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Spatial-temporal Evolution of the Urban-rural Coordination Relationship in Northeast China in 1990–2018

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Abstract: To comprehensively understand the law of urban-rural relationship and propose scientific measures of urban-rural coordinated development in Northeast China, this study uses the coupling coordination degree model and geographically and temporally weighted regression (GTWR) model to analyze the spatial-temporal patterns and the corresponding driving mechanisms of its urban-rural coordination since 1990. The results are as follows. First, the urban-rural coupling coordination degree in Northeast China was very low and improved slowly, but its stages of evolution is a good interpretation of the strategic arrangements of China's urbanization. Second, the urban-rural coupling coordination degree in Northeast China had spatial differences and was characterized by central polarization, converging on urban agglomeration, which was high in the south and low in the north. Moreover, the gap between the north and south weakened. Third, the spatial-temporal evolution of the urban-rural coordination relationship in Northeast China was influenced by pulling from the central cities, pushing from rural transformation, and government regulations. The influence intensity of the three mechanisms was weak, but the pulling from the central cities was stronger than that of the other two mechanisms. Furthermore, the spatial difference between the three mechanisms determines the spatial pattern and its evolution of the urban-rural coordination relationship in Northeast China. Fourth, to promote the development of urban-rural coordination in Northeast China, it is essential to advance urban-rural economic correlation, enhance the government's role in regulating and guiding, and adopt different policies for each region in Northeast China.

Keywords: urban-rural coordination relationship; spatial-temporal evolution; coupling coordination degree model; geographically and temporally weighted regression (GTWR); Northeast China

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1 Introduction

The industrial revolution has promoted the development of urbanization, and it has also greatly aggravated the urban-rural conflict. After the industrial revolution, the academic community has maintained a strong interest in achieving urban-rural coordination (Tacoli and Mabala, 2010). Before World War II, studies about urban-rural coordination relationship mainly focused on theoretical discussion of the urban-rural relationship in

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Western developed countries. The general evolution trend, spatial pattern, and interactive form of urban-rural coordination were studied, and various results were obtained. The disciplines covered include political economy, economics, geography, and urban planning (Xue and Huo, 2010). After World War II, the urban-rural coordination relationship in developing countries has become the focus of research. The theory of urban-rural interactions (Rondinelli, 1985; Lewis, 1989; Unwin, 1989; Douglass, 1998), the 'Desakota' model, the 'urban-rural continuum' model and the 'urban-rural dynamics' theory (McGee, 1989; Tacoli, 1998a) have been put forward by many scholars, which enriched the connotation and theoretical support of urban-rural coordination. Since the 21st century, the research on urban-rural coordination relationship has shifted from theoretical analysis to combining theory with practice. The objective of this research is to explore the development pattern, problems, and countermeasures of the urban-rural coordination relationship of an empirical region (Lynch, 2005; Chamarbagwala, 2010; Wokoun et al., 2010; Berry and Okulicz-Kozaryn, 2011; Kūle, 2014; Pagliacci, 2017; Mainet, 2017; Matern et al., 2018; Lazzarini, 2018; Warren et al., 2018).

Since 2003, China has entered a new period of coordinated urban-rural development that is dominated by a national strategy. As the strategic thinking of urban-rural coordination in China improves, the research on urban-rural coordination relationship goes deeper. Therefore, China has become the main battlefield of international urban-rural coordination relationship research. In the early years, the research focused on the theoretical discussion of the connotation, dynamic mechanism, and mode of development of urban-rural coordination. In recent years, a combination of theory and practice has been used. The literature on the urban-rural coordination relationship in China is very rich, which provides a strong theoretical and methodological support for this study. Currently, measuring the level of urban-rural coordination relationship quantitatively and characterizing its spatial-temporal pattern and forming mechanism, are important basis for formulating strategies for urban-rural coordinated development, and it is a hot topic in the empirical study of China's urban-rural relationship (Po, 2011; Liu et al., 2013; Yu et al., 2015; Wang et al., 2016; Chen et al., 2018; Gao et al., 2018; Smith et al., 2018; Zhang et al., 2019). However, there are still some topics in this field that need to be researched.

First, China has many regional types, with obvious regional characteristics of urban-rural development (Maldonado Rius, 2019). The evolution pattern and process of urban-rural relationship in different regions is the scientific basis for its urban-rural coordinated development strategy (Ma X D et al., 2020). However, most of the empirical studies focus on the developed coastal areas, whereas only a few studies focus on special types of areas and inland areas. Second, some scholars have already discussed the dynamic characteristics of the urban-rural coordination relationship. However, few long-term analyses are covering the major stages of urban-rural development in China. Third, the analysis of the factors affecting the spatial differentiation of the urban-rural coordination relationship is relatively simple, which is not conducive for an in-depth analysis of the formation mechanism and the adjustment of countermeasures.

In the national regional system, Northeast China is not only a traditional industrial area but also an important agricultural production area; therefore, it is both urgent and significant to research urban-rural coordinated relationship since it is a special type of region. As early as during the planned economy period of China, Northeast China embarked on urbanization that prioritized urban development, this led to its obvious urban-rural dual structure. In the 1990s, the increasing influence of the market economy on Northeast China promoted the urban-rural coordination process. Then, with the emergence of the 'Northeast Phenomenon', urban and rural areas in Northeast China experienced socioeconomic waning, which hindered the coordinated development of the urban-rural relationship. Although the implementation of the Northeast Revitalization Strategy in 2003 briefly revived the regional economy and the urban-rural relationship, with the optimization of China's economic structure and the transformation of development momentum since 2014, a 'New Northeast Phenomenon' has emerged. Thus, the urban-rural coordination relationship experienced a 'cold flow' once again (Li et al., 2014). The weak foundation of the urban-rural coordination, the tortuous development trajectory since the reform and opening up have increased the complexity of the urban-rural coordination relationship in Northeast

China. Currently, the gap between urban and rural development in Northeast China is still very large, and it is one of the main obstacles to developing a revitalization strategy in Northeast China.

Currently, there are studies on the urban-rural coordination relationship in Northeast China, but most of them were in local areas or for short periods. Research that analyzes the characteristics of the long-term evolution and the related influencing factors of the urban-rural coordination relationship in the special development background of Northeast China has not been conducted (Ma Z P et al., 2020). Therefore, this study is of great practical importance in predicting the trend of urban-rural coordination relationship, optimizing and regulating the new-type urbanization, and the comprehensive development of the revitalization of Northeast China. Therefore, we use the 34 prefecture-level cities in Northeast China as research objects; this study uses long-term data, covering the entire recession and revitalization process in Northeast China since 1990, to examine the development process, spatial pattern, and driving mechanism of urban-rural coordination in Northeast China. This study can serve as a reference for research on urban-rural coordination relationship in other types of regions in China and provide effective guidance on coordinating the development of urban-rural relationship and achieving high-quality urbanization in Northeast China.

