and 0.764, passing the 1% significance test. This indicates that TA is characterized by significant spatial agglomeration. However, these indices showed a downward trend over time, indicating weakening spatial agglomeration. The county TA in Guangdong from 2005 to 2020 was dominated by HH aggregation and LL aggregation in its distribution, with less HL and LH aggregation (Figure 7). HH concentrations of TA were mainly found in certain areas such as central Guangzhou, Foshan and Jiangmen; especially, the central and eastern parts showed a decline in HH concentrations. LL aggregations, on the other hand, were mainly found in the western and eastern parts of Guangdong, specifically in certain districts and counties in the eastern and western parts of the province, such as Zhanjiang, Maoming, Meizhou, Jieyang, Chaozhou and Shantou, except for in 2015, when they were found in certain areas in the northwest of the province. LL agglomerations decreased as a whole, especially in the eastern region.

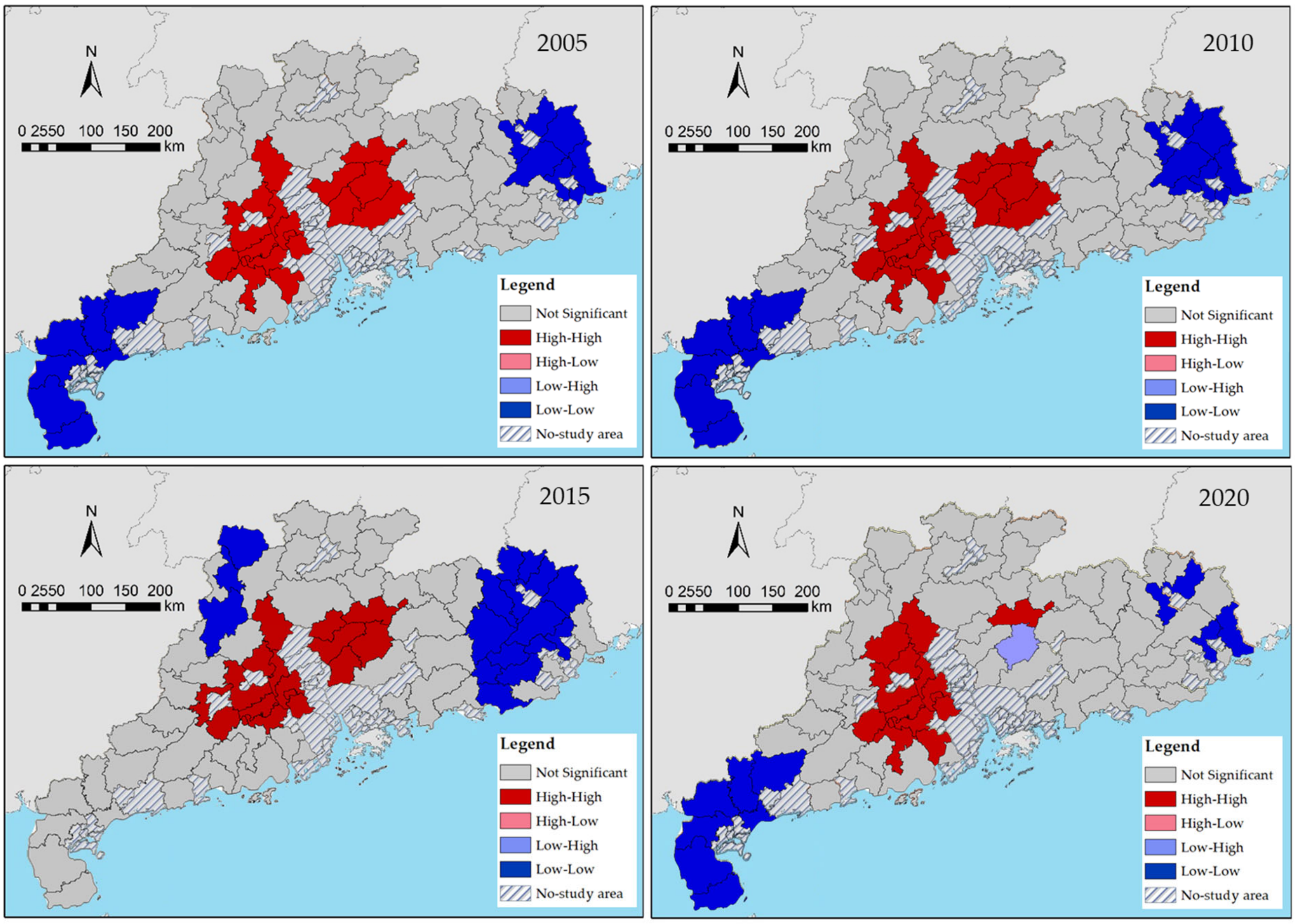

Figure 7. Moran's I for potential TA in Guangdong province from 2005 to 2020.

3.3. Spatial Correlation between TA and the CRI

