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Towards greener urbanization: Resource environmental effects and sustainable land use

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Towards greener urbanization: Resource environmental effects and sustainable land use

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Impacts of Different Rural Settlement Expansion Patterns on Eco-Environment and Implications in the Loess Hilly and Gully Region, China

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While the eco-environmental effects of rural settlement expansion are of great significance to rural sustainable land use, the relationship between rural settlement expansion and eco-environment under different expansion patterns is still unclear. To fill this gap, the current study used Baota district of the loess hilly and gully region as a case study area. We first investigated the spatiotemporal expansion patterns of rural settlements from 1990 to 2015 and then estimated their impacts on ecosystem services by implementing the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model and the global agro-ecological zones (GAEZ) model. Results showed the following: 1) edge expansion was the primary pattern of rural settlement expansion in Baota district from 1990 to 2015, and the area of edge expansion was 757.40 h m^2, accounting for 71.76% of the total expansion area of rural settlements. 2) Rural settlement expansion caused 1744.60 t loss of crop yield, 40,155.78 Mg C loss of carbon storage, and a significant decline in habitat quality of water areas during 1990–2015. 3) According to the unit expansion area, the edge expansion and leapfrog expansion patterns contributed more to ecosystem services loss than the infilling expansion pattern. 4) There were gradient differences in the impacts of three expansion patterns on ecosystem services, and the impacts were gradually weakened by the increased distance. Accordingly, we concluded that the expansion of rural settlements reduced surrounding ecosystem services, especially food production service, and that the edge expansion and leapfrog expansion patterns had higher levels of stress on ecosystem services.

Keywords: rural settlement, expansion patterns, ecosystem services, loess hilly and gully region, China

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1 INTRODUCTION

Rural settlement changes reflect development in society and economics and affect ecosystem services (ESs) in the rural regional system (Gude et al., 2006; Röder et al., 2015). Rural settlements in many countries have grown evidently due to influences such as rapid population growth and accelerated urbanization, which is especially the case in developing countries (Tassinari et al., 2010; Song and Liu, 2014). Unsystematic growth will encroach on a large amount of ecological space, which indeed will bring a series of ecological security problems like local temperature rise (Yang et al., 2021; Zhao et al., 2021; Ren et al., 2022), flooding (Tiepolo and Galligari, 2021), water pollution (Kröger et al., 2012; Wu et al., 2012), air pollution (Braniš and Domasová, 2003; Zhou et al., 2020), and food yield reduction (Ju et al., 2018; Zou et al., 2021). Therefore, regulating rural development and minimizing negative effects of rural settlement expansion on eco-environment are of great significance in achieving sustainable rural development.

To achieve this, many studies have been conducted to reveal rural settlement expansion. Through this, policymakers and rural planners can generate evidence-based suggestions for sustainable land use planning and harmonious development. For instance, Song et al. (2014) analyzed the impacts of socioeconomic factors (i.e., rural register population, rural housing investment, and per-capita rural housing area) on rural settlement expansion patterns in China. Similarly, Chen and Ye (2014) found that decisions made by individuals and village collective organizations play an important role in rural settlement expansion. Moreover, Li et al. (2017) analyzed the effects of rural settlement evolution on ecosystem service values in the western part of the Songliao Plain, China. In comparison, from the perspective of maintaining regional ecological security, Yin et al. (2020) put forward different optimization directions and management strategies of rural settlements for different areas of the Da'an city, China.

More recently, the concept of expansion patterns, describing or analyzing landscape pattern changes, has been introduced into rural settlement expansion studies (Bhatta, 2010; Xu et al., 2016; Chen et al., 2021a). This concept offers a scientific basis for rural sustainable land use planning from the perspective of the landscape pattern. For instance, Tian et al. (2014) defined rural settlement dynamics into three patterns of edge expansion, dispersion, and urban encroachment in the Beijing metropolitan region, China. Their results also found that the expansion of rural settlements was mainly developed around the metropolitan region, and it gradually extended into the periphery of the metropolitan region. Moreover, Chen et al. (2021b) analyzed the variation in the expansion scale, speed, and pattern diversity of rural settlements by increased distance to urban built-up areas. Tan and Li (2013) examined the impacts of socioeconomic factors (i.e., decrease in household size, increase in numbers of migrants, and improvements in living conditions) on rural settlement expansion patterns in Beijing, China.

It is, therefore, concluded that rural settlement expansion is affected by various factors such as physical geography, socio-economy, and policy, which also determine the diversity of its expansion patterns (Yang et al., 2015). Meanwhile, the impacts of diverse expansion patterns on eco-environment were different due to morphological characteristics and scale of expansion types (Xian et al., 2019). Accordingly, analyses of the effects on eco-environmental are required for specific cases and different expansion patterns in order to obtain the most accurate results for rural settlement planning. To the best of the authors' knowledge, this is one of the first studies examining the impacts of rural settlement expansion on ecosystem services from the perspective of different expansion patterns in the loess hilly and gully region. The study aims to understand such impacts through the case study of Baota, a typical county in the loess hilly and gully region, China. This study uses the landscape expansion index (LEI) to identify rural settlement expansion patterns and uses the ecological loss contribution rate to assess the impacts of different expansion patterns on eco-environment. This study sheds the light for rural development planning in ecologically fragile areas and further provides a reference for rural settlement expansion.

2 MATERIALS AND METHODS

2.1 Study Area

In this study, Baota district, a district in Yan'an in the Shannxi province of China, was selected as the case study area. It is recognized as a typical ecological fragile area with serious soil erosion (Yuan et al., 2019). The Baota district is situated in the south part of the loess hilly and gully region (36°10′N–37°02′ N, 109°14′E–110°50′E), with a total territorial area of approximately 3,539 km^2 (**Figure 1**). In terms of topography, 50.8% of the area is hillside land and the gully density ranges from 3.04 to 5.01 km/km^2. The soil erosion area of Baota district is 3,154 km^2 (89.12% of the total territorial area) with an average annual sediment loss of 22 million tons (Wang, 2009). Moreover, the average annual precipitation is about 550 mm, mostly from July to September. The annual average evaporation is 1,579.7 mm, which is about three times of precipitation.

The rapid economic and social development in Baota district has put tremendous pressure on the local eco-environment. By the end of 2018, Baota district governed 611 administrative villages, with a total population of 472,000, and achieved gross domestic product (GDP) of 32.89 billion CNY (Chinese Yuan). Along with the rapid urbanization, the rural residential area of Baota district expanded rapidly, which occupied massive ecological land. For example, from 1990 to 2015, the rural settlement area of Baota district expanded to 1,052 hm^2, 75.52% of which were transformed from agricultural lands, 6.32% transformed from woodlands, and 15.32% from grasslands (Chen et al., 2021b). Therefore, taking Baota district as a case in response to eco-environment to the expansion of rural settlements is highly representative of the ecological fragile areas.

2.2 Data Source

The rural settlements in this study are defined as rural land for residential purposes and commercial purposes. The resources of the land-use data (1990, 1995, 2000, 2005, 2010, and 2015; multispectral, 30-m spatial resolution) used in this study came from the Resources and Environmental Science Data Center (http://www.resdc.cn). The first-level land use types are divided into agricultural land, woodland, grassland, water area, construction land, and unused land, and the subclasses land use types are divided into 17 types. For the classification of land use/ cover change, its overall accuracy is more than 90%, which is the most exact land area utilized; the data monitoring is performed by remote sensing in China (Liu et al., 2014).

2.3 Methods

2.3.1 Landscape Expansion Index

The landscape expansion index was a vital indicator to define the construction land expansion pattern. In this study, the expansion pattern of rural settlements was determined by LEI (Liu et al.,

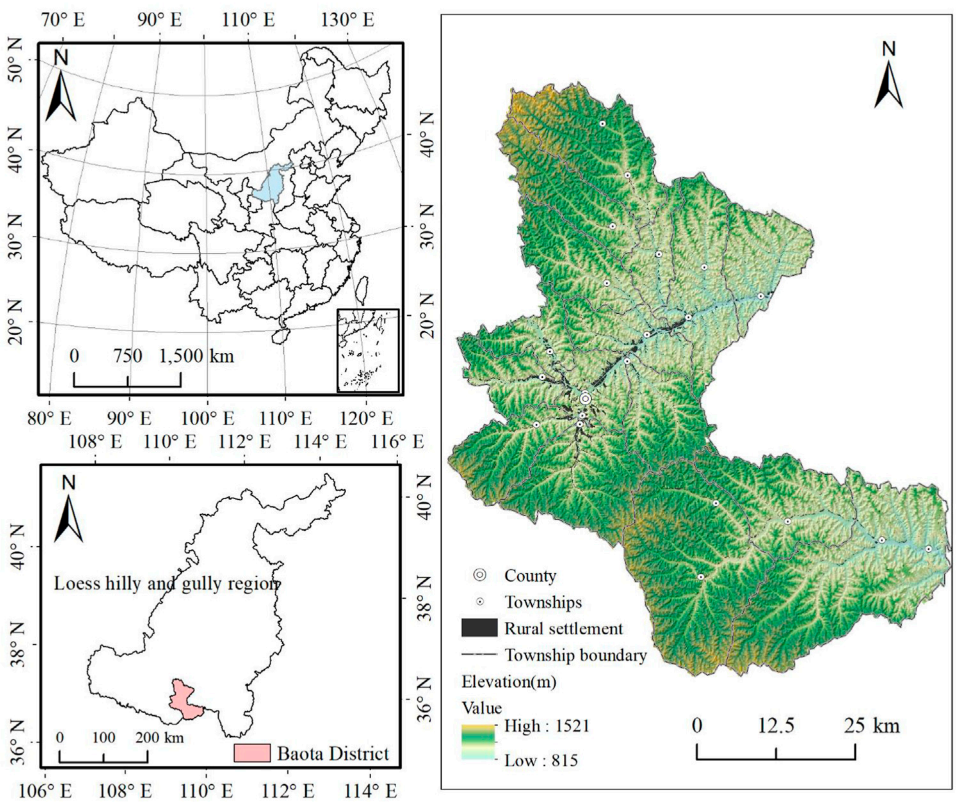

FIGURE 1 | Location of Baota district.

2010). The calculation of LEI for the novel patch of rural settlement was conducted using **Eq. 1**, as follows:

$$\mathrm{LEI} = \frac{A_1}{A_1 + A_2} \times 100, \tag{1}$$

where A_1 represents the intersecting area of the old patch of rural settlements and the buffer zone, while A_2 represents the cross-sectional area between the former zone of non-rural settlements and the buffer zone. The buffers are defined as the zones with specified distances around a newly grown settlement patch. The buffer radius in this formula was set to 30 m and equal to the resolution of land use raster data to ensure the reasonableness of the intersection area. In accordance with LEI, rural settlements could be divided into three expansion patterns: infilling expansion, leapfrog expansion, and edge expansion. The edge expansion pattern is defined as the novel patch of rural settlements growing from the edge, and its LEI range is between 0 and 50. The leapfrog expansion pattern is defined as the novel patch of rural settlements isolated from the old patches with the LEI equal to 0. The infilling expansion pattern refers to as a new rural settlement filling the gaps among old rural settlements with the LEI between 50 and 100.

2.3.2 Ecosystem Services Evaluation

In this study, we followed the United Nations Millennium Ecosystem Assessment (MA), which divides ecosystem services into provisioning services (i.e., production of food and water), regulating services (i.e., regulation of climate and water), supporting services (i.e., provisioning of habitat), and cultural services (i.e., spiritual, recreational, and cultural benefits) (Millennium Ecosystem Assessment, 2005). The cultural service is not discussed in this study because we are interested primarily in the eco-environment impacts of rural settlement expansion. Thus, we selected representative indicators of provisioning (food production), regulating (carbon storage), and supporting (habitat quality) services to quantify the impacts of rural settlement expansion on ecosystem services (Hou et al., 2017; Wu et al., 2018; Lyu et al., 2021).

2.3.2.1 Food Production

Food production, a critical provisioning service that ecosystems provide for human survival, is primarily assessed using census and remote sensing data (Tao et al., 2012; Tian and Qiao, 2014). However, it is difficult to assess the spatial variability of food productivity under complex environments using this regular approach. The GAEZ model comprehensively considers multiple factors (i.e., light, temperature, moisture, agro-climatic conditions, soil, and terrain) and provides a solution for evaluating food productivity under complex environmental conditions (Li et al., 2019). Considering the complex terrain in the loess hilly and gully region, the GAEZ model was used in our study to calculate the yield potential of crops under the average

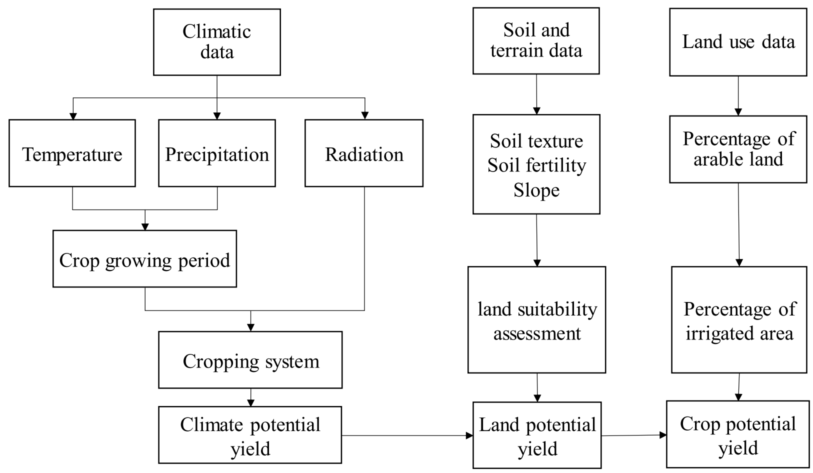

FIGURE 2 | Schematic diagram of overall structure and data integration of GAEZ.

climate conditions from 1990 to 2015. The GAEZ model calculated the crop potential yield utilizing a step-by-step limiting approach, containing the climate potential yield (i.e., limiting water, temperature, and light), land potential yield (i.e., limiting temperature, light, soil, and water), and crop potential yield (i.e., limiting management approaches and level of agricultural input) (**Figure 2**) (Jiang et al., 2020). Because of the accumulated temperature in Baota district above 10°C was 3,245°C, it meets the needs of the one-crop farming system (Liu et al., 2021). Therefore, the crop potential yield was determined using the one-crop farming system.