2 Materials and Methods

2.1 Study area and data source

The study area includes 36 prefecture-level cities in Liaoning, Jilin, and Heilongjiang (from south to north) (Fig. 1). The basic analysis unit in this study is the prefecture-level city; its central city and peripheral region are used as the urban and rural areas, respectively. Since no data were available on the Daxinganling Prefecture in Heilongjiang Province and the Yanbian Prefecture in Jilin Province, 34 prefecture-level cities were used in this study. In addition, since Daqing, Heihe, Suihua, Baicheng, and Songyuan were established after 1990, they were not included due to the lack of data before its establishment.

The research period is from 1990 to 2018, and the original data are from the China City Statistical Yearbook (1991–2019) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of China, 1991–2019), the Liaoning Statistical Yearbook (1991–2019) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of Liaoning, 1991–2019), the Jilin Statistical Yearbook (1991–2019) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of Jilin, 1991–2019), the Heilongjiang Statistical Yearbook (1991–2019) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of Heilongjiang, 1991–2019), the China County Statistical Yearbook (1991–2019) (Urban Socioeconomic Investigation Department, National Bureau of Statistics of China, 1991–2019). Missing data were interpolated using the data of adjacent years.

2.2 Research indicators

2.2.1 Comprehensive development indicators of urban and rural systems

It is essential to evaluate the level of comprehensive development of both urban and rural systems in order to use the coupling coordination degree model to measure the urban-rural coordination. The urban-rural coordination is a four-dimensional integration process that is based on the economy, population, space, and society. The economy is the driving force; population is a subject of behavior; space is the carrier, and society is the main embodiment. To show the connotation of these four dimensions, this study established a preliminary

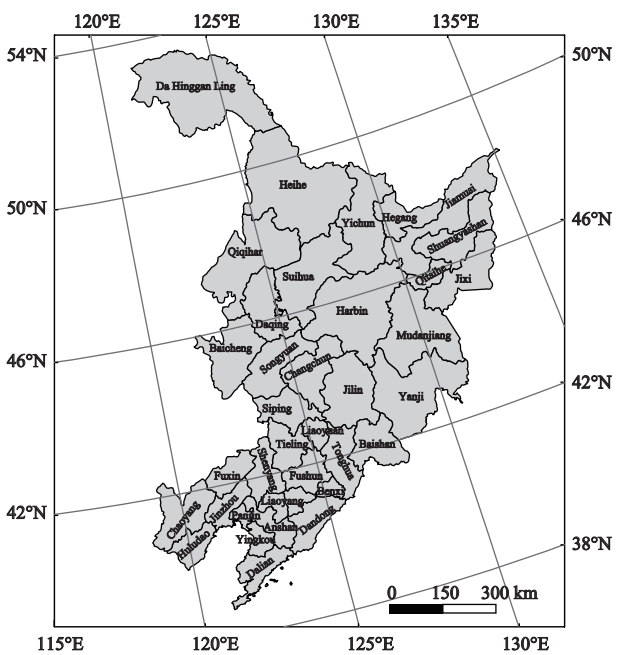

Fig. 1 Location of study area

database of urban and rural comprehensive development in Northeast China by consulting the literature on urban-rural relationship that used quantitative analysis from 2003 (Zhou et al., 2011). The primary data consisted of 20 indicators for the urban system and 20 for the rural system. Due to the many indicators and the obvious multicollinearity of indicators in the same field, it was essential to use a quantitative method to screen the primary indicators. Cluster analysis, variance analysis, and selection of representative indicators were used to quantitatively select the evaluation indicators. Finally, experts were consulted. Then, the evaluation indicator system of the comprehensive development of urban and rural areas in Northeast China was determined. It consisted of 23 indicators in 4 dimensions, 12 for the urban system and 11 for the rural system (Table 1).

2.2.2 Variables for the mechanism analysis of spatial-temporal pattern evolution

The GTWR model was used to discuss the main factors influencing the evolution of urban-rural coordination in Northeast China. The degree of urban-rural coupling coordination was used as the dependent variable, and the independent variables were selected because of the following reasons (Sun et al., 2013). The evolution dynamics of urban-rural coordination mainly include influences from the urban system, rural system, and government capacity. Regarding the urban system, the size of the central city, the speed of economic development, and the superiority of living environment are the basic prerequisites for the inflow of rural factors. Improving the rural production efficiency will lead to a crowding-out effect, resulting in a surplus of factors, which promote the flow of factors into cities. Moreover, improving rural construction conditions and developing non-agricultural industries will strengthen the connection between urban and rural industries, attract urban elements, and form the reverse thrust of the central cities. In addition, the government's urban-rural policies and functions can accelerate or hinder urban-rural linkages. Therefore, 14 indicators were selected from the three dimensions used as the independent variables (Table 2).

2.3 Research methods

2.3.1 Coupling coordination degree model

Urban-rural interaction is mainly through the process of allocating capital, population, land, and facilities between urban and rural systems (Tacoli, 1998b; Chen et al., 2016). In physics, the coupling coordination degree model is often used to measure the degree that two or more systems or forms of motion influence each other during an interaction (Liu et al., 2005; Wu, 2006). This study uses the coupling coordination degree model to measure the urban-rural coordination in Northeast China. The calculation formula is as follows:

Table 1 Comprehensive development indicators of urban and rural systems in Northeast China