The study conducted a bivariate spatial autocorrelation analysis using the TA as the independent variable and the CRI as the dependent variable for Guangdong in 2005, 2010, 2015 and 2020. The results showed that the Moran's I values from 2005 to 2020 were −0.414, −0.338, −0.337 and −0.399, respectively, indicating a significant negative correlation between TA and the CRI in county-level space in Guangdong. That is, the CRI was smaller in areas with higher TA, and the negative correlation showed a trend of increasing fluctuation over time, suggesting that improvement in TA plays an increasingly important role in promoting changes in and the development of all factors in rural areas. The bivariable LISA distribution map provides a clearer indicator of the spatial correlation between the value of a variable and the value of another variable in its neighboring region, revealing a high or low spatial positive correlation pattern and a low or high spatial negative correlation pattern (Figure 8). From 2005 to 2020, the counties in Guangdong mainly showed aggregation types of high (TA)–low (CRI) and low (TA)–high (CRI). Low (TA)–high (CRI) aggregations were mainly distributed in western and northern Guangdong and gradually shifted from the north to the northwest, while high (TA)–low (CRI) aggregations showed a more concentrated distribution, especially in Foshan and its neighboring regions in the central part of the province. In addition, there were also high (TA)–high (CRI) aggregations in Guangdong, but they were few and distributed irregularly.