The model of GAEZ contained the rain-fed and irrigated scenarios. Under the irrigated and rain-fed conditions, for each grid cell, the potential yields of crop are revealed as follows:

$$Y_t = Y_{rain} \times (1 - i) + Y_{irrigated} \times i, \tag{2}$$

where $Y_{irrigated}$ represents the potential yield of crop under the irrigated conditions in each grid cell (kg/hm^2), Y_{rain} represents the potential yield of crop under the rain-fed conditions in each grid cell (kg/hm^2), and Y_t represents the potential yield of crop in each grid cell (kg/hm^2), while i represents the ratio between total cultivated area and the irrigation-cultivated area. The results showed that the yield values followed a normal distribution, so the zonation outputs were divided in five categories using the natural breakpoint method: low yield ($0 < Y \leq 1{,}000$), medium–low yield ($1{,}000 < Y \leq 1{,}500$), medium yield ($1{,}500 < Y \leq 2000$), medium–high yield ($2000 < Y \leq 3{,}000$), and high yield ($Y > 3{,}000$).

2.3.2.2 Habitat Quality

Habitat quality is an ecosystem's ability of providing suitable living conditions for individual and population persistence (Sharp et al., 2015). In the model of InVEST, the habitat quality module utilizes threat factors and land use data as the major data sources, which offers an intuitive and fast approach to assess the habitat quality (Bai et al., 2019). The habitat quality index changes continuously from 0 to 1, and the closer the value is to 1, the more conducive it is for the maintenance of biodiversity (Sun et al., 2019; Li et al., 2021). The calculation of habitat quality was conducted using **Eq. 3**, as follows:

$$Q_{xj} = H_j\left(1 - \left(\frac{D^z_{xj}}{D^z_{xj} + k^z}\right)\right), \tag{3}$$

where Q_{xj} is the habitat quality value (unitless relative value of 0–1) at the xth pixel of the j type land; H_j represents the value of habitat suitability for the j type land; D^z_{xj} represents the relative sensitivity to threat sources at xth pixel of land type j; z is the normalization constant; and k represents the semi-saturation constant. Based on biodiversity conservation objectives, we selected agricultural land, woodland, grassland, and water area as habitats. Subclasses habitats consisted of paddy land, arid land, forest land, shrubwood, sparse woodland, other woodland, high coverage grassland, medium coverage grassland, low coverage grassland, river canal, lake, and reservoir pond. The parameters, habitat suitability, maximum distance of threat, and threat factors weight along with the sensitivity of distinct habitats to threat factors, are determined based on literature and expert knowledge (**Table 1**) (Polasky et al., 2011; Baral et al., 2014; Hou et al., 2017; Chen et al., 2021a). The zonation outputs were divided in five levels (equal interval) of habitat quality scores: low quality ($0 < Q \leq 0.2$), medium–low quality ($0.2 < Q \leq 0.4$), medium quality ($0.4 < Q \leq 0.6$), medium–high quality ($0.6 < Q \leq 0.8$), and high quality ($0.8 < Q \leq 1$).

2.3.2.3 Carbon Storage

The InVEST carbon storage module estimated the total carbon sequestration by using the land use-and-cover data and the amount of carbon stored in carbon pools (He et al., 2016). The formula for carbon stocks in the InVEST model is as follows:

$$CS_{xj} = A_{xj} \times \left(AC_j + BC_j + SC_j + DC_j\right), \tag{4}$$

where CS_{xj} is the carbon stocks value at the xth pixel of land type j, Mg C; A_{xj} represents the xth pixel area for the j type land, hm^2;

TABLE 1 | Habitat suitability and sensitivity of habitats to threats.

Habitats		Habitat suitability	Threats				
1st Level classes	Subclasses		Urban land	Rural settlement	Other construction land	Paddy land	Arid land
Agricultural land	Paddy land	0.4	0.5	0.35	0.2	0	1
	Arid land	0.3	0.5	0.35	0.2	1	0
Woodland	Forest land	1	0.9	0.7	0.5	0.5	0.6
	Shrubwood	0.7	0.6	0.4	0.2	0.3	0.4
	Sparse woodland	0.6	0.8	0.6	0.4	0.5	0.6
	Other woodland	0.4	0.8	0.6	0.4	0.5	0.6
Grassland	High coverage grassland	0.7	0.6	0.45	0.3	0.4	0.45
	Medium coverage grassland	0.6	0.65	0.5	0.35	0.45	0.5
	Low coverage grassland	0.4	0.7	0.55	0.4	0.5	0.55
Water area	River canal	1	0.8	0.6	0.4	0.5	0.6
	Lake	0.9	0.85	0.65	0.45	0.55	0.65
	Reservoir pond	0.9	0.9	0.7	0.5	0.6	0.7
Relative weight			0.8	0.5	0.8	0.6	0.6
MAX_DIST			5	2.5	6	1.5	1.5

[a]MAX_DIST: the maximum distance over which each threat affects habitat quality (measured in km).

TABLE 2 | Carbon density for each land use type (unit: Mg C/hm^2).

LULC type		Carbon density (Mg C/hm^2)				References
1st Level classes	Subclasses	C_{above}	C_{below}	C_{soil}	C_{dead}	
Agricultural land	Paddy land	4.7	0.68	34.8	0	Liu and Zhao (2018); Bao (2015)
	Arid land	4.02	0.76	25.9	6.5	
Woodland	Forest land	30.9	14.66	82.29	13	Bao (2015); Liang et al. (2021)
	Shrubwood	7.14	3.09	64.29	2	
	Sparse woodland	5.48	2.42	64.29	2	
	Other woodland	1.31	2.33	29.9	0.35	
Grassland	High coverage grassland	3.37	7.48	44.36	4.47	Cheng et al. (2011); Bao (2015); Liang et al. (2021)
	Medium coverage grassland	2.33	7.3	43.72	3.8	
	Low coverage grassland	1.66	3.41	10.86	2	
Water area	River canal	3.25	2.42	29.9	0.35	Bao (2015); Liang et al. (2021)
	Lake	2.75	0	144.13	0	
	Reservoir pond	2.3	0	146.26	0	
Construction land	Urban built-up land	0.01	0	23.3	0	Liu and Zhao (2018); Liang et al. (2021)
	Rural settlement	0.01	0	23.3	0	
	Other construction land	0.01	0	22.2	0	
Unused land	Bare land	0.01	0	3.6	0	Liu and Zhao, (2018)
	Bare rock	0.01	0	3.6	0	

Note: 1 Mg C = 1 × 10^6 g C.

AC_j represents the aboveground density of carbon for the j type land, Mg C/hm^2; BC_j represents the underground density of carbon for the j type land, Mg C/hm^2; SC_j represents the density of soil organic carbon for the j type land, Mg C/hm^2; and DC_j represents the density of dead organic carbon for the j type land, Mg C/hm^2.

The carbon density parameter determines the accuracy of the simulation. Therefore, it is necessary to reasonably define the carbon density. Carbon density is affected by various factors (i.e., climate, vegetation, parent material, and topography), and the carbon density parameters in different regions are quite different. In this study, we adopted the average value of the carbon density of each land use type based on the published literature in recent years, whose study areas were located in the loess hilly and gully region, and built a carbon density database of different land use types. (**Table 2**).

2.3.2.4 Ecological Loss Contribution Rate

The contribution rate of rural settlement expansion to ecosystem services loss refers to the loss of ecosystem services resulting from the expansion of rural settlements. This index can quantify the effect of rural settlement expansion on regional ecosystem services and help to study the major factors leading to the loss of ecosystem services. The formula is as follows:

$$R_{ij} = \frac{ES_{ij}}{ES_i}, \tag{5}$$

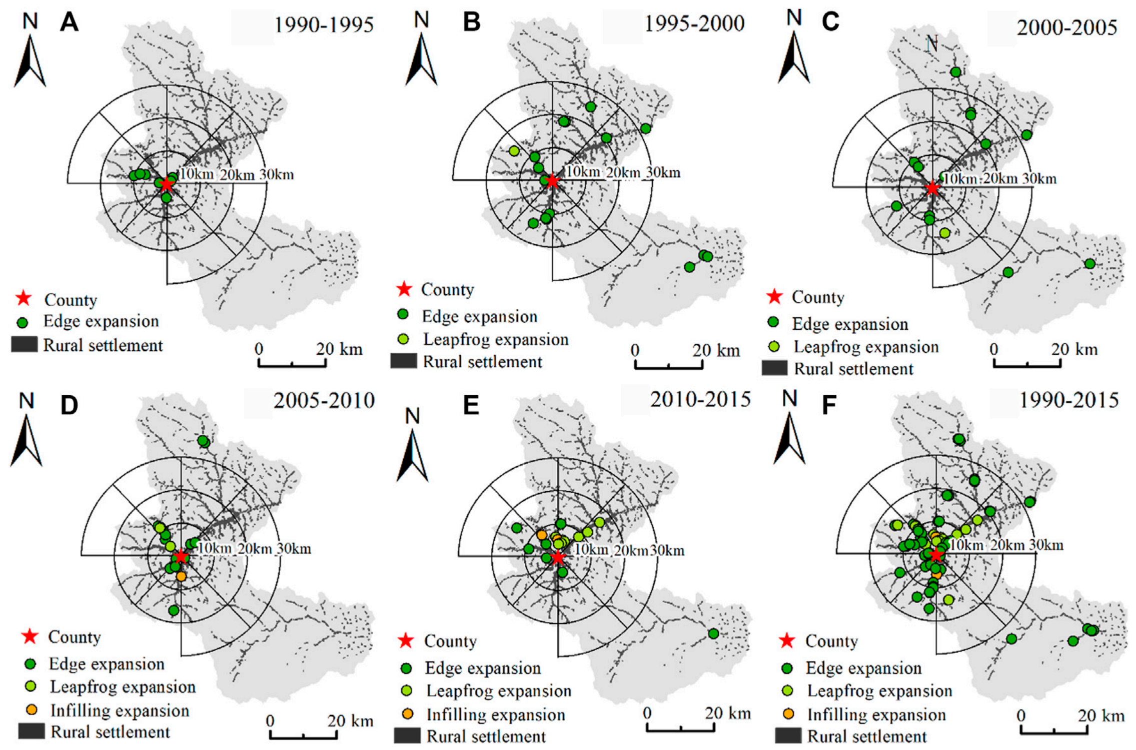

FIGURE 3 | Spatiotemporal expansion patterns of rural settlements in Baota district during different periods **(A)** 1990–1995, **(B)** 1995–2000, **(C)** 2000–2005, **(D)** 2005–2010, **(E)** 2010–2015 and **(F)** 1990-2015.

where R_{ij} is the loss contribution rate of the i-type ecosystem service caused by the rural settlement expansion pattern j; ES_{ij} is the loss value of the i-type ecosystem service caused by the rural settlement expansion pattern j; and ES_i is the loss value of the i-type ecosystem service caused by the rural settlement expansion. In addition, in accordance with He et al. (2016) and Goldstein et al. (2012), for residential land, we presumed that the ecosystem services of rural settlements can be ignored owing to its relatively small value of ecosystem services, which was hard to quantify for the residential land with high heterogeneousness.

3 RESULTS

3.1 Spatiotemporal Expansion Patterns of Rural Settlement

Edge expansion was the major rural settlement expansion pattern in Baota district from 1990 to 2015. The area with edge expansion was 757.4 h m^2, accounting for 71.76% of the total expansion area in the course of study. During the same time period, the areas with infilling and leapfrog patterns were 86.1 h m^2 and 211.9 h m^2, respectively, accounting for 8.16 and 20.08% of the total expanded area, respectively.

The rural settlement expansion patterns in central suburb areas (20 km within the county center) were diversified while those in far-flung suburb areas (20 km outside the county center) were simplistic (**Figure 3F**). Specifically, between 1990 and 1995, edge expansion was the main expansion pattern of rural settlement expansion and concentrated in central suburb areas (**Figure 3A**). From 1995 to 2005, with the “Grain for Green” Project implemented, rural settlements in Baota district gradually concentrated from hillsides to valleys. Thus, the edge expansion pattern dominated in far-flung suburb areas. Meanwhile, with the development of township enterprises, the leapfrog expansion pattern emerged in central suburb areas (**Figures 3B,C**). Although the expansion of rural settlements in Baota district was gradually active before 2005, it was difficult to form a filling expansion model due to the small scale of expansion. In the period between 2005 and 2010, the infilling expansion pattern emerged but in central suburb areas, and the area of leapfrog expansion pattern increased. The edge expansion pattern was still the primary mode in far-flung suburb areas (**Figure 3D**). In the period of 2010–2015, as a result, the area of leapfrog and infilling expansion patterns increased to 151.3 h m^2 and 55.3 h m^2 in central suburb areas (**Figure 3E**).

3.2 Ecosystem Services Change

3.2.1 Change of Food Production

The estimated total crop yield of Baota district in 1990 and 2015 were 254,913 t and 172,931 t, respectively, which decreased by 81,982 t based on the GAEZ model (**Figures 4A,B**). The change area of low yield, medium–low yield, medium yield, medium–high yield, and high yield areas were −44.6 km^2, 91.2 km^2, −88.5 km^2, −241.2 km^2, and −60.2 km^2, respectively

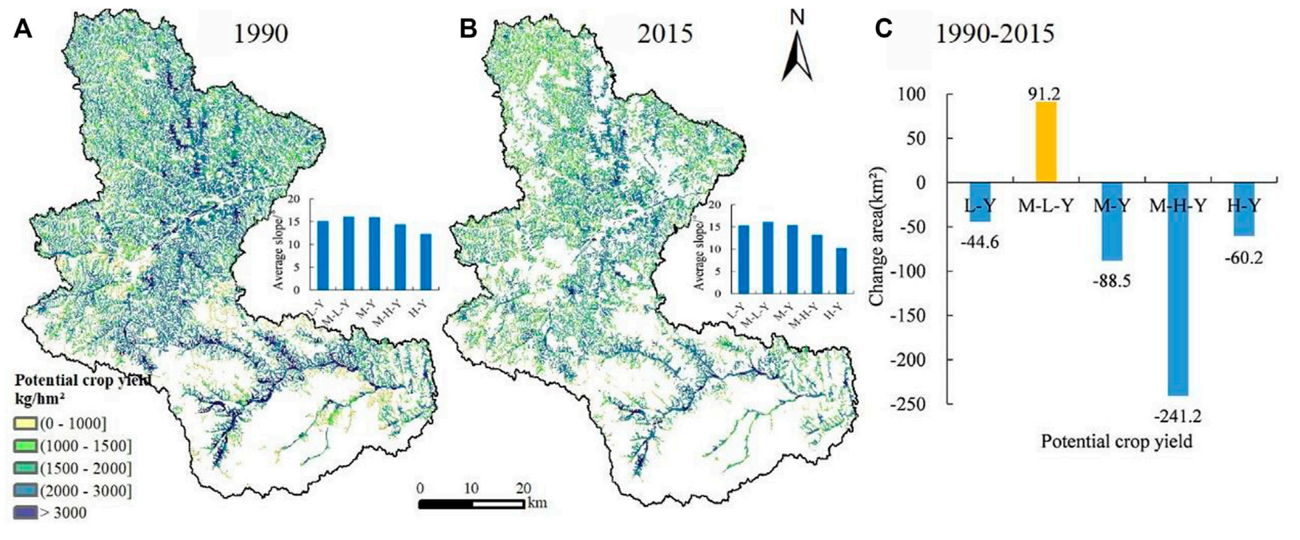

FIGURE 4 | Distribution of crop yield in Baota district for the years **(A)** 1990 and **(B)** 2015; **(C)** the area changes of different crop yield levels in Baota district from 1990 to 2015. HY: high yield, M-HY: medium–high yield, MY: medium yield, M-LY: medium–low yield, LY: low yield.