Target	Factor	Indicator	Target	Factor	Indicator
Urban system	Economy	GDP per capita / yuan (RMB)	Rural system	Economy	Primary sector output value per capita / yuan (RMB)
		Secondary sector output per capita / yuan (RMB)			Secondary sector output per capita / yuan (RMB)
		Tertiary sector output per capita / yuan (RMB)			Tertiary sector output per capita / yuan (RMB)
		Fixed asset investment / yuan (RMB)			Total power of agricultural machinery / W
	Population	Total urban population / person		Population	Total rural population / person)
		Number of employees in the city / person			Proportion of rural non- agricultural labor force / %
	Space	Built-up urban area / km^2		Space	Fixed asset investment / yuan (RMB)
		Urban green space per capita / m^2			Density of the road network / km / km^2
	Society	Average wage of urban on-the-job workers / yuan (RMB)		Society	Number of doctors per 10000 residents / person
		Number of doctors per 10 000 residents / person			Number of primary and secondary school teachers per 10000 residents / person
		Number of primary and secondary school teachers per 10000 residents / person			Number of books in public libraries per 100 residents / volume
		Number of books in public libraries per 100 residents / volume			

$$C = \left[U_1 U_2 / (U_1 + U_2)^2\right]^{1/2} \quad (1)$$

$$D = (CT)^{1/2} \quad (2)$$

$$T = \alpha f(U_1) + \beta g(U_2) \quad (3)$$

where C represents the coupling degree, which measures the degree of urban-rural interaction. Due to the limitation of the coupling degree, to thoroughly evaluate the urban-rural coordination, it is essential to calculate the coupling coordination degree, which is expressed as D in Equation (2) and indicates the harmony of urban and rural areas in the process of development (Wan et al., 2020). The values of both C and D range from 0 to 1; when the value is close to 1, it indicates a better effect. T represents the comprehensive evaluation index of the two systems; it reflects their overall efficiency or level. U_1 and U_2 represent the scores of the comprehensive development of urban and rural systems, respectively. α and β are undetermined parameters, which are necessary to satisfy $\alpha + \beta = 1$. Since urban and rural systems contribute differently to the coordinated development of the urban-rural relationship, following Sun Dongqi's prediction of urbanization in Northeast China (Sun et al., 2016), this study set the following values: $\alpha = 0.65$, $\beta = 0.35$. U_1 and U_2 were calculated as follows:

$$U_1 = U_2 = \sum \lambda_{ij} u_{ij} \quad (4)$$

where u_{ij} represents the standardized indictor value of index j in urban system (rural system) i, and λ_{ij} represents the weight of index j in urban system (rural system) i, which are necessary to satisfy $\sum \lambda_{ij} = 1$.

2.3.2 Research methods for urban-rural coordination evolution

The range, standard deviation, and coefficient of variation were used to measure the internal differences in the degree of urban-rural coupling coordination in Northeast China. The range represents the absolute developmental difference, whereas standard deviation and coefficient of variation reflect the relative developmental difference.

The relative development rate index (Nich index) measures the development rate of individual regions relative to that of the entire study area over a period. It was used to analyze the evolution characteristics of the growth in the degree of urban-rural coupling coordination in Northeast China; the formula used for the calculation is as follows:

$$Nich = (Y_{2i} - Y_{1i}) / (Y_2 - Y_1) \quad (5)$$

where Y_{1i} and Y_{2i} represent the degree of urban-rural coupling coordination at the end and beginning of a period in region i, respectively, whereas Y_1 and Y_2 represent the degree of urban-rural coupling coordination at the end and beginning of a period in the entire study area, respectively.

Table 2 Variables of the causes of urban-rural coordination evolution in Northeast China

Source	Independent variable	Definition	Unit
Urban system	Population of the central city	Census registered population of the urban area (CRPU)	Person
	Urban economic strength	Total GDP of the urban area (UGDP)	yuan (RMB)
	Urban employment income level	Average wage of urban on-the-job workers (AWUW)	yuan (RMB)
	Scale of urban space construction	Urban built-up area (UBA)	m^2
	Urban health service	Doctors per 10000 residents of the urban area (UD)	Person
	Urban education service	Teachers per 10000 residents of the urban area (UT)	Person
	Cash cost of rural population transfer	Consumption level per capita in the urban area (UCL)	yuan (RMB)
Rural system	GDP per capita in rural areas	GDP per capita in the rural area (RGDP)	yuan (RMB)
	Rural non-agricultural industrial base	Proportion of rural non-agricultural labor force (RNAP)	%
	Modernization level of rural agriculture	Total power of agricultural machinery (AMPT)	W
	Preference for investment in supporting agriculture	Rural proportion of local fixed asset investment (RPFAI)	%
	Density of the road network	Level of rural transportation facilities	km / km^2
Governmentcapacity	Regional construction level	Regional fixed assets investment per capita (RFAI)	yuan (RMB)
	Regional economic level	Regional GDP per capita (RGDP)	yuan (RMB)

2.3.3 Geographically and temporally weighted regression (GTWR)

The GTWR is an extension of the geographically weighted regression (GWR), which is a spatial-temporal non-stationary regression model. However, in the GTWR, a time factor is added to the GWR. Space and time coordinates are required to calculate the space-time weight matrix in the model, whereas in the traditional GWR analysis, there is no temporal dimension. The GTWR extends the traditional GWR analysis by constructing three-dimensional coordinates from space position and time-series coordinates, and it considers the effect of space and time on the regression coefficient of each explanatory variable simultaneously. In the space-time coordinate system, the coordinates of the space-time position i are (u_i, v_i, t_i). Therefore, the GTWR model may be expressed as follows (Gelfand et al., 2003; Huang et al., 2009; 2010):

$$Y_i = \alpha_0(u_i + v_i + t_i) + \sum_{j=1}^{m} \alpha_j(u_i + v_i + t_i) X_{ij} + \xi_i \quad (6)$$

where Y_i represents the value of the interpreted variable at sample point i (i = 1, 2, 3, …, n); m represents the number of explanatory variables; t_i represents the time coordinate of the sample point i; α_0 (u_i,v_i,t_i) represents the spatial-temporal intercept term of sample point i; X_{ij} represents the value of explanatory variable j at sample point i; α_j (u_i,v_i,t_i) represents the regression coefficient of variable j at sample point i, which is a function of space-time coordinates, and ξ_i represents residuals. By introducing spatial-temporal coordinates in the model, the GTWR improves the accuracy of the model fitting, and it makes it possible to analyze the effect of each explanatory variable on the dependent variable from a spatial-temporal three-dimensional perspective. Thus, it has an efficient explanatory power than previous models.

3 Results

3.1 Spatial-temporal characteristics of urban-rural coordination

3.1.1 Characteristics of the time series evolution

The mean value of urban-rural coupling coordination degree in Northeast China from 1990 to 2018 is very low, increasing from 0.226 to 0.351; it indicates that the overall urban-rural coordination was not ideal. The overall difference in the urban-rural coupling coordination in Northeast China also increased slowly (Fig. 2); the range, standard deviation, and coefficient of variation increased from 0.148 to 0.235, 0.036 to 0.061, and 0.168 to 0.175, respectively. The reasons are as follows: from 1990 to 2018, the urban-rural coupling coordination degrees of Shenyang, Changchun, Harbin, and Dalian were higher than that of the average level of the entire region and has improved rapidly, whereas that of the underdeveloped regions increased very slowly; thus, the range kept getting wider. However, in most areas of Northeast China, except for the four major cities, the urban-rural coupling coordination degree showed an increasing trend, but the increase was not obvious; thus, the mean value of the urban-rural coupling coordination degree in Northeast China was good in all the regions, and the relative difference in the urban-rural coupling coordination increased slowly.