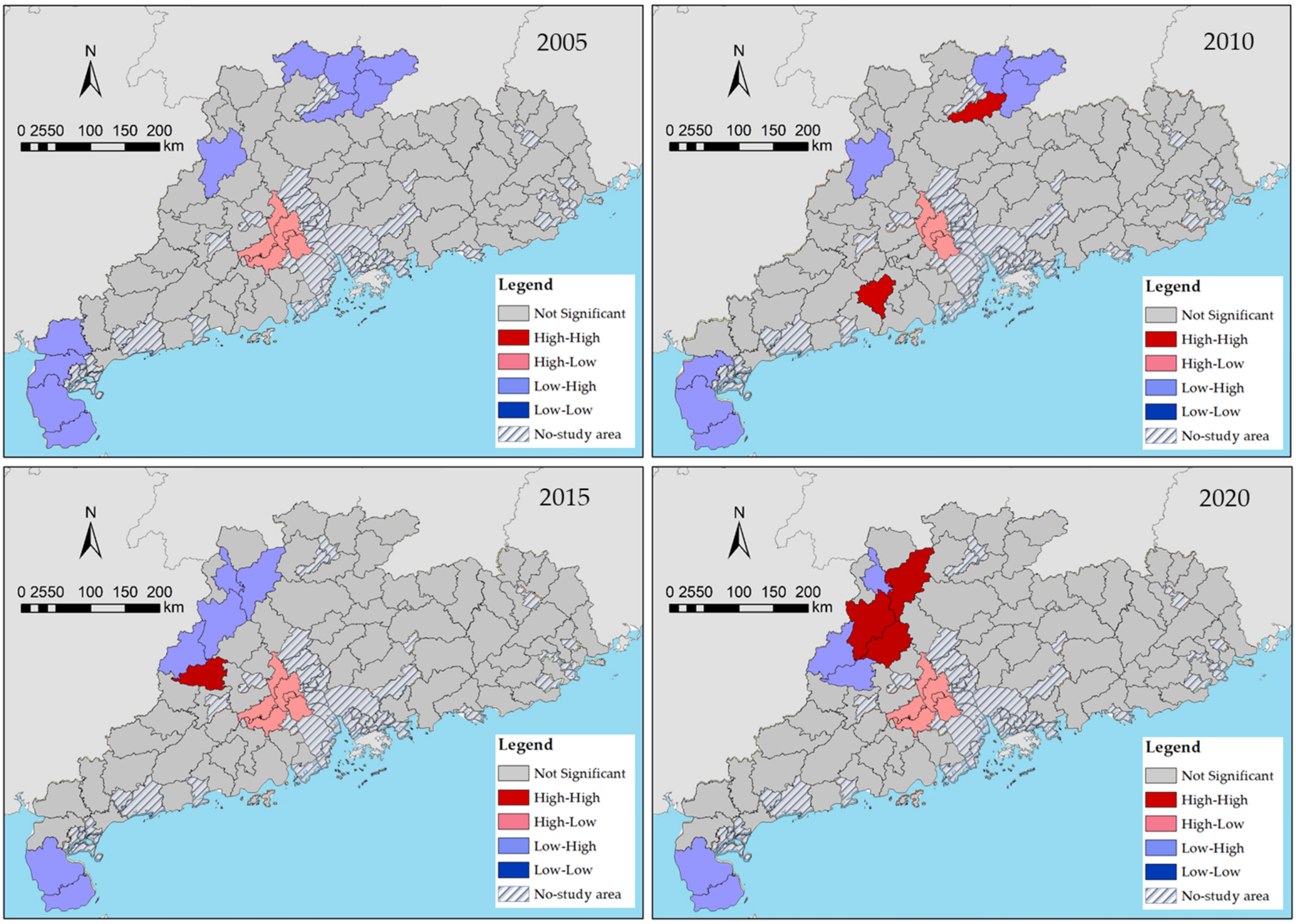

Figure 8. LISA clusters between CRI and TA in Guangdong province from 2005 to 2020.

3.4. The Influence Effect of TA on the CRI

Based on the ArcGIS 10.2 research platform, this paper conducted ordinary least squares (OLS) and GWR analyses with rurality, industry rurality, population rurality, society rurality and land rurality as the dependent variables and TA as the independent variable and visually expressed standardized residuals from the findings to highlight the effect of the independent variables on the CRI in the local geospatial context. The results showed that the R^2 and adjusted R^2 values of the OLS model, from 2005 to 2020, were 0.274 and 0.264, 0.166 and 0.155, 0.196 and 0.185 and 0.288 and 0.278; the R^2 and adjusted R^2 values of the GWR model were 0.725 and 0.558, 0.653 and 0.665, 0.617 and 0.467 and 0.528 and 0.542; the R^2 and adjusted R^2 values of the GWR model were higher than those of the OLS model, indicating that the GWR model has a better fitting effect than the OLS model. In addition, the standardized residuals of the GWR model in the range of [−2.5, 2.5] accounted for about 98.7%, 98.7%, 97.4% and 98.7% (Figure 9), which further confirmed that the GWR model is better than the OLS model in general.