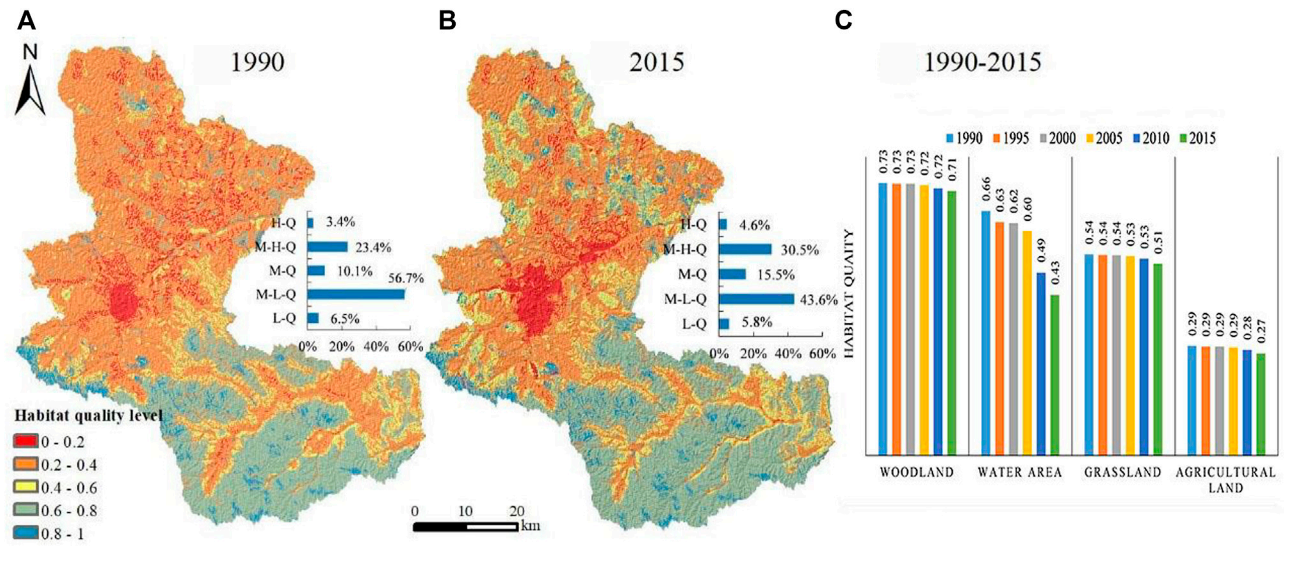

FIGURE 5 | Distribution of habitat quality in Baota district for the years **(A)** 1990 and **(B)** 2015; **(C)** the habitat quality of different land use types in Baota district from 1990 to 2015. HQ: high quality, M-HQ: medium–high quality, MQ: medium quality, M-LQ: medium–low quality, LQ: low quality.

(**Figure 4C**). Obviously, the medium–high yield area had largest loss, and the area ratio dropped by 12.5%. From the spatial distribution perspective, the crop yield was high in valleys and low in hillside. Specifically, the high yield and medium–high yield areas were concentrated in the valley fields with slopes below 15°. The low yield, medium–low yield, and medium yield areas were distributed in the hillside fields with slopes above 15°. Previous studies reported that newly added rural settlements were primarily concentrated in areas with slope below 15° in Baota district (Chen et al., 2021b), which resulted in a large loss of medium–high yield areas.

3.2.2 Change of Habitat Quality

The habitat quality value of Baota district in 1990 and 2015 were 0.43 and 0.48 based on **Eq. 3**, which indicated that the overall quality of habitat has improved over the course of study. The proportion of the low-quality areas was maintained at approximately 6%. The proportion of areas with medium–low quality reduced in this period. Particularly, the proportion of the areas with medium–low quality reduced from 56.7 to 43.6%. On the contrary, from 1990 to 2015, the proportion of high quality, medium–high quality, and medium quality areas raised, with rates of 1.2, 7.1, and 5.4%, respectively. In general, the expanded

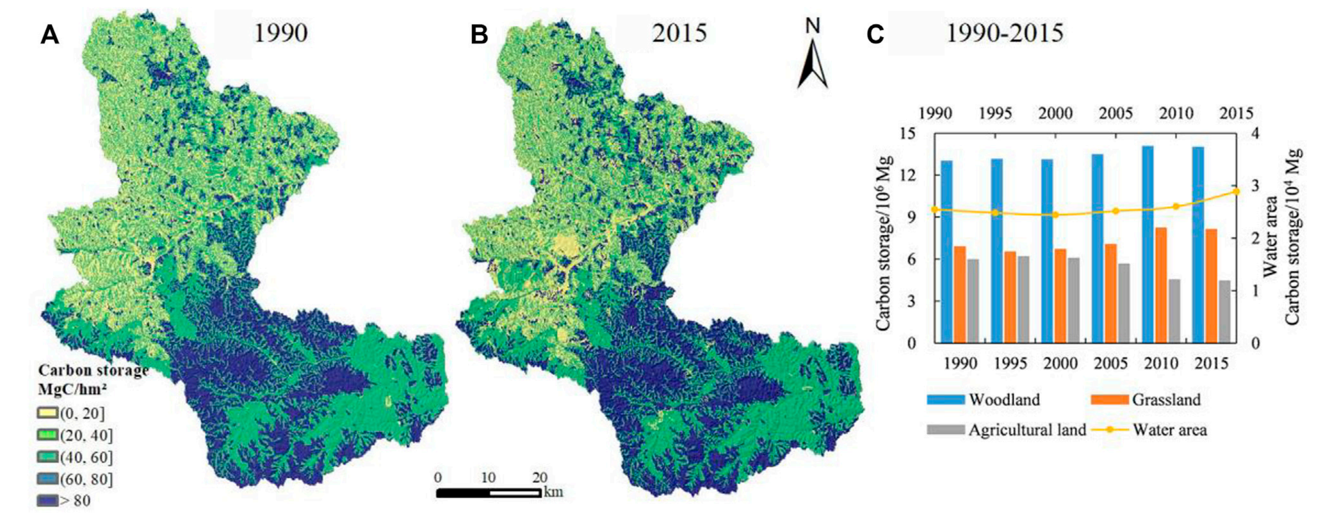

FIGURE 6 | Distribution of carbon storage in Baota district for the years **(A)** 1990 and **(B)** 2015; **(C)** the carbon storage of different land use types in Baota district from 1990 to 2015.

areas of medium quality habitats and declined areas of medium–low quality habitats led to the regional habitat quality improvement over the past 25 years in Baota district (**Figures 5A,B**).

The habitat quality of diverse land use types presented a downward trend during the study period (**Figure 5C**). Specifically, the habitat quality of water areas in Baota decreased by 34.2% from 1990 to 2015, and the rate of annual average change was −1.66%. The average habitat quality of woodland, grassland, and agricultural land decreased by 2.9, 4.7, and 6.8%, respectively, from 1990 to 2015, and the rate of annual average change was −0.12, −0.19, and −0.28%, correspondingly.

The habitat quality of Baota district revealed the spatial distribution pattern of "low in the north and high in the south", and the overall spatial manner had a remarkable regional difference during 1990–2015. The medium–high quality areas and high quality areas were mainly distributed in the southern part of Baota district, and the primary types of land use were grassland and forests. The medium–low quality areas decreased significantly in the northern part of Baota district. However, the changing features of medium–low quality and medium quality areas were opposite in the northern area of Baota district from 1990 to 2015. There was a noticeable increase in the medium quality areas, while the low quality areas showed a trend of gathering to urban built-up areas.

3.2.3 Change of Carbon Storage

The estimated total carbon storage value of Baota district in 1990 and 2015 were 2.59×10^7 Mg C and 2.66×10^7 Mg C, respectively, based on the results of the InVEST model. The carbon storage had a strong relation with the land-use type and topography in the area of research. As a result, the carbon storage in Baota district exhibited significant regional differences in the overall spatial pattern. For the carbon storage, the high-value parts were mostly in the southern areas of Baota district, and the land-use types were mainly grassland and woodland, while the area of low-carbon storage was mainly distributed in the northern areas of Baota district, and the land use types were primarily agricultural land, rural settlement, and urban built-up areas (**Figures 6A,B**).

From 1990 to 2015, the carbon storage for distinct land use types exhibited diverse changing characteristics (**Figure 6C**). The carbon storage of woodland, grassland, and agricultural land revealed a fluctuated pattern. Specifically, the woodland carbon storage increased by 9.9×10^5 Mg C and showed an "increase → decrease → increase → decrease" route during the study period. The carbon storage of grassland increased by 1.24×10^6 Mg C and revealed a route of "decrease → increase → decrease" in this period. The carbon storage of agricultural land decreased by 1.51×10^6 Mg C and showed an "increase → decrease" route during the time period. The carbon storage of water area remained around 3×10^4 Mg C.

3.3 Impacts of Rural Settlement Expansion on Ecosystem Services

Rural settlement expansion inevitably had a negative impact on local ecosystem services (**Table 3**). Specifically, the habitat quality of Baota district improved from 0.43 to 0.48, which related to more than 300 km^2 agricultural land transformed into woodland and grassland. Yet, the quality of different habitats decreased during the time period, especially in the water area. This was mainly due to the fact that most of the recently developed settlements situated near the water area were highly sensitive to threat sources. In addition, the total carbon storage in Baota district increased during 1990–2015, but the loss of carbon storage resulting from the expansion of rural settlement was up to 40,155.78 Mg C. Furthermore, the total output of crop in Baota district decreased to 1744.60 t during the study period. The reduction in food production was shown to be related to various explanations, such as climate

TABLE 3 | Land use transition and ecosystem services loss contribution rate in Baota district.

Land use transition	Habitat quality loss		Carbon storage loss		Crop yield loss	
	Loss area (hm^2)	Contribution rate (%)	Loss (Mg C)	Contribution rate (%)	Loss (ton)	Contribution rate (%)
Agricultural land → Edge expansion	556.20	39.43	20,679.52	51.48	1,210.10	69.36
Woodland → Edge expansion	63.20	13.45	3,840.48	9.56	–	–
Grassland → Edge expansion	120.20	17.04	3,285.22	8.18	–	–
Water area → Edge expansion	17.80	3.78	1,403.22	3.49	–	–
Agricultural land → Leapfrog expansion	163.00	11.56	6,060.34	15.09	384.70	22.05
Woodland → Leapfrog expansion	2.10	0.45	141.85	0.35	–	–
Grassland → Leapfrog expansion	35.40	5.03	1,001.37	2.49	–	–
Water area → Leapfrog expansion	11.40	2.41	672.01	1.56	–	–
Agricultural land → Infilling expansion	77.80	5.51	2,829.60	7.20	149.80	8.59
Woodland → Infilling expansion	1.40	0.30	71.64	0.18	–	–
Grassland → Infilling expansion	6.00	0.86	109.24	0.27	–	–
Water area → Infilling expansion	0.9	0.18	61.29	0.15	–	–
Total	1,055.40	100.00	40,155.78	100.00	1744.60	100.00

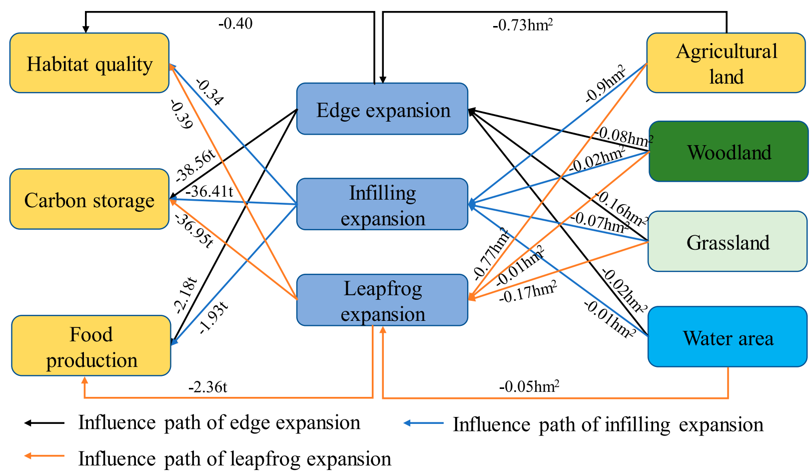

FIGURE 7 | Ecological land and ecosystem services loss resulting from per hectare of rural settlement expansion patterns.

change, returning agricultural land to woodland, abandoning agricultural land, and rural settlement expansion (Brown, 2016; Liu et al., 2021). Our research found that the decrease of medium–high yield areas was the main reason that led to regional food production decline over the past 25 years in Baota district, and 461.52 h m^2 of medium–high yield areas was transformed into rural settlements.

The transition from agricultural land, grassland, and woodland to the edge expansion pattern of rural settlements explained 69.92% of the loss contribution rate, which deteriorated the quality of human settlements in Baota district. The transformation from agricultural land and woodland to edge expansion and from agricultural land to leapfrog expansion pattern was the major types of land transition that resulted in the reduction of carbon storage in Baota district, and their contribution rate reached 76.13%. Furthermore, the transition from agricultural land to edge expansion pattern was the primary type of land transition that led to the reduction of crop yield in Baota district with the contribution rate of 69.36%.