Based on the different indices of the urban-rural coupling coordination degree in Fig. 2, the evolution of Northeast China's urban-rural coordination can be divided into four distinct stages, from 1990 to 1999, 1999 to 2004, 2004 to 2014, and 2014 to 2018. This is consistent with the process of 'rural urbanization', 'land urbanization', and 'new urbanization' in China since 1990. From 1990 to 1999, Northeast China experienced economic recession in its cities, whereas the impact of rural urbanization penetrated Northeast China, rural reform, and the loosening of the household registration system pushed the urban-rural coordination to a moderating stage. The mean value and internal differentiation of the urban-rural coupling coordination degree increased steadily. At the end of the 1990s, China entered a land urbanization stage. However, like the cities, the rural area in Northeast China also fell into the development dilemma, resulting in only a small increase in the mean value of urban-rural coupling coordination degree, but the fluctuations in the different indices were obvious. After 2004, the revitalization of Northeast China accelerated its rural population's outward transfer, the interaction between urban and rural areas in various prefecture-level cities has increased. The speed of development in the four major cities, Shenyang, Dalian, Changchun, and Harbin, was the fastest. Thus, the range was continuously widening, and the standard deviation and coefficient of variation were changing slightly. Since 2014, China's economy went into a new normal development stage, and a new urbanization strategy has been

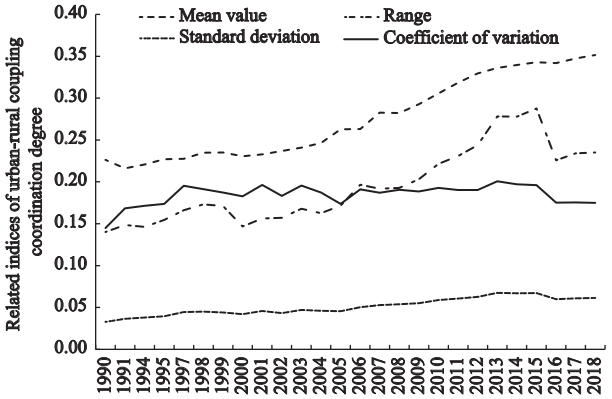

Fig. 2 The overall difference in the urban-rural coupling coordination degree in Northeast China from 1990 to 2018

implemented. The urban-rural coupling coordination degree of most cities in Northeast China has declined, and the decline in mega-cities, big cities, was more serious; thus, the range has reduced, whereas the standard deviation and coefficient of variation have further reduced.

3.1.2 Evolution of the spatial pattern

This study selected 1990, 1999, 2004, 2014, and 2018 as the major nodes of the evolution of the urban-rural coordination. The urban-rural coordination in Northeast China in each year was classified into five categories, very high, high, medium, low, and very low, using the natural breaks (Jenks) method in ArcGIS 10.2. As shown in Fig. 3, Northeast China experienced a relatively stable spatial characteristic of 'central polarization, converging on urban agglomeration, high in the south and low in the north'. First, the four major cities, Shenyang, Dalian, Changchun, and Harbin, had significant advantages in urban-rural interaction. Their urban-rural coupling coordination degrees have always been the highest in the region, and their increasing rate from 1990 to 2018 was the highest. The urban-rural coupling coordination degrees of Shenyang, Dalian, Changchun, and Harbin increased by 0.160, 0.224, 0.221, and 0.211, respectively, which were significantly higher than that of the regional average level of 0.125. Second, the continuous development of the two urban agglomerations in the central-southern part of Liaoning and Harbin-Changchun has made them a highland for the interactive development of urban and rural systems in Northeast China since all the 'very high' and 'high' level areas were there. Moreover, the urban-rural coupling coordination degree of the central-southern part of Liaoning, a relatively mature urban agglomeration, was always the highest. Third, the inter-provincial differences in the urban-rural coupling coordination degree in Northeast China showed a decreasing pattern from south to north. In 1990, the highest mean value of the urban-rural coupling coordination degree was in Liaoning Province (0.235), followed by Jilin (0.224) and Heilongjiang provinces (0.214), whereas in 2018, the highest was in Liaoning Province (0.359) again, followed by Jilin (0.357) and Heilongjiang provinces (0.339). This indicated that the difference in the urban-rural coordination in Northeast China was stable from north to south, but the gap between south and north reduced.

Equation (5) was used to calculate the Nich index of the four stages of the urban-rural coupling coordination degrees in Northeast China. Based on the results, in every period, the entire research area was divided into five sub-areas, very high, high, medium, low, and very low, and the spatial pattern of the differences in the growth of the urban-rural coordination in Northeast China was obtained (Fig. 4). In the four periods, the number of cities with high growth and very high growth of urban-rural coupling coordination degree in Northeast China increased from 8 to 11. Regarding spatial distribution, the four central cities and the two urban agglomerations were the main distribution area of the high growth and very high growth cities in the first three periods. From 2014 to 2018, the regions with very high and high growth rate were in Jilin and Heilongjiang provinces; the growth of urban-rural coupling coordination degree was high in the north and low in the south. This was the main reason why the difference between the urban-rural coupling coordination degree in the north and south decreased.