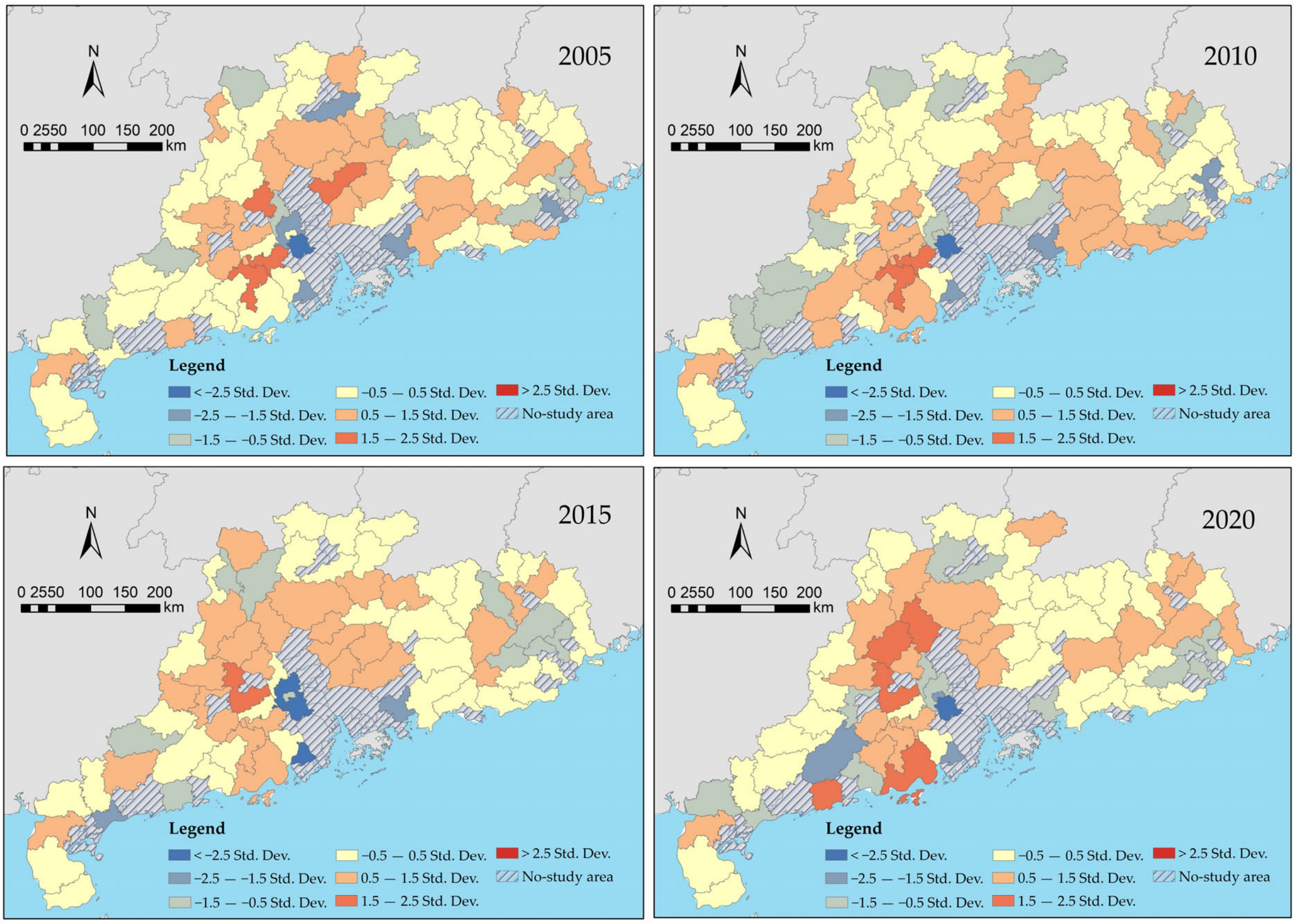

Figure 9. Standardized residuals of GWR between rurality index and accessibility.

An analysis of the impact of county TA on the dimensions of the CRI in Guangdong found that in 2005, county TA had a significant negative impact on rurality, industry rurality, population rurality, society rurality and land rurality, and the impact of TA on the dimensions of the CRI shifted from society rurality > land rurality > rurality > industry rurality > population rurality to society rurality > industry rurality > rurality > land rurality > population rurality in 2020. Compared to 2005, the impact of TA on all the dimensions of the CRI in 2020 decreased significantly, with the largest decrease in land rurality, followed by society rurality, population rurality and rurality and the smallest decrease in industry rurality. This indicates that the impact of TA on social and land rurality was significant in 2005, while in 2020, it showed a strong impact on society rurality and industry rurality, reflecting that rural development is gradually shifting from land use to industrial development. In terms of spatial heterogeneity, the impact of TA on different dimensions of the CRI showed significant spatial differences at different stages. In 2005, the impact of TA on the dimensions of the CRI showed a decrease in intensity from the west to the east, indicating that the impact of TA in the western region was greater than that in the east. In 2020, the impact of TA on the dimensions of the CRI showed more significant heterogeneity in its spatial distribution. The impact of TA on rurality and industry rurality decreased in intensity from the southern coast to the north, while its impact on population rurality and society rurality decreased in intensity from the west to the northeast. The impact on land rurality showed a circular distribution pattern of decreasing from the central south to the periphery (Figure 10).