4 DISCUSSION

4.1 Differentiated Impacts of Three Expansion Patterns on Ecosystem Services

Edge expansion and leapfrog expansion patterns increased the risk of ecosystem services loss. According to **Table 3**, leapfrog expansion and edge expansion in total contributed up to 93.15% of the habitat quality loss; these two expansion patterns together contributed to 92.20% of the loss of carbon storage, and their total contribution rate to the loss of crop yield was 91.41%. According to the unit area of the expansion of rural settlement, the ecological effects of the diverse rural settlement expansion patterns were different (**Figure 7**). More than 38.56 Mg C carbon stocks were lost for each additional hectare of the edge expansion pattern, more than 36.95 Mg C carbon stocks were lost for each additional hectare of the leapfrog pattern, and more than 36.41 Mg C carbon stocks were lost for each additional hectare of the infilling pattern. Meanwhile, the edge and leapfrog expansion patterns caused more habitat quality loss than the infilling pattern. Additionally, the leapfrog expansion pattern caused 2.36 t

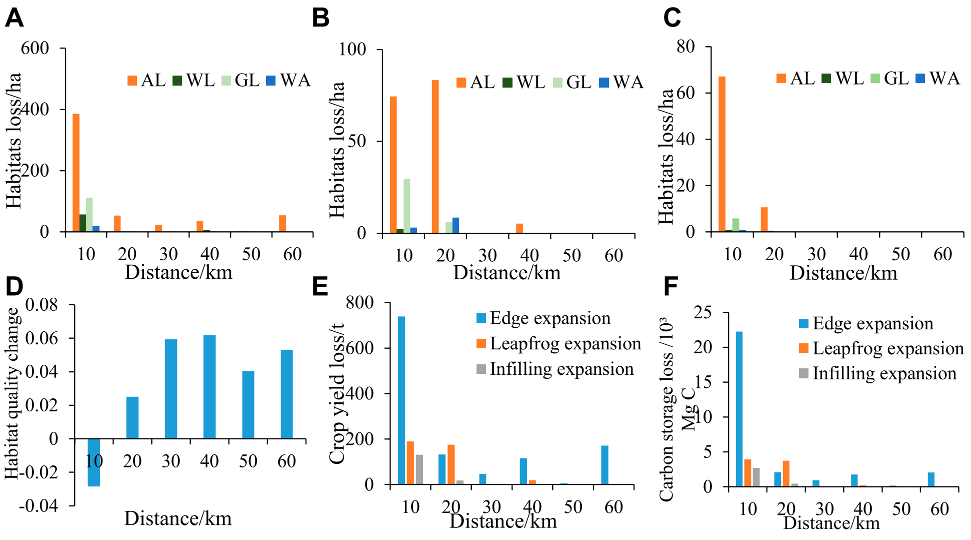

FIGURE 8 | Gradient changes in the impacts of three expansion patterns on ecosystem services. **(A)** Edge expansion pattern on habitat quality; **(B)** leapfrog expansion pattern on habitat quality; **(C)** infilling expansion pattern on habitat quality; **(D)** habitat quality change; **(E)** three expansion patterns on crop yield; **(F)** three expansion patterns on carbon storage. AL: agricultural land, WL: woodland, GL: grassland, WA: water area.

crop yield loss for each additional hectare, more than the edge pattern (2.18 t) and the infilling pattern (1.93 t). To summarize, the leapfrog and edge expansion patterns caused more habitat quality, carbon storage, and crop yield loss than the infilling expansion pattern. Our results, to some extent, supported previous findings that the edge and leapfrog expansion patterns were the primary mode causing dramatically declines in ecosystem services (Tian et al., 2014; Xu et al., 2016).

4.2 Gradient Changes in the Impacts of Three Expansion Patterns on Ecosystem Services

We took the county government location as the center and conducted a gradient analysis with equal intervals of 10 km. Results indicated that there were gradient differences in the impact of three expansion patterns on ecosystem services. The impacts of the edge and infilling expansion patterns on the four type habitats were mainly concentrated within 10 km, and the impacts were gradually weakened by increased distance (**Figures 8A,C**). The impacts of the leapfrog expansion pattern on the four type habitats were mainly concentrated in the range of 20 km, particularly the impact on agricultural land was mainly within 10–20 km (**Figure 8B**). This further confirmed the phenomenon of habitat quality degradation around urban built-up areas (**Figure 8D**). Furthermore, the impacts of three expansion patterns on crop yield and carbon storage were mainly concentrated within 10 km, and the impacts again were gradually weakened by increased distance. It is noted that in the 10–20 km range, the impacts of the leapfrog pattern on ecosystem services were higher than the edge and infilling expansion patterns (**Figures 8E,F**). This was similar to the circle-level expansion characteristics of cities (Yang et al., 2018). The "inner circle" was dominated by the edge and the infilling expansion modes, while the "outer circle" was dominated by the leapfrog expansion mode. With the continuous expansion of city, the built-up area of the "inner circle" was increasingly connected with the leapfrog patches of the "outer circle", thus forming a new urban built-up area (Bhatta, 2010).

4.3 Key Issue Causing the Conflict Between Rural Settlement and Ecosystem Services

The unbalanced growth between population and residential land have led to conflicts between human and ecosystem services (Castro-Prieto et al., 2017). The aforementioned analysis suggested that the area of rural settlement in Baota district has grown remarkably with an average annual growth rate of 3.13% during the study period. Especially after 2005, with the stimulation of the "New Countryside Construction" policy and other policies for rural development, the expansion speed of rural settlement was accelerated (Li and Song, 2020), and in Baota district specifically, the average annual expansion rate of the rural settlement increased to 4.31%. However, the incoordination between rural settlement expansion and rural population growth has become increasingly noticeable. In particular, the average annual change rate of rural settlement in Baota district were 1.93%, 2.58%, and 6.08% in 2000–2005, 2005–2010, and 2010–2015, respectively. Yet, the changing characteristics of rural populations in Baota district were opposite. The average annual change rate of rural populations continuously decreased from 3.47% to 0.25% during the time period. Despite the decline in rural population growth rate, our study found that the rural settlement expansion in Baota district was still dominated by the edge and leapfrog expansion patterns which was in line with previous studies (Tan and Li, 2013; Tian et al., 2014; Xu et al., 2016).

4.4 Implications for Rural Land Management

In the course of rapid urbanization and economic development, the ecologically fragile region is facing dual pressures of rural development and eco-environment protection (Yu et al., 2018). Rural settlements, therefore, should be appropriately planned in order to balance environmental and socioeconomic benefits and then achieve the rural sustainable development. (Pacione, 2013; Tudor et al., 2014). In this study, the spatial distribution, degree, and eco-environment effects of rural settlement expansion patterns are quite different in Baota district, which determine that the governance strategies of rural settlements should be tailored to local conditions. For example, in the far-flung suburb area, where outside 20 km from the county center, the expansion intensity of rural settlement is relatively weak. The most prominent problem is food production loss due to the occupation of cultivated land in edge expansion. In this type of area, the red line for cultivated land protection should be focused on preventing further loss of cultivated land. At the same time, the gully land consolidation project should be carried out to achieve a balance between the occupation and compensation of cultivated land. In area within 10–20 km from the county center, the problem of food production and carbon storage loss caused by the leapfrog expansion is most prominent. In this type of area, the red line of "planning and development of villages" extremely needs more attention, so as to limit the disorderly expansion of rural settlements and improve the efficiency of land use. In area within 10 km from the city center, the land used for settlements expanded rapidly, and the habitat quality, carbon storage, and grain yield all declined obviously. In this type of area, strict space utilization control measures should be implemented, focusing on the delineation of ecological protection red lines to prevent ecological land from being further eroded.

In addition, there are inevitably some limitations in this study. For instance, we mainly analyzed the expansion of rural settlements and their ecological effects from 1990 to 2015. In the follow-up study, we will supplement the research on the latest dynamics of rural settlement expansion and its impact on eco-environment. In addition, the parameters for the InVEST model in this study are mainly based on experts' experience and published literature. We would further improve our approach by field sampling or a biogeochemical model in future study.

5 CONCLUSION

This study analyzed the dynamic changes of rural settlement and used GAEZ and InVEST models to quantitatively examine the associated effects of ecosystem services in Baota district. The results showed the following: 1) the change of rural settlement in the area of research is extensive during 1990–2015, reflecting the rapid expanding features of the edge expansion pattern, and those areas with edge expansion are mostly transitioned from agricultural lands. 2) Overall, the total yield of crop decreased over the last 25 years. The habitat quality and carbon storage were also affected by rural settlement expansion, although the average habitat quality and total carbon storage of Baota district increased during the time period. 3) The habitat quality deterioration was mainly due to the conversion from agricultural land, grassland, and woodland to the edge expansion pattern; the predominant reason of the decreased carbon storage was the transformation from agricultural land and woodland to the edge expansion pattern, and the decrease of crop yield was mainly caused by the transition from agricultural land to edge expansion pattern. This study suggested that the governance strategies for rural settlements should be tailored to local conditions and appropriately planned in order to balance environmental and socioeconomic benefits and then achieve the rural sustainable development.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZC: conceptualization, methodology, and writing–original draft. YL: formal analysis and writing–review and editing. ZL: formal analysis and writing–review and editing. JW: supervision and funding acquisition. XL: formal analysis and data curation.

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Mixed Land Uses and Community Decline: Opportunities and Challenges for Mitigating Residential Vacancy in Peri-Urban Villages of China

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Residential vacancy is a visible symptom of community decline in peri-urban villages of China. Mixed-use development has emerged as a possible approach for land use planning to help mitigate community decline and residential vacancy. By applying an integrated framework, this study explores whether mixed land use (MLU) can help counter residential vacancy based on the classification of four types of peri-urban villages. Results show that the degree of MLU and residential vacancy rate both present increasing tendencies. Also, impacts of MLU on residential vacancy differ across villages: the disorderly and excessive mixed uses in some villages exacerbated residential vacancy, even threatening the neighborhood safety and livability; whereas for some villages with compatible mixed uses, the land use pattern could assist in reducing the residential vacancy, as well as promoting the compact and high-density development. Undeniably, planning for the increased mixed-use environment like urban communities is unsuitable for rural communities. Sustainable planning to counter residential vacancy should combine the compatible mixed-use development together with the rational functional zoning, which is also considered a constructive tool in mitigating community decline, and bringing human settlements development, vitality, and diversity. This research contributes to reconcile residential vacancy in the depopulating and declining communities.

Keywords: mixed land uses, community decline, residential vacancy, impacts, sustainability planning

1 INTRODUCTION

Rural communities, the areas where rural residents live and produce (Yang et al., 2015; Ma et al., 2018a), are facing various global challenges, such as, depopulation, economic decline, unemployment, poverty, housing vacancy, and land abandonment. Mixed land uses (MLU) is one of the crucial indicators for land use development pattern and also is usually regarded as being desirable for building a livable and healthy community (Niemira, 2007; Herndon, 2011; Robledano-Aymerich et al., 2014; Nabil and Eldayem, 2015; Sahu, 2018; Motieyana and Azmoodeh, 2021). Whether mixed uses can be a basic element to achieve compact and sustainable planning in rural communities has been a crucial issue for rural development.

The idea of MLU was derived from the mixture of residential and non-residential activities in Roman cities (Zhuo et al., 2019). Then, with rapid urbanization and urban population growth over the globe, relentless urban sprawl and the obsessively strict division of land uses by zoning have resulted in numerous unwanted influence for human society, such as urban traffic jam, the decay of city centers, and social isolations (Fainstein, 2005; Karen. et al., 2012; Song et al., 2013). Therefore, the Congress of New Urbanism (2001) and the Smart Growth Network (2006) promoted the closer integration of residential, commercial, and recreational uses. They claimed that compact, smart land use, complementary function, and mixed-use planning policies are essential for building sustainable cities (Musakwa and Niekerk, 2013; Jacobs-Crisioni et al., 2014). MLU, however, is also accompanied by some negative effects. For instance, the externalities of industrial land use always have significant impacts on residential use and values (Burnell, 1985; Tian et al., 2017). Cozens (2015) and Sohn (2016) claimed that mixed uses could adversely affect community safety. Whether advocating or opposing the idea, MLU is a controversial matter for many researchers.

In fact, this concept has expanded rapidly with many other aspects having been encompassed up to now. Since the 1970s, the vigorous development of rural economy has changed the economic activities dominated by agricultural production in developed areas and transformed the rural economy into a comprehensive economic structure involving agriculture, industry, commerce, and tourism (Kruska et al., 2003; Holmes, 2006; Ma et al., 2019). In addition, there has existed a natural tendency of mixing of land uses for human settlements in rural areas (Raman and Roy, 2019). Classifying rural communities following land use types, such as residential, commercial, and industrial, is an established strategy of rural planning (Ma et al., 2018b). One such example is China's peri-urban areas, where rural communities are mixed with a great diversity of landscapes (Leaf, 2002; Fan et al., 2015). Mixed use pattern has provided diverse daily services and choices for local residents, such as retail shops, grocery stores, restaurants, etc. Compared to cities, however, these facilities in villages occupied less land and always mixed with residential houses or industrial factories to decrease space costs (Zhao et al., 2015; Zhou et al., 2016). During the past decade, a growing number of studies pay attention to the intermixed functions of rural community (Zhen et al., 2009; Wang and Li, 2011; Yuan et al., 2017). For instance, Zhang (2014) and Ma et al. (2018a) have found that land use functions within rural communities can be categorized into residential, production, and ecological functions from the perspective of land use multifunctionality. Zhang et al. (2019) characterizes the mixed use of residential and industrial land in villages. These studies have produced important views on MLU in rural communities.

Along with urban–rural transformation, many villages have already experienced significant depopulation, primarily due to urban–rural gaps. Consequentially, depopulating residential areas are sometimes characterized by high unemployment, poverty, as well as increased housing vacancy and land abandonment (Wiechmann and Pallagst, 2012; Gu et al., 2019; Pan et al., 2021). Residential vacancy, as a visible symptom of community decline, has been another critical issue in the countryside. Currently, there exist various forms of land abandonment and residential vacancy, including abandoned and vacant houses, abandonment of infrastructure, idle factories, and bare land(Li et al., 2014), which can be reflected on the area of vacant land within a rural community. These abandoned and vacant lands not only have declined the rural vitality but also have profound ecological effects on the lives of rural inhabitants, biodiversity, soil erosion, and carbon sequestration (Queiroz et al., 2014; Miguel et al., 2015). Revitalizing abandoned and vacant land is critical to ensuring the long-term sustainability of rural development.