3.2 Mechanisms of the spatial-temporal evolution of urban-rural coordination

3.2.1 Evaluating the major mechanisms

Using the urban-rural coupling coordination degree as the dependent variable and the 14 indicators in Table 2 as the independent variables, the data of all the research units in each year were processed with ArcGIS 10.2. After processing the data, the GTWR plug-in of ArcGIS 10.2 developed in 2010 by Huang (Huang et al., 2010) was used. The x and y space coordinates were the coordinates of the geometric center of each prefecture-level city, and the minimum step of the time coordinate (t) represented a day. The bandwidth was automatically optimized, and the ratio of spatial-temporal dis-

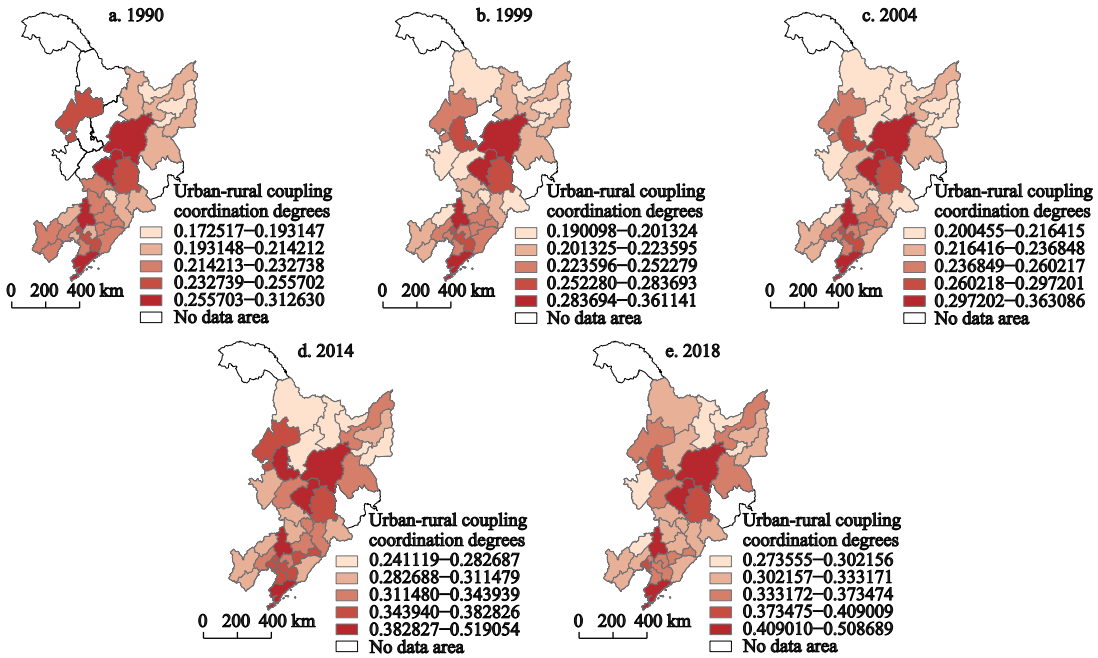

Fig. 3 Spatial pattern evolution of the urban-rural coupling coordination degree in Northeast China

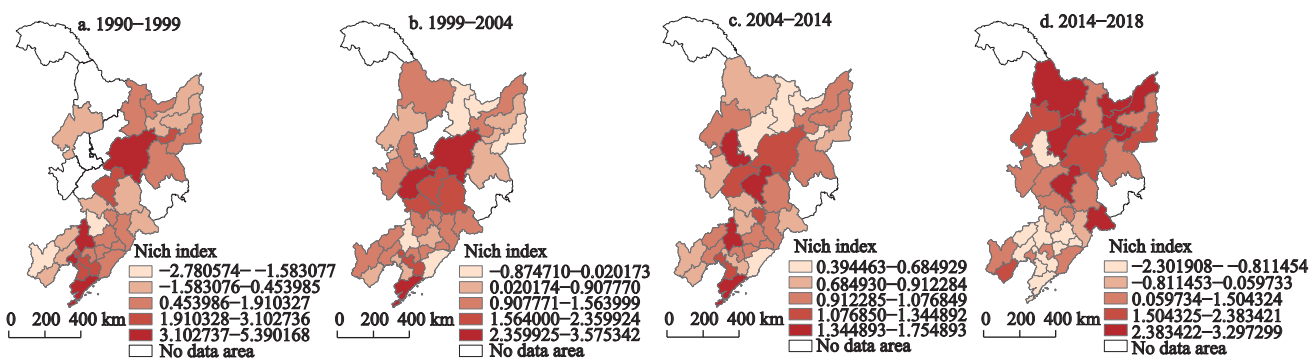

Fig. 4 The spatial pattern evolution of the Nich index of urban-rural coupling coordination degree in Northeast China

tance parameter was set to 1. Then, the influence parameters of each variable in the model were obtained; the higher the value of the parameter, the higher the degree of influence on the dependent variable and vice versa (Brunsdon et al., 1996). In this study, the regression fitting degree R^2 was equal to 0.579; the fitting effect was good and passed the F test of 0.05.

Furthermore, the principal component analysis method was used to reduce the dimensions of the 14 main influence indicators. The results of the analysis reveal that four indicators, CRPU, AWUW, UD, and UT, in the first major component of the load were large. The RGDP carried a significant load in the second principal component. Moreover, the load of RNAP was significant in the third principal component. Finally, the UCL carried a significant load in the fourth principal component. The first and fourth principal components reflected the pulling mechanism of the central cities; the second principal component reflected the government's regulation mechanism (Pace et al., 2000; Song et al., 2008; Dubé and Legros, 2013), and the third principal component represented the pushing mechanism of rural transformation. The sum of the influence parameter values of all the independent variables in each mechanism was the influence intensity value of this mechanism.

3.2.2 Evolution of the major mechanisms

As is shown in Fig. 5, from 1990 to 2018, the average influence intensity values of the three mechanisms had always been weak in Northeast China, which led to the slow growth in the average urban-rural coupling co-

ordination degree. Moreover, the average influence intensity values of the three mechanisms showed the characteristics of a stage evolution, which determined the stage evolution of urban-rural coupling coordination in Northeast China.

Pulling from the central cities. This was the most important influence in the changes of the urban-rural coordination pattern in Northeast China, its mechanism was manifested in the transfer of rural migrant population who were attracted to the advantages of income and facilities in well-developed central cities. From 1990 to 1999, Northeast China experienced a severe economic recession, and the facilities of cities lagged behind. Thus, the average influence intensity value of the pulling from the central cities showed a relatively negative effect, but the situation improved from 1999, especially from 2007, the effect of revitalization on Northeast China began to appear; this led to the rapid development of the urban economy and increase in labor remuneration, attracting many rural residents to work in the cities. The average influence intensity value of the mechanism turned positive and started increasing rapidly, which lead to the rapid development of urban-rural coordination in Northeast China. After 2014, when China entered the new normal development stage and the economy in Northeast China went back into recession, the average influence intensity value of this mechanism was stable at a relatively low level of 0.36, as a result, the development of urban-rural coordination slowed down.