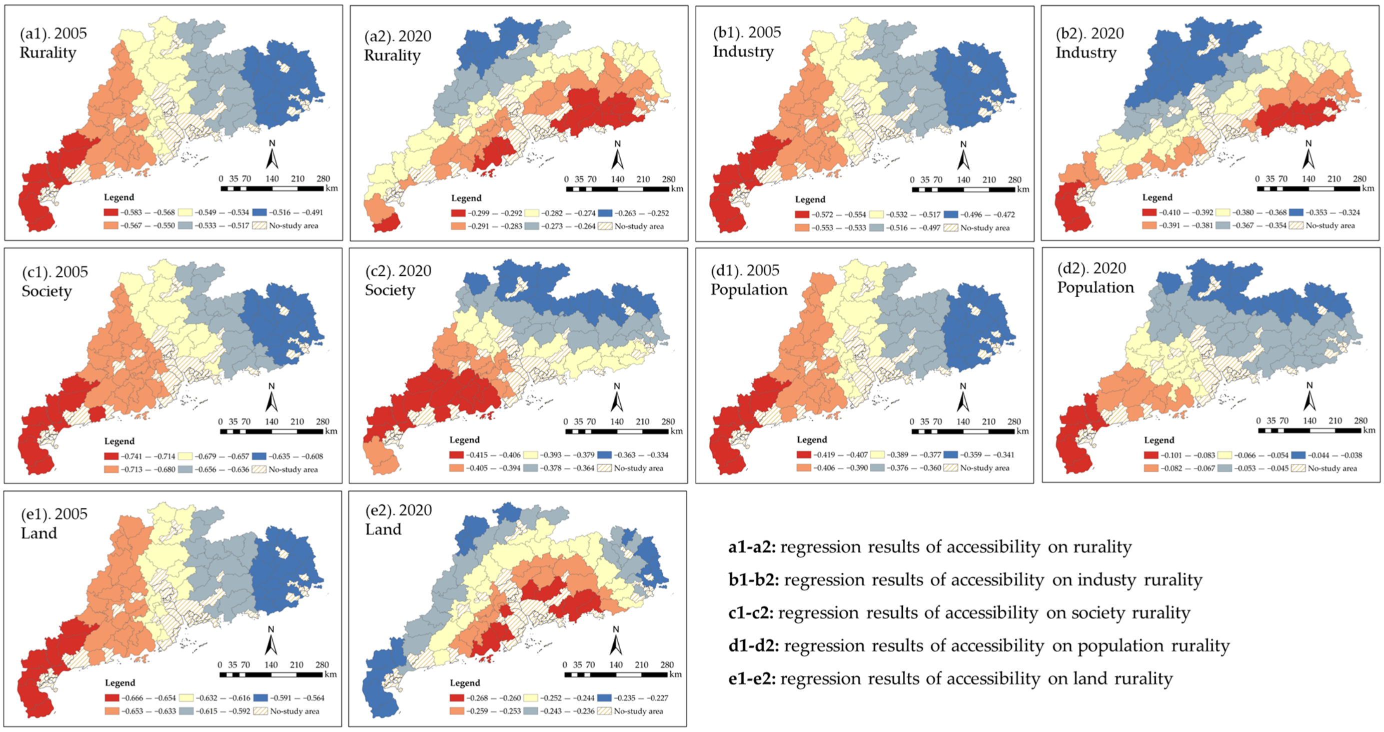

Figure 10. Spatial distribution of regression coefficients of driving factors.