Facing these problems, some scholars proposed a series of theories and practices, including strategic planning for countryside (Anne and Gertrud, 2016), the Rural Renaissance Project (Baker, 2010), and land consolidation (Pašakarnis and Maliene, 2010). Among them, Liu et al. (2009) stated that the continual population loss, as well as single land use structure easily led to the vacancy of housing function and functional abandonment, and this phenomenon can be defined as the "hollow villages". Several scholars have introduced smart growth policy to solve this issue, claiming that mixed-use zoning can help mitigate the effects of community decline for vacant or abandoned residential properties (Williams, 2005; Bramley and Power, 2009; Haas, 2012). Nonetheless, given the small-sized area of villages, the interference of residential and industrial use easily led to environmental degradation (Tian, 2015). Strict zoning regulations were, therefore, considered a more salutary planning concept than MLU (An et al., 2018; Liu et al., 2019).

In spite of growing research interests on the MLU and rural residential vacancy resolution, studies on quantifying MLU and its impacts on rural residential vacancy have been fairly scarce. What are the impacts of mixed uses on community decline? Does mixed-use development effectively counter the residential vacancy? All of these questions should be further explored. Given the regional differentiation in Chinese villages in terms of geographical conditions, demographic structure, and industrial activities, the likely consequences of mixed-use development may differ across villages. Empirical analysis for its impacts can serve as a means of understanding whether MLU is beneficial for community decline and residential vacancy mitigation, and thus has significance for every strategy of human settlements. It could also provide feasible approaches to sustainable planning for rural transformation, renewal, and regeneration.

To achieve this, we attempt to analyze and compare the changing patterns of MLU and residential vacancy rate of rural community in various types of villages, and model the impacts of mixed uses on residential vacancy rate to determine whether MLU has a significant role on countering residential vacancy. Two issues should be addressed: (a) whether all mixed uses have favorable effects on rural compact development and (b) how can this information be used to mitigate residential vacancy in rural communities? This study continues with a comprehensive framework and the methods employed in the study, including measuring MLU and its relationship to vacant land. The findings then are described, demonstrating the spatiotemporal changing patterns of MLU and residential vacancy rate, respectively, and their relationship. The study

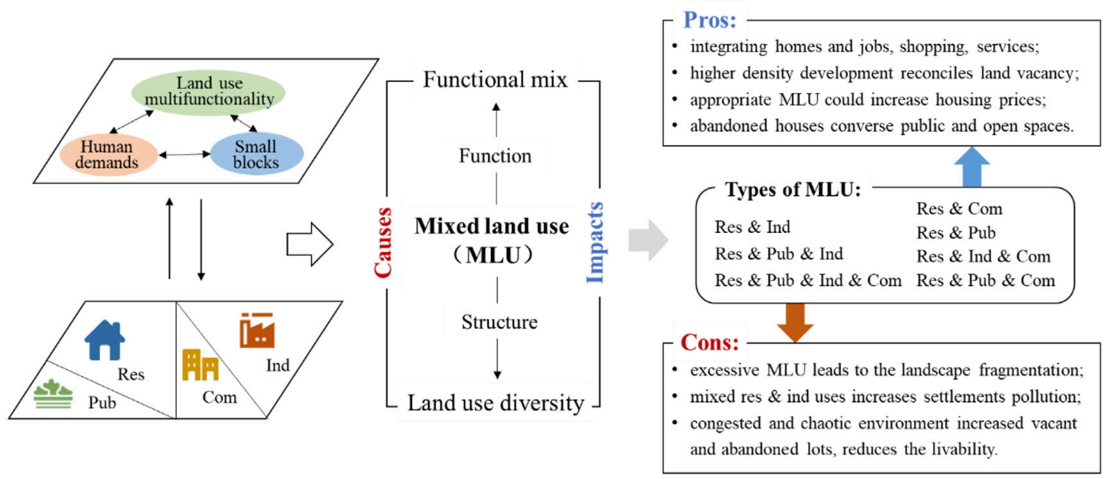

FIGURE 1 | Theoretical framework of MLU in rural communities. Notes: Res, Pub, Ind, and Com are abbreviations for residential land, public infrastructure land, industrial land, and commercial land, respectively.

also refers to a case study at the microlevel by using four typical villages, and vitalization strategies for community decline. The last section of this study summarizes the findings by referring to existing literature and the key implications for policy makers and researchers are highlighted.

2 THEORETICAL FRAMEWORK

2.1 What Is MLU in Rural Communities?

Atlanta Regional Commission (2011) has defined MLU as a type of land use pattern that blends different land-use types, which may be functionally integrated, and provide a sustainable development trend. There are four components of this concept: 1) different types of land uses/activities, 2) limited spatial range, 3) interaction and integration of these land uses/activities, and 4) a certain development goal, such as satisfying the multiple human demands, enhancing community vitality as well as promoting spatial allocation (Zhuo et al., 2019). MLU initially derived from urban communities (Williams, 2010; Jacobs-Crisioni et al., 2014); afterward, it was found in villages due to the rural multifunctionality (Holmes, 2006), especially in the peri-urban areas, where the frequent non-agricultural production and high-density residential activities have accelerated the possibility of land use conversion. Simultaneously, the small-sized villages would cause the interaction and overlapping of residential and non-residential spaces, thereby leading to a paradigm shift in practice from single-purpose partitioning to MLU (Tian et al., 2017; Zhang et al., 2019).

The MLU of rural communities could be defined as the mixture and interaction of multiple land uses covering residential, industrial, commercial, and recreational, that is, a series of land uses or activities within a rural community providing complementary functions. This phenomenon is more likely to happen in peri-urban areas and developed areas, where the diversification of the rural economy and livelihood has aroused the increasing demands for the land use multifunctionality comprising residence, non-agricultural production, recreation, etc., and mixed uses within rural communities can be regarded as the outcome of diverse land use choices to satisfy these demands (Cheng et al., 2017; Zhu et al., 2017). Consequentially, as discussed in **Figure 1**, land use multifunctionality and the limited spatial range of rural communities, are the underlying cause for the MLU; meanwhile, increasing demands from inhabitants for rural residential land functions can be identified as the proximate causes of MLU.

In the agricultural society of China, agricultural economic activities played a crucial role in rural communities, whose major function was to provide space for agricultural production and human settlements (William, 1964; Satsangi, 2007). Therefore, the rural community began with residential land mixing with a small number of public facilities in China, and residential function can be viewed as the primary and basic function in these areas. Afterward, along with the unprecedented process of industrialization and urbanization came the livelihood transition for farmers for residential land (Liu and Liu, 2016). Since then, the human–environment balance in the agricultural society has been broken, and more farmers were engaged in non-agricultural activities for both material and commercial purposes (Sharpley and Vass, 2006; Siciliano, 2012). As a consequence, there existed land use multifunctionality (including residence, industrial production, commercial service, leisure, recreation, etc.) and intermixed landscape within rural communities to meet these needs (DeFries et al., 2004; Ma et al., 2019). Mixed uses are commonly observed in the rural community, such as the mix of residential and commercial uses, mix of residential and industrial uses, mix of residential, and infrastructure uses. Simultaneously, since there were some other elements (e.g., physical geography conditions, economic location, and socioeconomic level) said to primarily determine the spatial structure and the mixed use pattern within rural communities, MLU presented a remarkable spatial differentiation in China.

2.2 How MLU Affects the Residential Vacancy and Community Decline?

Over the last few decades, with rapid urbanization and economic growth, the rising socioeconomic inequality between rural and urban areas has become a major threat to China's development. Consequently, community decline was emerging over the countryside, reflecting in continual population loss, low-density sprawl, environmental pollution, and excessive vacant or abandoned houses (Long et al., 2012; Li et al., 2016; Han, 2017; Liu, 2018).

Among these problems, residential vacancy and land abandonment, as the results of human-environment systems degradation, have been urgent issues in rural areas (Khanal and Watanabe, 2006; Askland, 2018). It is widely agreed that MLU, as a key part of landscape patterns in rural communities, is correlated with land vacancy and abandonment (Zhao, 2013). However, the density and degree of mixing can ultimately result in varying impacts on rural residential vacancy. Therefore, it is essential to understand how MLU affects residential vacancy, and how a planner use the tool of mixed-use development to help rural residential land planning and public policy making.

A large amount of literature has offered empirical evidence that MLU can be a feasible alternative to create settlement patterns livable and sustainable (Duncan et al., 2010; Jacobs-Crisioni et al., 2014; Zhao et al., 2015). The benefits of MLU in rural communities can be categorized into two aspects: (1) multiple land uses can foster greater compact by integrating homes and jobs, shopping, services within small blocks, and therefore may assist in increasing interaction capabilities (Song and Knapp, 2004; Bao and Jiang, 2007). Ideally, it could also trigger higher density development through the provision of industries, services, and amenities, which, however, would escalate the risk of residential vacancy, industrial decline, infrastructure abandonment, and population loss in settlements with large numbers of abandoned buildings (Karen. et al., 2012; Gu et al., 2019). (2) The appropriate mixed-use development with residential and commercial components has the potential to raise land values. More importantly, the location of vacant land uses in mixed use zones has been shown to easily converse to community public land uses and open spaces (Cervero and Duncan, 2004; Han, 2014). This is a common phenomenon in organically developed villages and well-planned countryside.

Of course, MLU is also associated with some inherent challenges and problems. The opponents often claim that human settlements with higher mixed-use are likely to be more vulnerable to vacancy: 1) In general, it is suitable for one land parcel accommodating two or three types of land uses. Unfortunately, mixed uses, often based on small blocks where land suitable for development, are excessively complex and diverse in rural communities. This phenomenon not only leads to the fragmentation of landscape and functions, but also increases the difficulty of land use planning and regulation, thereby resulting in low-density development patterns with an excessive mix of residential, industrial, and commercial land uses a lack of adequate infrastructure, and increased vacant and abandoned lots (Keenan, et al., 1999; Sohn et al., 2012). 2) Different types of MLU will eventually produce different effects. As mentioned previously, mixing residential and commercial land uses has favorable effects on housing values, while larger ratios of industrial land use in human settlements tend to generate adverse spillover effects onto adjacent properties, such as lowering the value of tangent lots, and polluting the surrounding environment (Shultz and King, 2001; Taleshi and Bishehii, 2012). For most human settlements in China, as residential and industrial land occupied almost 80% of the total area, it is quite common for the mix of residential and industrial land use. In addition, Wang et al. (2014) found that this type of land use mix accompanied with the improper handling of mixed-use development caused the serious environmental pollution. Its negative externalities are highly concentrated around abandoned lots. This implies that the interference of industrial and residential land uses can easily lead to land abandonment, and then inevitably reduce the livability of human settlements. Such theoretical contradictions make it difficult to reach a conclusive agreement regarding how MLU effects rural residential vacancy. We can find that the level and degree of mixing, as well as the types of mixed uses (i.e., land use structure) determine the relationship between MLU and rural residential vacancy.

3 METHODOLOGY

3.1 Study Area

Pinggu District (40°02′- 40°22′N, 116°55′21″- 117°24′07″E) is a peri-urban district in the northeast of Beijing (the capital of China). The land area of Pinggu is 107,500 ha. The population was approximately 456 thousand according to the 2018 Pinggu Statistical Bureau. Its industrial sector mainly involves in the agricultural production, construction, production of metal products, garment processing, and tourism service. Pinggu District consists of 16 towns and 275 villages, and there are three area landform types: plains, mountainous, and semi-mountainous areas, each of which accounts for the 1/3 of the total region (**Figure 2**).

As land use pattern presents a remarkable spatial differentiation in various regions, a very broad and familiar classification of villages is based on the economic structure and GDP for various industries. This classification refers to the results of rural development assessments noted by Long et al. (2009) and Zhang and Zhang (2020), in terms of which we classify villages as agricultural production villages, industrial production villages, commercial agritourism villages, and comprehensive development villages. See details of classification in **Table 1**.

3.2 Data

Land use data of Pinggu in 2005 and 2018 used in this study were obtained from Google Maps. At the same time, accurate land

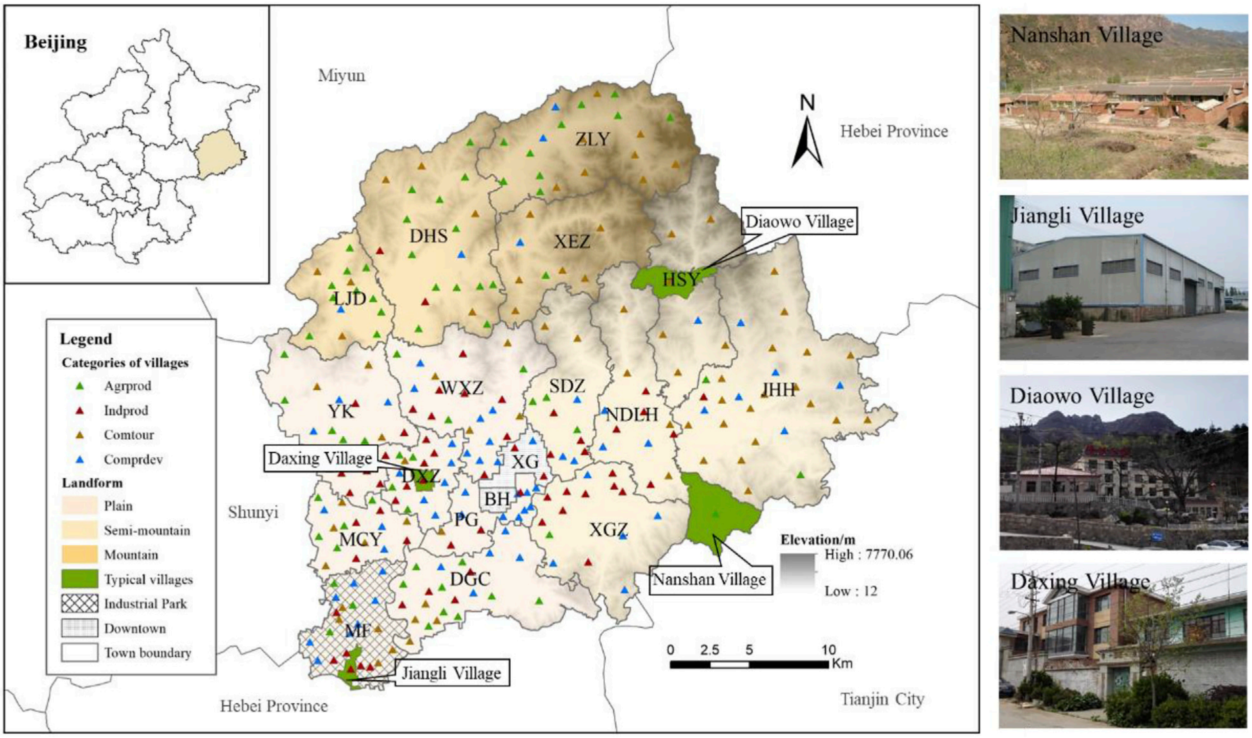

FIGURE 2 | Study area—Pinggu District in Beijing.