Pushing from rural transformation. The function of this mechanism was mainly through the 'bottom-up' urban-rural economic linkages promoted by the development of rural non-agricultural industries in Northeast China. This mechanism had a positive influence from

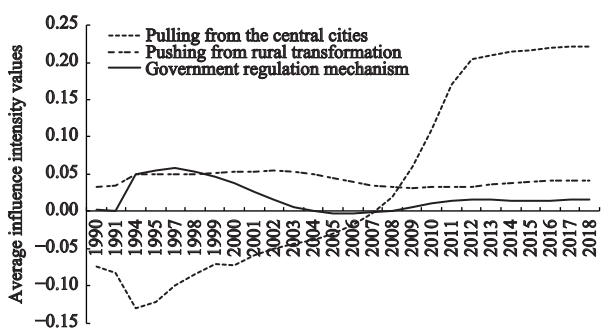

Fig. 5 Evolution of the average influence intensity values of the three mechanisms of urban-rural coordination relationship in Northeast China

1990 to 2018. Before 2003, the effect was the most obvious. Then, from 2003 to 2012, the average influence intensity of this mechanism was weak, and since 2012 it has strengthened. Before 2003, under the influence of rural urbanization, the rural areas in Northeast China formed an industrial distribution and strengthened their relationship with the central cities in the production field; this promoted the urban-rural coupling coordination. However, the 'city-oriented' land urbanization had a significant effect on the industrial development of rural areas in Northeast China and weakened the urban-rural coordination from 2003 to 2012. In recent years, Northeast China has greatly accelerated the development of agricultural product processing industry, which promoted the urban-rural connection and strengthened the urban-rural coupling coordination. However, due to the decline in rural urbanization and the small scale of towns in the rural areas of Northeast China, the development conditions of rural non-agricultural industries were not sufficient, so the promotion of rural transformation through rural-urban linkages was always weak.

Government regulation mechanism. The function of this mechanism in Northeast China was that the government's economic ability guarantees the development of urban-rural coordination. The influence intensity value of this mechanism was low and fluctuated downward. From 1990 to 2003, the influence of government regulation on the urban-rural relationship in Northeast China was relatively high. After 2003, China implemented a strategy to plan both urban and rural areas. However, land urbanization made the central cities the focus of China's urban-rural relationship. Governments at all levels in Northeast China had invested a large amount of funds in urban industrial productivity construction; this was used to invigorate the traditional industrial area in Northeast China, whereas the rural development was neglected. Thus, the influence of the government on the urban-rural coordination in Northeast China was always weak. Since 2014, the economic decline in Northeast China has affected the government's investment capacity, and the role of the mechanism on urban-rural integration has shown a slow growth trend.

3.2.3 Spatial differentiation of the major driving mechanisms

The influence intensity values of the three types of mechanisms in each prefecture-level city in 1990, 1999, 2004, 2014, and 2018 were plotted, and the spatial vari-

ation law of the three driving mechanisms were obtained.

Pulling from the central cities. As shown in Fig. 6, from 1990 to 2004, the mechanism showed a relatively stable spatial distribution pattern; it was high in the south and low in the north. The high-value regions were in the urban agglomeration of the central-southern part of Liaoning, whereas the areas with negative values were in the northern provinces of Jilin and Heilongjiang. Since 2004, the influence of this mechanism has been enhanced in all areas, especially in the northern region. The high-value areas were concentrated in the urban agglomeration of Harbin-Changchun, and the spatial differentiations were high in the north and low in the south. The reason is that, before 2004, the income and service capacity of the cities in the central-southern part of Liaoning was relatively good, whereas the urban unemployment rate was high and the facilities were underdeveloped in the resource-based cities that are widely distributed in the northern provinces. After 2004, the revitalization of Northeast China led to a significant improvement of the situation in all cities, especially the development of Harbin-Changchun urban agglomeration, which led to the faster development of the urban-rural coordination in this area. However, the typical coal resource-based cities in Northeast China were still the weakest due to its slow industrial transformation.

Pushing from rural transformation. As shown in Fig. 7, in 1990, 1999, and 2004, the influence intensity value of this mechanism was high in the central zone of Northeast China. In 2014 and 2018, this pattern changed, and it was high in the south and low in the north. Moreover, the mechanism had always been weak in promoting the regional urban-rural relationship. The negative values were always distributed in the eastern and northern parts of Northeast China. The reason was that conditions of rural non-agricultural development in most of the northern and eastern parts of Northeast China were inherently weak since these areas had a small population, scattered settlements, and lacked the impetus for rural industrial development. In parallel, most cities in the central and southern parts of Northeast China had entered a proliferation stage, and an improved non-agricultural industrial base in rural areas was the prerequisite for close interaction between urban and rural systems.

Government regulation mechanism. As Fig. 8 shows, this mechanism had a weak impact on urban-rural coordination in Northeast China, and there were always some cities that government regulation had negative impacts on. The spatial variation of the intensity of the influence of government regulation on urban-rural coordination in Northeast China was obvious. In 1990,

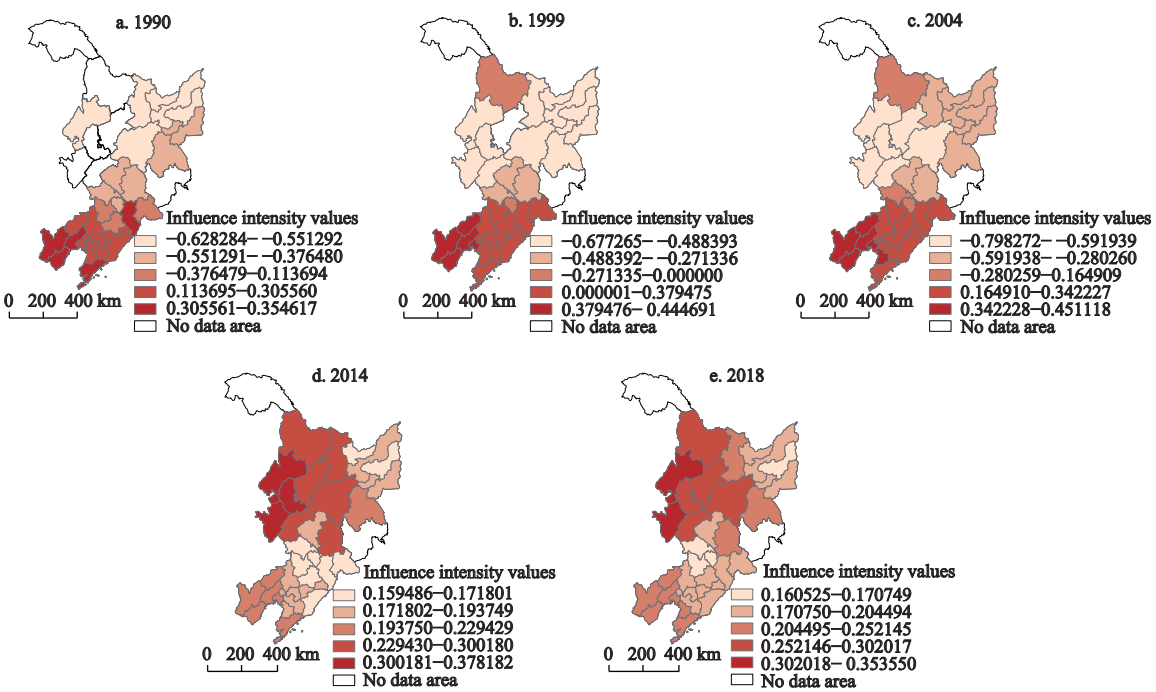

Fig. 6 Spatial pattern evolution of the influence intensity values of the pulling from the central cities in Northeast China