4. Discussion

4.1. External Evidence and Theoretical Thinking

This paper found that the CRI in Guangdong showed a downward trend, with large differences and prominent development unevenness between counties. An uneven CRI is widely found in many places around the world. For example, Long and Yang pointed out that differences in rural resources, location and traffic conditions lead to strong heterogeneity and imbalances in rural space [85,86]. Berkel et al. pointed out that in EU countries, the rurality characteristics vary considerably between regions due to variations in environmental and socio-economic conditions, as well as region-specific constraints [87]. Li et al. found, by studying the spatial pattern of China's rural areas, that the level of rurality in inland regions is significantly higher than that in the eastern coastal regions [27]. Xiao et al. found that rurality in the western mountainous area of Fujian province, with poor economic development, is more prominent than that in the southeast coastal area, with better economic development [39]. Furthermore, this paper found that the Moran's I values of the CRI in Guangdong were all greater than 0.6 during the study period, showing significant spatial agglomeration. Aggregation of the CRI in other geographic areas has been observed in the studies available. For example, Zhang and Han's study shows that rurality in northeastern China and rapidly industrializing regions exhibits more obvious spatial clustering characteristics, with Moran's I in the range of 0.33–0.41 [44,88]. Li et al. studied the rurality of Jiangsu province in China and found that its Moran's I value is 0.53, with significant spatial agglomeration [4]. The findings of this paper are largely consistent with the conclusions of the scholars above, which has further consolidated the spatial agglomeration and imbalance in rural development and contributed to a deeper understanding of the characteristics of rurality.

This paper further detected a negative effect of TA on the CRI in Guangdong, i.e., regions with higher TA showed lower CRIs and a higher level of rural development. This finding is consistent with some of the existing study results. Li, Caschili, Panagiotopoulos, Yao, Kaiser and Ahmed and other scholars have pointed out that the convenience of transportation infrastructure has a significant impact on rurality and that rural characteristics are more pronounced in regions with poorer infrastructure conditions in the transportation network, with lower levels of rural development [54–56,59,89]. However, some scholars have also come up with quite different views. They believe that while changes in rural characteristics are affected by TA, the impact of the quality of transportation (including pavement quality, mode of transportation, level of service, etc.) should not be ignored. For example, Kaiser studied rural transportation infrastructure in low- and middle-income countries and found that changes in rural geographic characteristics were more significantly influenced by factors such as pavement quality, transportation interventions, transportation investments and rural bridges [60]. Rural bridges are often considered an extension of the transportation infrastructure network. However, they are often overlooked in rural transportation studies despite their active role in determining the accessibility and function of important roadways [48,90,91]. Wang and Sun revealed that transportation investment has a positive impact on rural transportation service levels and changes in rural character from a transportation infrastructure investment perspective [12]. Afukaar et al. noted that rural transportation means, the frequency of public transportation and the quality of transportation services have a substantial impact on rural characteristics in their study of rural transport services in Ghana [92]. Bassey et al. found, in their study on the connection between changes in rural characteristics and transportation in Nigeria, that although rural transportation is crucial, its service level does not have a significant impact on the socio-economic development of the region [93]. Kamaludin et al., in their study on rural development in Indonesia, noted that in addition to accessibility, improved transport quality significantly increases the likelihood of rural economic development [94]. It was also observed that the impact of TA on the multidimensional CRI showed a phased dynamic, that is, the impact of TA on society rurality and land rurality was more pronounced in 2005 compared to 2020. This may be due to the fact that rapid urbanization in China in the early 21st century dramatically changed the structure of rural land use and boosted rural incomes, resulting in a stronger effect of transportation on society rurality and land rurality. However, in recent years, with the implementation of the "rural revitalization" strategy, rural development policies have shifted more towards the revitalization of agriculture-centered industries, leading to a more pronounced impact of transportation on industry rurality. These new findings and perspectives constitute the original conclusions of this paper. They provide a valuable supplement on the interaction between transportation infrastructure and rurality which will help to implement more precise and classified policies according to the characteristics of rurality according to different dimensions.

4.2. Policy Suggestions for Sustainable Development

The previous text has confirmed the significant correlation between county TA and the CRI. In this paper, we further categorized the TA and CRI in 2020 at two levels (high and low) and constructed a matrix with natural breakpoints as grading thresholds, according to the analytical idea of the Boston Consulting Group matrix (BCG matrix) [95], and grouped the rurality and transport accessibility development characteristics of 77 county units in Guangdong into coordination types, lagged types of accessibility, lagged types of rurality and double lagged types (Figure 11). As mentioned above, regions with higher rurality levels tend to be associated with poorer rural development, while regions with lower rurality levels tend to have better rural development. Therefore, based on the connection between rurality and the rural development level, this section uses the level of rural development to show the development of rurality.