TABLE 1 | Classification of villages in Pinggu.

Categories	Abbrev	Criteria	Industrial Characteristics	The Number of Villages
Agricultural production village	Agrprod village	GDP 1% ≥ 31.95%	Producing food, feed, fiber, and many other desired products through cultivating certain plants Raising of domesticated animals (livestock)	72
Industrial production village	Indprod village	GDP 2% ≥ 60.49%	Manufacturing and processing production industries	61
Commercial agritourism village	Comtour village	GDP 3% ≥ 41.79%	Commerce, agritourism, recreational, and service industries	75
Comprehensive development village	Comprdev village	Exclusion for the above three types	Diversification of rural economy and industries	67

parcel information was obtained through image interpretation and practical survey. Then, according to the classification standard GDP J01-2013 of the geographical condition survey data, we identified vacant land as land cover characterized by waste, abandonment, idleness, and vacancy within rural communities.

Land use within rural communities refers to the lands for houses building, industrial production, construction for living needs, and necessary public facilities and infrastructure (Banski and Wesolowska, 2010). In China, there are five land-use types within rural communities: residential, industrial, commercial, public infrastructure, and vacant.

We also collected some socio-economic data from the 2005 and 2018 Statistical Yearbook, including gross output of industrial sectors, rural population, labor employment, etc. (Ma et al., 2018b). In addition, a household survey was conducted in collaboration with the head of the village, between October 2017 and January 2019 in Pinggu District. Household information includes household livelihood (such as farm and non-farm activities), income by source, and area of family houses (see **Table 4** for a detailed description of the variables and their quantification).

3.3 Methods

3.3.1 Measurement of MLU

As regards the definition of MLU, it refers to a heterogeneous pattern of land uses within an area, and usually involves the diversity of uses. MLU can be measured by a series of indices (Yoshida and Tanaka, 2005; Comer and Greene, 2015), including but not limited to spatial accessibility, entropy index, and

TABLE 2 | Measurement of mixed degree index.

Indices	Formulas	Explanation
Land-use richness	$0D = \sum_{i=1}^{N} p_i^0$	Designed for measuring species richness
Land-use randomness	$1D = \exp(-\sum_{i=1}^{N} p_i ln p_i)$	The exponential of Shannon entropy index
Land-use concentration	$2D = 1/\sum_{i=1}^{N} p_i^2$	This is the inverse of Simpson concentration. The superscript 2 on diversity (D) indicates that this is a second-order diversity
Mixed degree index	$D = 0D + 1D + 2D$	The higher value means the more degree of land use mix

dissimilarity index. However, the heterogeneous pattern of land use structure usually be neglected in these indices. Besides, in Chinese villages, residential land occupies an absolute dominant position, in contrast, other types of land use are almost negligible (Bordoloi et al., 2013). Therefore, we measured the degree and types of MLU by proposing two indices—mixed degree index and Weaver–Thomas index—which account for the extent to which complementary land uses adjoin one another—using only basic land use data.

1) Mixed degree index

We proposed a new mixed degree index—Hill Numbers—based on various existing parameters characterizing the degree of mixing, which mostly correlated to the land use interaction method (see **formula 1**). Conversion of some entropies such as the Shannon–Wiener and Gini–Simpson indices to the effective number of species is the key to a unified and intuitive interpretation of land use mix degree, including richness, randomness, and concentration (Manaugh and Kreider, 2013). Detailed analysis of land use mix degree quantification is given in **Table 2**.

$$^{q}D = \left(\sum_{i=1}^{N} p_i^q \right)^{1/(1-q)} \quad (1)$$

where p is the proportion of each land use type in rural settlements; N is the number of land uses. The exponent and superscript q can be called the "order" of the diversity, which depends only on the value in **Table 2**.

2) Weaver–Thomas index

In order to better identify the types of MLU, we adopted the Weaver–Thomas index (Marshall, 1892; Ma et al., 2018a). It can help explore the heterogynous pattern of MLU which cannot be characterized in the mixed degree index. Also, it can depict the types of MLU by analyzing the land use structure within rural communities.

3.3.2 Measurement of Residential Vacancy Rate

Residential vacancy is used as an indicator to measure community decline. The residential vacancy rate is the area vacancy rate of rural communities, which can be calculated by using the area proportions of vacant land within rural communities, as illustrated in **formula 2**.

$$VR = A_v / A, \quad (2)$$

where VR is the residential vacancy rate; A_v is the area of vacant land within a rural community; and A is the total area of the rural community.

3.3.3 Model Fitting

1) Variable design

According to the empirical studies, except for MLU, residential vacancy, as the visible symptom of rural community decline, is affected by other socioeconomic factors at the village level, such as location condition, population density, and non-agricultural gross value (Munroe et al., 2013; Newman and Bowman, 2018). More specifically, residential vacancy can be considered as the preferred outcome caused by rational choice of some farmers. For example, farmers who are engaged in non-farm activities in urban areas preferred to abandon their houses in the villages. Thus, some family characteristics such as income levels, household livelihood, and area of houses could affect the residential vacancy rate (Thorpe, 2018; Xu et al., 2019).

By reviewing existing research frameworks, MLU variables can be used to measure factors that affect vacancy rates. Residential vacancy rate was used as the dependent variable, and the MLU variable was used as independent variables. More importantly, the study fully considered influential household and village variables, two constructs of the independent variables were operationalized with the household family and village level characteristics. See Table 3 for detailed description of the variable design.

2) Hierarchical Linear Modeling

As shown in **Table 3**, these variables are usually hierarchical or multilevel (i.e., families are nested within villages), which means they cannot be explained by traditional regression models such as ordinary least squares (Raudenbush and Bryk, 2002). Therefore, we adopted hierarchical linear modeling (HLM), a two-level linear model of family and village variables, to explore the correlation between MLU and vacant land. This model is an extension of OLS, and it can take account of hierarchical data. Household family was the study unit for level-1, and village was the study unit for level-2. HLM combines variables at both layers and explains how the dependent variables are subjected to the influences of the first layer and second layer, respectively. The

TABLE 3 | Descriptive statistics of the variables used in the regression models.

Variable		Definition
Dependent variable	Residential vacancy rate	
Independent variables	**Level-1: Household family level**	
	Household income	
	Household livelihood	
	Full-time farming	Whether it is full-time farming (0 = no; 1 = yes)
	Part-time farming	Whether it is part-time farming (0 = no; 1 = yes)
	Non-farming	Whether it is non-farming (0 = no; 1 = yes)
	Area of family houses	
	Level-2: Village level	
	Terrain	
	Average elevation	
	Average slope	
	Spatial accessibility	
	Accessibility to roads	
	Accessibility to downtown	
	Per capita arable land	
	Population density	Rural resident population/total area of the village
	Growth rate of real GDP	Average growth rate of real GDP in the period
	Non-agricultural gross value	
	Non-agricultural employment	The number of labor in non-agricultural activities/total number of labor
	Adequate degree of infrastructure	The number of public infrastructures, such as schools, hospitals, libraries, etc.
	Villages compactness	Shape compactness = P^2/A P is the perimeter of the shape; A is the area of the shape
	Mixed land uses	Mixed degree index

final model for math achievement took the form of the following formulas:

$$\text{Level} - 1\ \text{Model}: Y_{ij} = \beta_{0j} + \beta_{1j}X_{ij} + \varepsilon_{ij} \quad (3)$$

$$\text{Level} - 2\ \text{Model}: \beta_{0j} = \gamma_{00} + \gamma_{01}W_{1j} + \mu_{0j} \quad (4)$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}W_{1j} + \mu_{1j} \quad (5)$$

where *i* stands for farmer households; *j* stands for the village; *X* is the household family level variable; Y_{ij} is the dependent variable; β_{0j} and β_{1j} are the intercepts and slopes of unit *j* at the first layer, respectively; ε_{ij} is the random element of Y_{ij}; γ_{00} and γ_{10} are the average values for β_{0j} and β_{1j}, respectively, and their fixed components, which means that they are constant among the village variables; γ_{10} and γ_{11} are regression coefficients; W_{1j} is the first predictor variable at the village level; and μ_{0j} and μ_{1j} are random elements of β_{0j} and β_{1j}, respectively, representing the difference between village units.

4 RESULTS

4.1 Changing Patterns of MLU in Rural Communities

4.1.1 Land Use Change Within Rural Communities

Through surveys and data collection, we obtained the relevant statistics for the land use change within rural communities in Pinggu District. The gross land area of rural communities increased from 5918.53 ha in 2005–8090.8 ha in 2019. Furthermore, we measured its internal land use change (**Figure 3**). In general, residential function is often regarded as the primary and basic function in rural land use system. This phenomenon was relatively prominent in 2005 when residential land occupied the predominant position in residential areas. Whereas, it has been altered in the later period in which the proportions of all other land use types have been increased, especially for commercial land with the area proportion growing from 2.29% to 18.33%.

4.1.2 Spatiotemporal Changing Pattern of MLU in Rural Communities

Table 4 presents that the statistical results of mixed degree index, and it shows that the mixed degree index increased from 0.33 to 0.57 from 2005 to 2018. The increased index mainly suggested more about multiple land use structure, which changes from simple land use structure (such as single residential land, or mixed residential and industrial uses) to complex land use structure (such as mixed residential and commercial uses, mixed residential and public infrastructure uses, or mixed residential, industrial, and commercial uses).

Spatially, it is observed that the phenomenon of MLU was unremarkable in 2005; most areas presented the single residential land, and only the downtown area and the *Mafang Industrial Park* presented the mixed residential and industrial uses. In 2018, the areas with a high degree of MLU spread widely (see **Figure 4**), and the mixed degree index increased remarkably in plain and mountainous areas. On the one hand, under the influence of urbanization, what is likely to happen in plain areas was the prominent non-agricultural production and living service functions in urban-like human settlements, it was always accompanied by the MLU changing pattern from single residential land, mixed residential and industrial uses to mixed residential and commercial uses, as well as mixed residential, industrial, and commercial uses; on the other hand, MLU in the mountainous areas was occurring due to the booming of

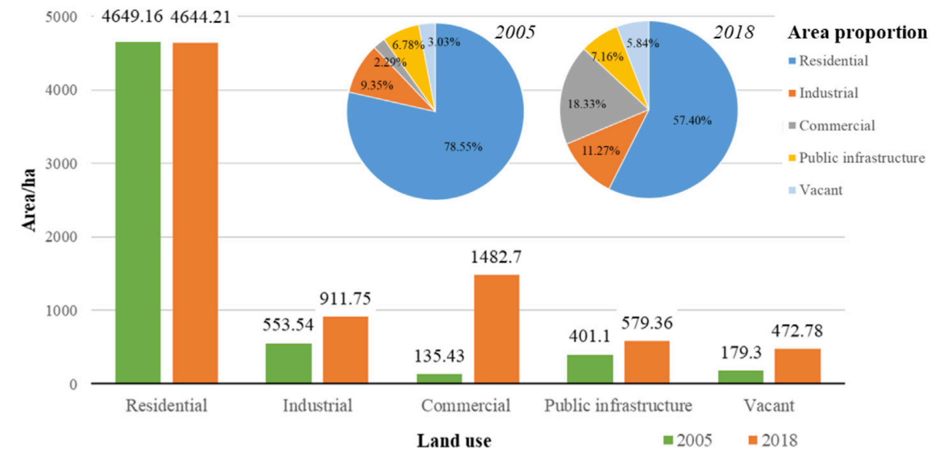

FIGURE 3 | Characteristics of internal land use change of rural communities from 2005 to 2018.

TABLE 4 | Characteristics of MLU and rural residential vacancy between 2005 and 2018.

Categories	Mixed Degree Index		Vacancy Rate	
	2005	2018	2005	2018
Agrprod village	0.15	0.33	0.028	0.012
Indprod village	0.30	0.51	0.031	0.0951
Comtour village	0.17	0.35	0.040	0.067
Comprdev village	0.28	0.45	0.033	0.111
Plain areas	0.21	0.42	0.041	0.085
Semi-mountainous areas	0.27	0.43	0.019	0.087
Mountainous areas	0.16	0.30	0.028	0.050
Total	0.33	0.57	0.030	0.058

agritourism (such as Jingdong Canyon and Jinhai Lake) have aroused some commercial, recreational, and leisure land uses.

At the village level, as shown in **Table 4**, the mixed degree in all types of villages has been enhanced greatly from 2005 to 2018, especially for agrprod and comtour villages where land use structure changed from residential land use to mixed residential and commercial uses. Moreover, the degree and types of MLU differ among village types, and the order is as follows: agrprod < comtour < indprod < comprdev. The reason behind this order is that the diversification of rural economy is often associated with the multiple land uses and high mixed degree in rural communities (Siciliano, 2012).

For agrprod villages, the self-sufficient economic status (including crop farming, planting, and breeding) and the lagging non-agricultural industrial development has constrained the multiple land uses. Its major function is merely to provide space for residential and simple public facilities service. In terms of comtour villages, they are endowed with numerous social, historic, and natural qualities. Consequently, aside from the land use pattern noted in agrprod villages, this type of village also has the potential to provide more recreational and tourism space, whereas the strict control of ecological environmental protection in the local region has altered the land use diversity and MLU. In indprod and comprdev villages, the prosperous industries, as well as the population agglomeration easily generated the land use multifunction (including recreation and leisure, residence, industrial and commercial production, public service, etc.), and multiple types of MLU have emerged, such as mixed residential and industrial uses; mixed residential, industrial and commercial uses; as well as mixed residential, industrial, commercial, and public infrastructure uses.