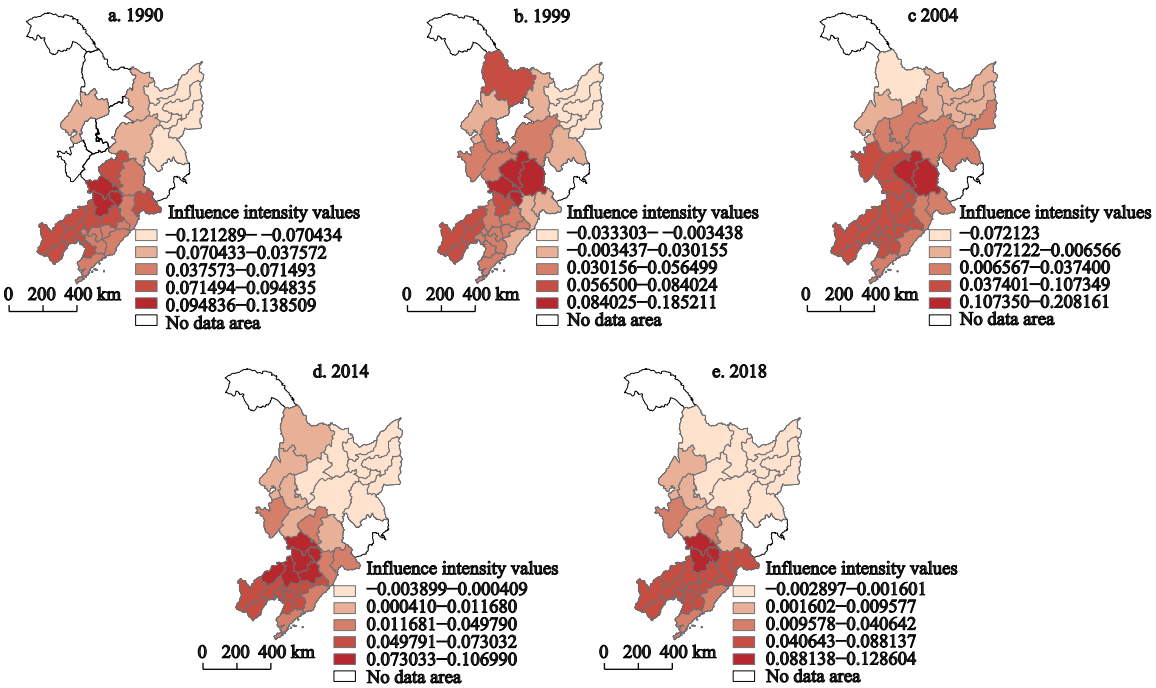

Fig. 7 Spatial pattern evolution of the influence intensity values of the pushing form rural transformation in Northeast China

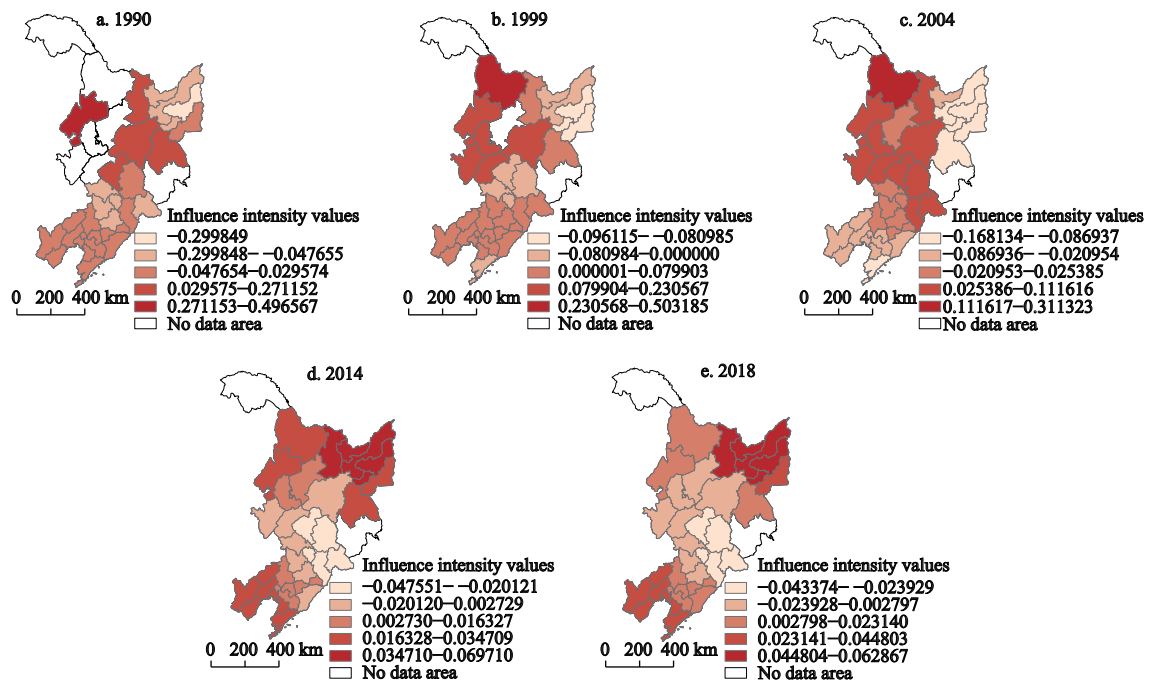

Fig. 8 Spatial pattern evolution of the influence intensity values of government regulation mechanism in Northeast China

1999, and 2004, the government played a significant role in the Harbin-Changchun urban agglomeration, this intensity value of this mechanism was high in the north and low in the south. Then, from 2004 to 2018, it gradually evolved into a 'dumbbell-shaped' spatial pattern with high values in the coastal areas of Liaoning province and the northern areas of Heilongjiang province, respectively. The reason was that these two urban agglomerations had the highest economic strength in Northeast China, funds for government expenditures were relatively sufficient, and the urban-rural coupling coordination degree was relatively high. The cities in

marginal and resource-based areas in the northern part of Heilongjiang were small in scale, and their urban-rural coordinated development was seriously lagging behind. However, it had become the focus of the government and investment in these cities was relatively large, and government regulation mechanism of urban-rural coordination in these cities was more prominent.