Coordination types are characterized by a "double high" character, accounting for 16.88%. The county units of coordination types enjoy high TA and a high level of rural development, mainly clustered around the core cities, such as Guangzhou, Shenzhen, Dongguan and Zhuhai. Lagged types of accessibility are characterized by "a high level of rural development and lagging accessibility", accounting for 12.99%. In the county units of such types, transportation accessibility still needs to be improved despite a low rurality index, mainly found in the eastern and western regions. Lagged types of rurality were characterized by "high accessibility and lagging rural development", accounting for 24.68%. The regions of such types featured transport accessibility but a low rurality index, indicating that transportation has not revealed its full impact in promoting rural development. They were mainly scattered in the northern, east–central and central–western regions. Double lagged types are characterized by "double low" values, accounting for 45.45%. The county units of such types are at a low level in terms of both rurality and transportation accessibility, mainly found in the peripheral regions of eastern, western and northern Guangdong.

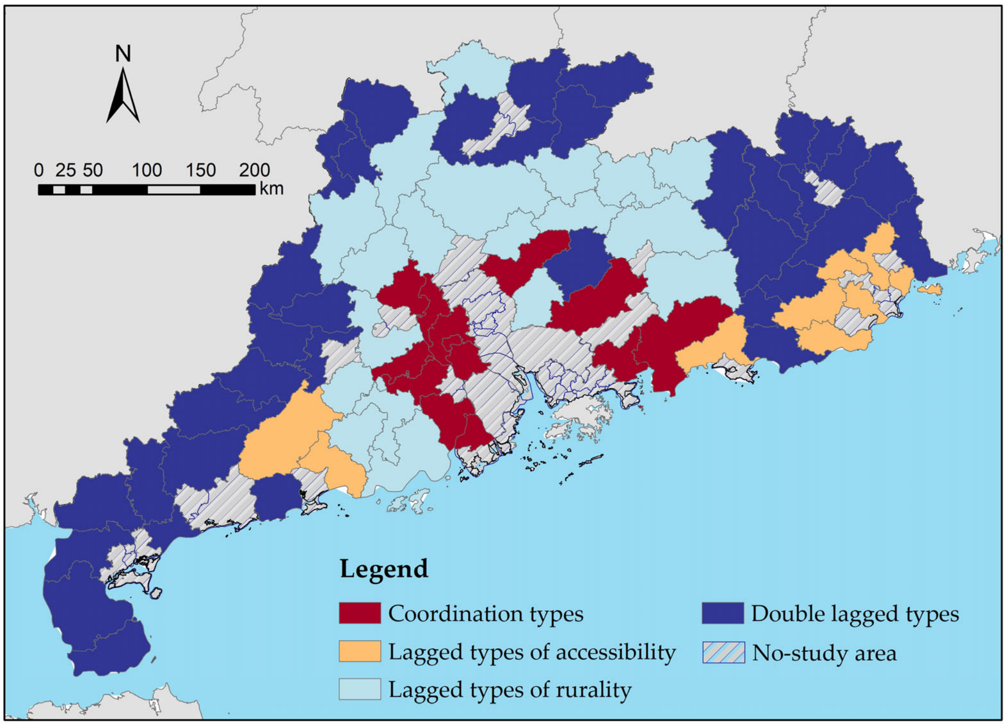

Figure 11. Policy zoning of rurality and accessibility in Guangdong province.

Regions with coordination types have a high level of TA and rural development, and therefore it is recommended that the status quo be maintained without excessive policy interventions to avoid unnecessary waste of resources and disruption to the existing positive development dynamics. Lagged types of accessibility, lagged types of rurality and double lagged types require the intervention of certain regulation policies. With a low level of TA, regions with lagged types of accessibility should focus on rural accessibility as a policy optimization priority and promote rural–town connectivity through improved transportation infrastructure, thereby further stimulating rural development potential. For regions with lagged types of rurality, with superior transportation conditions but a low level of rural development, they should take rural development factors as a focus within policy regulation and promote sustainable rural development by leveraging the interaction between transportation and the countryside. Regions with double lagged types, with both TA and the CRI at a low level, require the intervention of more comprehensive policies. Because of the large differences in the types of rural development in eastern, western and northern Guangdong, it is necessary to establish development policies according to the local conditions and formulate coordinated development policies according to the two aspects of traffic development and rural development.