According to the above considerations and results, there are various factors influencing the MLU in rural communities, including economic locations, physical conditions, urban driving effects, and industrial structure. In general, along with the urbanization and industrialization process comes the more complex and multiple MLU. In this case, residential land is no longer the predominant land use. Also more and more inhabitants prefer the MLU to satisfy their diverse needs.

4.2 Changing Patterns of Residential Vacancy

From 2005 to 2018, the total area of vacant land changed from 179.3 to 472.78 ha, increased by 163.68%; meanwhile, vacancy rate increased from 0.03 to 0.058 (**Table 4**). Then, we identified the vacancy rate based on a comparative regional analysis. As discussed in **Figure 5**, in 2005, the vacancy rate in different regions ordered as plain areas > mountainous areas > semi-mountainous areas. The vacancy rate in plain areas (such as YK, DXZ, and MF) and northern mountainous areas (such as ZLY) is much higher. In 2018, the area of high vacancy rate enlarged, especially in some villages located in plain and semi-mountainous areas (such as JHH, SDZ, and NDL) where the suitable location and terrain provided a convenient foundation for the sprawl of rural build-up land, thereby, leading to the lack of the awareness of local residents for the importance of compact land use, and land use patterns became more fragmented. On the contrary, inferior geographical conditions and economic locations in mountainous areas were often accompanied by the insufficient land supply, and inhabitants preferred to put more effort into the

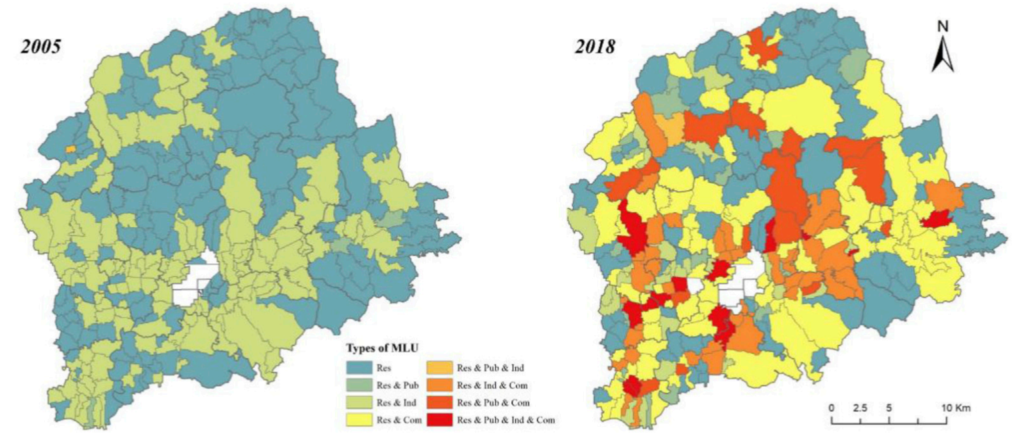

FIGURE 4 | Changing pattern of MLU in rural communities from 2005 to 2018.

shortfall of residential land. In addition, this area can be conceived as a slow-growing rural communities with relatively stable residents and low rates of land use conversion. Therefore, the compact and stable pattern decreased the vacancy rate of rural residential land.

For comparison with four categories of villages, it illustrated that there was no significant differentiation of vacancy rate in 2005; instead, the vacancy rate differed across the village types in 2018, showing as comprdev > indprod > comtour > agrprod. This tendency was consistent with the MLU. Compared with 2005, the residential vacancy rate grew remarkably among these villages except agrprod villages. In particular, residential vacancy rate in indprod and comtour villages increased 236.36 and 206.77%, respectively. In terms of indprod villages, the introduction of market economy has promoted the reorganization and restructure of enterprises to ensure the sustainable operation of rural industries. Consequently, some concentrated low-yield, polluting enterprises eventually closed down. These abandoned businesses and factories eventually transformed into vacant lots. For some comprdev villages, the income gap between urban and rural areas has forced more and more migrants moving to cities for economic and employment opportunities (Siciliano, 2012; Chen et al., 2014; Ma et al., 2018b). A large quantity of abandoned and vacant houses in villages can be characterized as the results of rural population loss.

4.3 Modeling the impacts of MLU on Residential Vacancy

MLU and rural residential vacancy are the two significant characteristics of paddy fields change in the study area, and we find a sharp increase in the residential vacancy rate and MLU in rural communities over the whole period from 2005 to 2018 in suburban areas of Beijing. As expected, the impacts of MLU on residential vacancy rate presented spatial non-stationarity. Moreover, as noted by Munroe et al. (2013), regardless of MLU, a number of factors showed association with residential vacancy, and their influences differed at the multilevel. Therefore, HLM and OLS analysis were used to explore the correlation between MLU and residential vacancy rate. **Table 5** presents the results of model fitting for the HLM with the reference values for the OLS. High *pseudo*-R^2 (McFadden's Adjusted) proved HLM to better explain the correlation between the MLU and residential vacancy rate.

As shown in **Table 5**, MLU in agrprod villages was non-significantly related to the increase of vacant land in any model; instead, some other variables like household livelihood, average elevation, per capita arable land, and adequate degree of infrastructure were found to be consistently significant in both models, and had negative signs ($p < 0.05$). According to the results in **Sections 4.1**, **4.2**, it revealed that values of mixed degree index and residential vacancy rate in this type of village were relatively low. Moreover, the changing patterns of MLU and residential vacancy rate were opposite. Although the MLU increased in the study period, the land used for production and living activities was limited, and farmers preferred the highly intensive land use pattern as a consequence. MLU has non-relationship with rural residential vacancy, and the vacant and abandoned land and others (such as bare land, and wild grassland) were mostly attributed by the adverse geographical conditions.

Based on the HLM, the MLU had a significant and positive sign ($p < 0.01$) in indprod villages, while the compactness had a negative sign, indicating that the residential vacancy is likely to happen in villages with higher MLU and low-density of land use pattern. At the village level, location conditions, adequate degree of infrastructure, and economic factors were significantly related to residential vacancy rate. The coefficients of these variables suggested that a higher residential vacancy rate was associated with a lower growth rate of real GDP and non-agricultural gross value, longer distance to roads, and inferior infrastructure construction. These results indicated that the MLU cannot cope with the traditional low-density development and sprawl patterns, with amounts of abandoned and vacant land, increased reliance on automobile travel, and the shortfall of adequate infrastructure. Because of the "orderly relocating all non-essential functions" implemented in 2015, indpro villages in the suburban area of Beijing have become the best places to supply land for undertaking

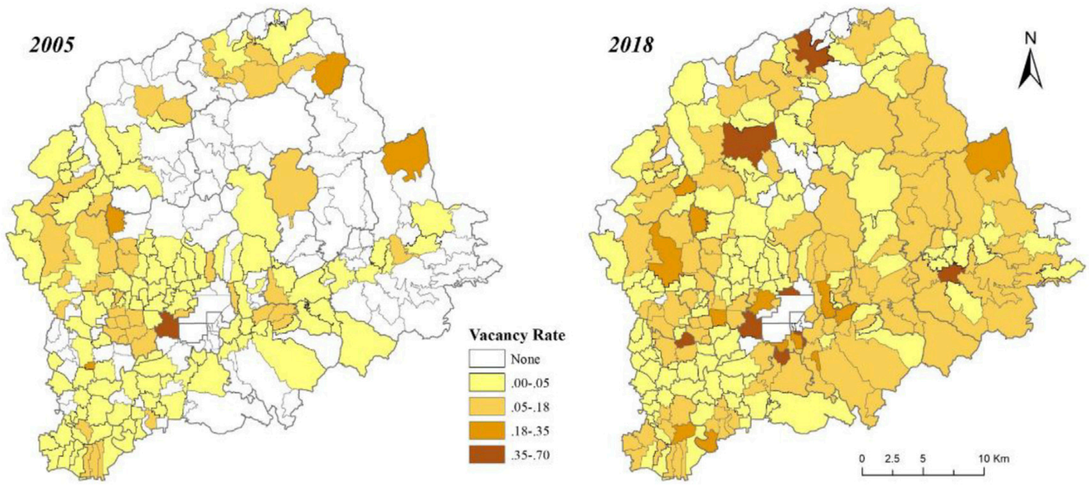

FIGURE 5 | Changing patterns of residential vacancy from 2005 to 2018.

TABLE 5 | Results of HLM and OLS analysis.

Variable	Agrprod Villages		Indprod Village		Comtour Village		Comprdev Village	
	HLM	OLS	HLM	OLS	HLM	OLS	HLM	OLS
Household family level								
Household income	-0.147	-0.153	0.372	0.373	-0.321***	-0.716***	0.658	0.658
Household livelihood								
Full-time farming	-0.429***	-0.566***	-0.318	-0.342	-0.641	-0.485	0.432	0.432
Part-time farming	0.145	0.121	0.394	0.348	-0.173***	-0.244***	0.267**	0.184**
Non-farming	0.729	0.645	0.479	0.479	0.523	0.404	0.579	0.521
Area of family houses	0.018	0.036	0.023	0.064	0.052	0.052	0.044**	0.029**
Village level								
Terrain								
Average elevation	-0.150***	-0.174***	-0.284	-0.461	-0.163	-0.332	0.271**	0.817**
Average slope	0.092	0.131	0.079*	0.079	0.104	0.106	0.082*	0.025
Spatial accessibility								
Accessibility to roads	0.977	0.849*	3.142**	4.358**	2.873*	2.967*	3.617	4.842
Accessibility to downtown	0.528	0.463	0.663	0.745	0.412	0.393	-0.364***	-0.161***
Per capita arable land	-0.474***	-0.474***	-0.523	-0.523	-0.484	-0.199	-0.846	-0.466
Population density	-0.038*	-0.049	-0.073	-0.045	-0.044	-0.031	-0.024***	-0.024***
Growth rate of real GDP	-0.053	-0.047	-0.022***	-0.048***	-0.068**	-0.054**	0.021	0.027
Non-agricultural gross value	0.079	0.079	0.037	0.021	-0.021**	-0.021**	0.058**	0.053**
Non-agricultural employment	0.615	0.615	-0.894***	-0.662***	0.567	0.293	0.779**	0.386**
Adequate degree of infrastructure	-7.852***	-8.366***	-6.424**	-6.424**	-6.386	-4.614	-4.438	-7.621
Villages compactness	-0.513	-0.664	-0.498***	-0.493***	-0.627	-0.844	-0.58**	-0.586**
Mixed land uses	-0.155	-0.213	0.329***	0.315***	-0.105**	-0.224**	0.179***	0.194***
N	72		61		75		67	
pseudo-R^2	0.388	0.387	0.425	0.379	0.442	0.414	0.341	0.293

*p < 0.1. **p < 0.05. ***p < 0.01, two-tailed test.

these non-essential industries and enterprises. However, land use conflicts occurred between new and original industries because the industrial structure allocation in some villages was unsuitable for these exterior industries. Some approval but not built exterior industrial land as well as the outdated interior industrial land, therefore, caused amounts of factories abandonment and vacancy.

In terms of comtour villages, the MLU and residential vacancy rate presented the opposing relationship ($p < 0.01$), indicating that MLU had the potential to reduce the residential vacancy. This result is consistent with the findings of prior research (Zhao et al., 2015; Gu et al., 2019). Furthermore, variables like household income and part-time farming at the household family level ($p < 0.01$), as well as the growth rate of real GDP and non-agricultural industries gross value at the village level ($p < 0.05$) had significant and negative signs. Recently, the policy "beautiful countryside" and the agritourism booming forced some traditional villages with adequate infrastructure and prosperous economy to transform into comtour villages, together with the types of

MLU changing from mixed residential and public infrastructure uses to mixed residential and commercial uses. This changing pattern assisted in increasing the compatibility of MLU, which could not only guarantee the land use diversity but also help battle against rural residential decline over time.

MLU was also positively related to the residential vacancy in comprdev villages ($p < 0.01$), whereas the compactness of villages showed a negative sign ($p < 0.05$). The results were similar to that in indprod villages, revealing that MLU cannot effectively reduce the residential vacancy. At the household family level, the non-farming variable and the total area of houses variable were statistically significant ($p < 0.05$). At the village level, terrain variables had a negative relationship with residential vacancy rate ($p < 0.05$), suggesting that the residential vacancy easily occurred in the plain areas. Moreover, non-agricultural gross value and non-agricultural employment showed positive relationships with residential vacancy rate ($p < 0.01$). Also, the coefficients of the accessibility to downtown and population density variables suggested that a higher residential vacancy rate is associated with lower population density and longer distance to downtown ($p < 0.01$). Due to superior locational conditions, the inhabitants living in the suburban areas obtained accessibility to downtowns and cities to pursue livelihood improvement. This detachment between human and land under rural–urban migration has generated a growing number of abandoned houses and vacant land.

5 DISCUSSION

5.1 Why Do Impacts of MLU on Residential Vacancy Differ Across the Village Types? A Case Study of Four Typical Peri-Urban Villages

In order to better explore and verify the relationship between MLU on residential vacancy in different types of villages, we selected four typical villages by stratified sampling, including Nanshan Village, Jiangli Village, Diaowo Village, and Daxing Village (see in **Figure 1**). We used the participatory rural appraisal and field survey to obtain the internal spatial structure (**Figure 6**) and tried to explain why impacts of MLU on residential vacancy differ across the village types.

1) Agrprod village: Nanshan village

This village, located in the southeast of Pinggu District, is surrounded by mountains. The majority of the economically active population is engaged in agricultural production for both subsistence and commercial purposes. From 2005 to 2018, the value of mixed degree index increased from 0.043 to 0.132. Residential land was predominant in 2005, with the area proportion of 96.85%. It presented a scattered distribution to take full advantage of the convenient transportation and the limited plain terrain. In 2018, the area of land used for public facilities and infrastructure (such as roads, squares, hospitals, and schools) has increased by 38.91%, and the spatial structure presented the circling-layering land use layout pattern (**Figure 6**). Also, adequate infrastructure has beneficial in reducing the residential vacancy rate, and some vacant and abandoned land along with the roads has been used. Residential vacancy rate has decreased from 0.043 to 0.01. However, there still existed 73.55% of vacant land (such as bare land and wild grassland) in mountains hard to utilize, which also proved that MLU cannot be the effective resolution for reducing natural land abandonment.