4 Discussion

(1) By using a long period data, this study deepens our understanding of the urban-rural coordination relationship in Northeast China since 1990. Over the past 30 yr, the evolution of the urban-rural coordination relationship in Northeast China was synchronous with China's urbanization and urban-rural development strategy. Since China has entered a new stage of urbanization and urban-rural integration, an optimized development of the urban-rural relationship in Northeast China is an inevitable trend. However, due to the weak driving mechanisms of the evolution of the urban-rural coordination relationship, the coupling coordination degree of the urban-rural relationship in Northeast China had been low. It can be predicted that the urban-rural coordination in Northeast China will continue to develop slowly.

(2) Mechanism of the evolution of urban-rural coordination relationship shows that the problem of urban-rural dual division in Northeast China has not been effectively solved due to the lack of the basis for industrial linkage between urban and rural areas. To achieve the coordinated development of urban and rural areas in Northeast China, it is essential to examine urban-rural industrial linkages. For a long time, the objective of government regulation was to restrict and suppress the coordinated development between urban and rural areas in Northeast China. In the future, the government's regulation, guidance, and support have to strengthen the optimization of urban-rural coordination in Northeast China.

(3) Our results have wide-ranging policy implications. According to the spatial-temporal pattern of the urban-rural coordination in Northeast China, the spatial differences should be fully considered in its regulation and guidance. The mega-cities in central Northeast China should speed up their industrial upgrading and improve urban functions. In this way, they can realize a 'back-feeding' effect on the urban-rural functional integration and promote the growth and development of rural areas. The underdeveloped resource-based cities and cities in traditional rural areas should explore the characteristic mode of urban-rural coordination. They can promote rural agricultural product processing industrial clusters and gathering space to enhance the connection between urban and rural industries. They can also focus on agricultural landscape and ecological resources and promote tourism to enhance urban-rural industrial linkages.

(4) We used the GTWR model to analyze the driving forces of the evolution of the urban-rural relationship, this is not found in previous mechanism studies. However, the application of the GTWR model still needs further correction. For example, the determination of 2D coordinates the parameter ratio of the time and space dimensions, the bandwidth optimization of the model, and the choice of the time step unit need to be further investigated. In addition, under the background of new-type urbanization and a new round of revitalization of Northeast China, there should be follow-up studies about the urban-rural coordination relationship of Northeast China in the future.

5 Conclusions

This study explores the urban-rural coordination relationship in a special type of region and period. Based on the regional characteristics of Northeast China, this study observed the urban-rural coordination relationship for a long period, comprehensively analyzed the spatio-temporal evolution, and introduced the GTWR model to analyze the driving mechanism. The conclusions are as follows:

(1) From 1990 to 2018, the urban-rural coupling coordination degree in Northeast China was low. The average value of the urban-rural coupling coordination degree in Northeast China increased from 0.226 to 0.351, the growth was only 0.108 in the past 30 years. Since 1990, the coordinated development of urban and rural areas in Northeast China can be divided into four obvious stages, which is generally consistent with the national urbanization development strategy and the evolution process of urbanization and urban-rural relationship.

(2) From the perspective of spatial pattern, the urban-rural coupling coordination degree in Northeast China had obvious and relatively stable spatial differences.

From 1990 to 2018, it always displayed a pattern of central polarization, converging on urban agglomeration, and it was high in the south and low in the north. Four central cities, Harbin, Changchun, Shenyang, Dalian, always led the development of urban-rural coordination, which led to a high level of urban-rural coordination along the central Harbin-Dalian economic belt. Another high-value zone of urban-rural coordination formed in Northeast China was dominated by the urban agglomerations of Harbin-Changchun and the central-southern part of Liaoning. The differences in urban-rural coupling coordination degree among provinces are as follows. The highest was in Liaoning Province; the second was in Jilin Province, and the lowest was in Heilongjiang Province. Moreover, due to the rapid coordinated development of the urban-rural relationship in the north, the pattern of 'high in the south and low in the north' loosened.

(3) The development of the urban-rural relationship in Northeast China mainly depended on pulling from the central cities, pushing from rural transformation, and government regulation. However, the three mechanisms were relatively weak, which was the main reason for the slow development of the urban-rural coupling coordination in Northeast China and the relative stability of the spatial pattern in each period. Among the three mechanisms, pulling from the central cities was stronger than the other two mechanisms, it also shows that the urban-rural integration in Northeast China was at the initial stage of development, and the cities played a leading role in the overall development of the urban-rural system.

(4) The changes in the three influence mechanisms led to the evolution of urban-rural coordination in Northeast China. From 1990 to 1999, pushing from rural transformation and the government regulation mechanism had a positive impact, whereas pulling from the central cities had a strong negative effect, and the overall development of urban-rural coordination was slow. From 1999 to 2004, the influence of pushing from rural transformation and the government regulation mechanism changed slightly, whereas the negative effect of the pulling from the central cities weakened rapidly, and the fluctuated development of urban-rural coordination was obvious. From 2004 to 2014, the city-oriented land urbanization had increased the influence of the pulling from the central cities mechanism; it became the most important force in the evolution of the urban-rural coordination in Northeast China and promoted the rapid development of urban-rural coordination. From 2014, the urban economic recession in Northeast China stabilized the pulling from the central cities, and the coordinated development of urban and rural areas had entered a deceleration stage.

(5) The spatial differentiation of the major mechanisms determined the spatial pattern of the urban-rural coupling coordination degree in Northeast China. In 1990, the pushing from rural transformation played the most important role in Northeast China; this mechanism showed the spatial pattern of 'center polarization, high in the south and low in the north', which established the overall spatial pattern of the urban-rural coordination in Northeast China. Since then, pulling from the central cities and government regulation mechanism showed obvious 'high in the north and low in the south' pattern or development trend, and the difference in the urban-rural coupling coordination between the south and north had gradually reduced.

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