5. Conclusions

Transportation infrastructure is one of the key drivers enhancing urban and rural connectivity and promoting rural sustainability. In this context, this paper constructed a transportation network and county rurality index evaluation system based on data on Guangdong in China from 2005, 2010, 2015 and 2020. It analyzed the spatio-temporal characteristics of transport accessibility and the rurality index of 77 counties using an accessibility model and rural village indexes. And it explored the spatial differences and clustering characteristics of transport accessibility and the county rurality index through cluster analysis and ESDA and further explored the impact of transport accessibility on the county rurality index according to all dimensions using GWR. The findings are as follows:

(1) The transport accessibility and county rurality index of Guangdong are characterized by obvious spatial inequality. The overall rural index is gradually weakening, showing a distribution pattern of "high in the north and low in the south, high in the west and low in the east". Overall, transportation accessibility is on the rise, showing a stable distribution pattern of "high in the middle and low in the periphery".

(2) The county-level transport accessibility and county rurality index in Guangdong exhibit certain spatial agglomeration characteristics. The transport accessibility and county rurality index distribution types in Guangdong are dominated by HH and LL aggregations, with rare mixed aggregations (HL and LH aggregations) in the high- and low-value areas. High- and low-concentration areas for the county rurality index decrease in the north of Guangdong but increase in the northwest, while LL concentrations are mainly concentrated in the central areas of Foshan and Jiangmen, compared to reduced HL concentrations of transport accessibility.

(3) The impact of transport accessibility on multidimensional rurality in Guangdong shows stage-dependent dynamic changes. The impact of transportation accessibility on the dimensions of rurality shifted from society rurality > land rurality > rurality > industry rurality > population rurality in 2005 to society rurality > industry rurality > rurality > land rurality > population rurality in 2020. Transport accessibility had a significant effect on society rurality and land rurality in 2005, while society rurality and industry rurality in 2020 was greatly affected by transport accessibility.

(4) This paper divided the 77 counties into four policy zonings based on the interaction between transport accessibility and the county rural index in Guangdong, coordination types, lagged types of accessibility, lagged types of rurality and double lagged types, and proposed corresponding development suggestions.

This paper provides a multi-temporal analysis of the spatial evolution characteristics of TA and the CRI in Guangdong at the county level and verifies that at the county level, TA has a significant impact on the multidimensional CRI. This finding provides new ideas and perspectives for rural identity shaping, transportation development and coordinated urban–rural development in the context of rapid urbanization. In theory, this paper explores the correlation mechanism between TA and the CRI and undertakes a detailed analysis of the impact of TA on the multidimensional CRI, which helps us more deeply understand the coordination pattern between rurality and transportation while offering new insights for related theoretical research. In practice, it also confirms that transport infrastructure in some countries and regions is obviously correlated with rurality, and transport infrastructure construction has a significant impact on rural regional characteristics, such as in Nigeria [96], Sardinia [56], Southern Moravia [57], India [63] and low- and middle-income countries [60]. The results of this paper will provide references for research on rurality in other similar areas domestically and internationally and will help the government and decision makers explore suitable strategies for rural development. However, there are some limitations to the study within this paper. First, it mainly focuses on the impact of county TA on the CRI in Guangdong, with no in-depth study on different types of transportation modes and their impact on the CRI. Second, the selection of the CRI indicators is mainly based on the literature review and the development characteristics of Guangdong, not fully covering all rural development elements. For example, insufficient consideration has been given to key factors such as pavement quality, transportation and resource endowment, which may limit the accuracy of its reflection of the development of rural infrastructure. In response to these shortcomings, the authors will make continued efforts to deepen the study in future work, with a view to providing a more comprehensive and in-depth analysis that will lay a more solid theoretical and practical foundation for the comprehensive evaluation of rurality and the formulation of strategies for rural sustainability.

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