2) Indprod village: Jiangli village

This village is located in the southern plain of Pinggu and is positioned in the center of MF. In 2018, its secondary industry output value reached to 92,915 thousand *yuan*, accounting for 89.31%. During the study period, lots of factories moved from the center city, such as textile mills, and electronics companies, which have aroused the area increase of industrial land (increased by 3632.21%). Also, the degree of MLU changed from 0.32 to 0.42. Spatially, these industrial land often sprawled along with the road networks, showing a centrifugal-radial land use changing pattern. Ultimately, a part of them agglomerated within *Mafang Industrial Park*, while others mixed with residential land.

The centrifugal-radial changing pattern, however, has broken the compact and orderly spatial layout in the village. For example, new and old houses, as well as interior and exterior factories sometimes led to chaotic and over-mixed residential and industrial uses. Moreover, these lands were at risk of being abandoned as a result of industrial pollution from adjacent enterprises. The absence of appropriate land use planning before the implementation of MLU and legal enforcement after the introduction of MLU might lead to illegal and abandoned non-residential activities in residential areas. Therefore, the residential vacancy rate of this village increased from 0.035 to 0.047.

3) Comtour village: Diaowo village

This village is located in the HSY Town, northeast of Pinggu. It is famous for the beautiful scenery such as Jiongdong Canyon, and the rich folk culture. Based on the statistic results, the gross output of primary and tertiary industry accounted for 34.93%, 63.23%, respectively. From 2005 to 2018, the degree of MLU increased from 0.49 to 0.60: residential and infrastructural land have composed the early living space within the village in 2005, with the area proportion of 52.52 and 32.06%, respectively; in 2018, some new types of MLU like mixed residential, commercial, and public infrastructure uses, were found as a result of industrial transformation from agriculture to commerce and agritourism. Spatially, the new commercial land presented a striped distribution between residential and public infrastructure land—the living space filled with productive space—showing a compact spatial pattern.

Meanwhile, the residential vacancy rate of this village decreased from 0.067 to 0.021, indicating that this compact pattern was conducive to reduce the residential vacancy and land abandonment. The main reason behind this change was the implementation of a “beautiful countryside” policy, including dismantling some “illegal” houses and factories, consolidating old villages, etc., all of which were helpful in achieving the smart growth of this village. Furthermore, the houses owning the mixed residential and commercial uses were easily rented, thus local inhabitants were

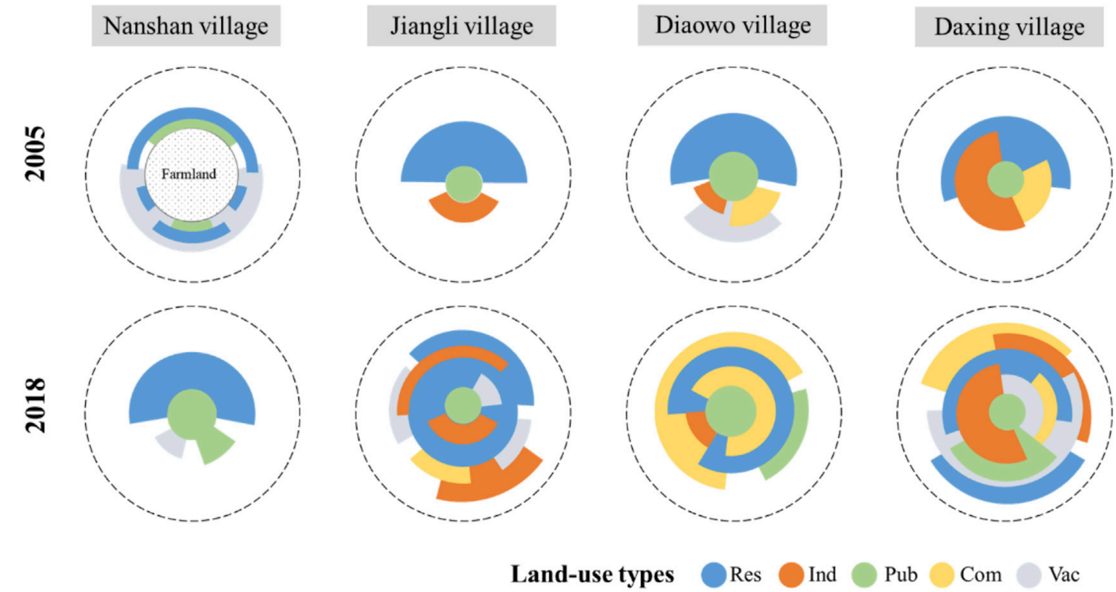

FIGURE 6 | Spatial structure of four typical villages.

inclined to utilize the vacant land around their houses to increase the economic benefits.

4) Comprdev village: Daxing village

This village is located in the urban–rural interface of Pinggu District. The diversification of the rural economy and industry (including agriculture, industry, and commerce) has been realized under the influence of urbanization process. The degree of MLU increased from 0.64 to 0.71 during the study period. It can be seen in **Figure 6** that in 2005, the compact land use layout pattern formed within the village with the mixed residential, industrial, and public infrastructure uses, where residential land was located in the center of the village, and other types of land distributed in the fringe of the village. Afterward, the diverse livelihood of inhabitants led to a more complex MLU, and some residential and industrial land were replaced and combined by commercial land.

Recently, one of the major threats for the village was residential vacancy and environmental degradation, and residential vacancy rate increased by 21.21%. The phenomenon was attributed to excessive and complex MLU. In particular, the inappropriate mix of residential, industrial, and commercial land would worsen the livability of the village. The majority of inhabitants, therefore, migrated to cities to pursue a high-quality lifestyle. The demographic census results illustrated that 51.48% of inhabitants had their own houses in the downtown. As a result, there emerged considerable rural houses being abandoned in the village.

5.2 Implications for Rural Community Sustainability Planning

Nowadays, the magnitude and the rapidity characterizing the urbanization process in the Chinese countryside have aroused the diversification and heterogeneity of rural community transformation, thereby resulting in the land use multifunctionality and mixed-use development. According to the previous considerations and results, some villages with MLU have high rates of residential vacancy and housing abandonment, which is questionable. Land use strategies that prioritize MLU, by placing residential, industrial, and commercial areas in close proximity, cannot always promote compact development and the efficient use of land. Whether functional zoning or mixed-use development, feasible approaches to land use planning are important for human settlements in decline. These findings bring potential implications for future sustainability planning in rural areas.

First, considering the spillovers of industrial pollution to adjacent residential spaces, it is necessary to separate the residential land from high-pollution industrial land and divide land uses in residential areas into industrial zones, residential zones, and recreational zones. This policy tool—functional zoning—could reconcile conflicts between industrial and residential land in ways that create livable and sustainable settlement patterns, as well as put idle factories and vacant industrial land to better use, which have potential to provide spatial support for rural industrial development and vitalization strategies.

Second, as MLU failed to reconcile the residential vacancy and houses abandonment, a combination of functional zoning and mixed-use development together with the introduction of marketing rural collective land programs may be a feasible alternative to compact development. The focus of land use planning in rural communities should sufficiently emphasize the orderliness and compatibility of land use patterns. When referring to the development and utilization of land, it is necessary to follow the principle—residential function takes precedence over the non-residential functions—which could solve the problem of "land use function exceeding the village carrying capacity." Compatible and predicted MLU should rely on functional zoning.

Third, the vacant land utilization and consolidation should not only consider land suitability, but also refer to village functions and human demand. For example, some vacant land distributing as a striped pattern between residential and public infrastructure space should be exploited as green space (e.g., garden beds or green land) to enhance the livability and ecological function of human settlements. Moreover, some large-scale vacant land can be reserved as potential land resources for future village development. Additionally, lawful rural residential land property trading could guarantee abandoned houses and vacant land to be utilized legitimately.

With the advent of the 21st century, the coexistence of MLU and rural residential vacancy has been employed as one of the common phenomena, which occurs due to the process of industrialization and urbanization in rural China. Sometimes, the inclusion of MLU is considered as a carrier of compact development, and even resulting in community decline. All of these points are connected by a series of influences—primarily driven by the urban–rural gap. Indeed, functional zoning and mixed-use development should not contradict with each other. Considering the village characteristics, integrating mixed-use development into rational functional zoning is a useful and effective tool to achieve the rural sustainability planning.

5.3 Contribution to Research, Limitations, and Future Work

The link between MLU and regional compact development has been extensively researched in the field of urban studies. The advocates of MLU claim that the combination of the residential, industrial, and commercial uses can reduce neighborhood decline and community vacancy (Karen. et al., 2012; Gu et al., 2019). In contrast to those in urban studies, increased mixed-use environments in some Chinese rural areas may have adverse effects on the livability of settlements, even deteriorating the residential vacancy. Therefore, whether MLU is a feasible strategy for residential vacancy resolution is a critical issue in rural sustainability.

This study helps to understand the relationship between MLU and community decline, and reconcile residential vacancy in the countryside suffering rural depopulation. It brings together several separate areas of literature concerning MLU, spatial structure, and residential vacancy in rural areas, and opposes previous research findings that increased mixed-use planning is playing an important role in altering community decline. In addition, the introduction of HLM analysis, which takes into MLU, and other driving factors at the multilevel, provides a quantitative method to explore their correlation with rural residential vacancy. Also, this study presents implications concerning the effectiveness and feasibility of rural community sustainability planning policies drawn to build livable and healthy communities in rural areas.

When interpreting these results, some limitations of this study should be regarded. First, the pseudo R-square values (more than 0.3) for the two models were relatively low, and the HLM does not demonstrate the causation between the MLU and residential vacancy thoroughly. We will perform longitudinal analysis to examine causal relationships carefully. Second, because of the limitation of the database, the case study—Pinggu District in Beijing is relatively small. Future studies will use other cases for comparison to verify the conclusions in this study. It could provide a significance to wider a wider scientific community and lead to more feasible rural community sustainability planning.

6 CONCLUSION

By applying an integrated framework, this study has analyzed and compared the changes in MLU and residential vacancy in peri-urban areas. During the study period, the degree of MLU and residential vacancy rate both showed increasing tendency. Their changing patterns, however, differed across four types of village, which referred to the village with the complex MLU was often associated with the high residential vacancy rate. To account for this, a model approach was used to explore impacts of MLU on rural residential vacancy. The findings show a substantial difference among village types: the disorderly and excessive mixed uses in indprod and comprdev villages exacerbated residential vacancy, even threatening the neighborhood safety and livability, whereas compatible MLU in comtour villages assisted in reducing the residential vacancy rate, as well as promoting the compact and high-density land use pattern.

When it comes to prototyping residential vacancy solutions, it is important to understand and consider the major village characteristics in China. For most villages, although urbanization process arouses the MLU, land use change in rural communities remains as the traditional way of relentless sprawl. Undeniably, planning for increased mixed-use environment like urban land uses, according to this research, is unsuitable for rural communities. Sustainable planning to counter residential vacancy should combine the compatible mixed-use development together with the rational functional zoning, which can also be considered a constructive tool in mitigating community decline, as well as bringing human settlements development, vitality, and diversity.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

In this study, WM processed the data and wrote the main contents of the article. GJ, TZ and RZ provided ideas for the paper. All the authors discussed the results and implications and commented on the manuscript at various stages.

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Withdrawal and Transformation of Rural Homesteads in Traditional Agricultural Areas of China Based on Supply-Demand Balance Analysis

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Idle and abandoned rural homesteads not only waste land resources, they also affect the quality of life of farmers and occupy land that could be used for agricultural production and ecological space. Analysis of the supply–demand relationship of rural homesteads is an important prerequisite for the implementation of rural homestead withdrawal and transformation, which is important for improving rural residential quality and land-use efficiency, promoting sustainable development and the classified revitalization of rural areas. Based on high-resolution remote sensing images of typical villages in traditional agricultural areas, a participatory evaluation method was used to analyze the supply–demand balance of rural homesteads and to propose countermeasures for their withdrawal and transformation. The results showed that: 1) rural homesteads have gradually realized the separation of living space and production space, the living function has gradually been enhanced, the production function has gradually weakened, and the ecological aesthetic function has emerged. 2) Farmers' demand for rural homesteads is driven by various factors, including social and economic development level, lifestyle and livelihood. 3) There are a large number of idle or abandoned rural homesteads in traditional agricultural areas, with great withdrawal potential. The difference between the supply and demand of rural homesteads in use is obvious. The supply of living space of adobe house and mud-brick houses is less than the demand for them, and there is mixed use of space. The supply of production space for brick houses is less than the demand; in general, the supply of buildings is greater than the demand. 4) For rural homesteads still in use, exit and transformation strategies should be formulated according to the relationship between supply and demand, construction quality, spatial independence, and the wishes of farmers. The withdrawal and transformation of rural homesteads based on the balance between supply and demand is in line with the reality of rural development and the Chinese government's strategy of national rural revitalization.

Keywords: rural homesteads, supply and demand balance, withdrawal of rural homesteads, structural and functional evolution, transformation

1 INTRODUCTION

Human society has entered the urban age, with more than half of the global population living in urban areas, and this proportion is expected to reach two-thirds by 2050 (Malakoff et al., 2016; Lemoine -Rodriguez et al., 2020). In recent decades, rural decline has become an indisputable fact and a global problem (Dahms, 1995; Muilu and Rusanen, 2003; Markey et al., 2008; Hedlund and Lundholm, 2015; Li et al., 2019). As a developing country, China has experienced unprecedented rapid urbanization and industrialization since the start of reform and opening up in 1978, with the urbanization level rising from 17.92% in 1978 to 60.60% in 2019 (Bai et al., 2014; Dong et al., 2021). However, the countryside has long been exploited due to urban biased development policies (Li et al., 2019; Gao et al., 2020). This imbalance between urban and rural development has made the decline of rural China a serious problem for future generations (Muilu and Rusanen, 2003). On the one hand, there is a massive outflow of rural populations in search of better education, medical resources and employment opportunities. On the other hand, against the background of the urban–rural dual structure, with increasing household incomes, it is now common for people to return home from urban centers in order to build new or to improve existing housing. Due to the absence of rural planning, lax supervision and the absence of a rural homestead withdrawal mechanism, the rural population has decreased, but the area of homesteads has increased, and many rural homesteads have been left idle or even abandoned, forming a large number of "hollow villages" (Liu and Li, 2017). Along with these changes in farmers' lifestyles and livelihoods, farmers' functional demands for rural homesteads have become increasingly diversified, and rural homesteads now show the characteristics of transformation and multifunctional utilization (Jiang et al., 2016; Su et al., 2019; Zhao et al., 2019). In summary, idle, abandoned and multifunctional use rural homesteads not only result in wastage of land resources, they also affect the quality of life of rural residents and occupy land that could otherwise be used for agricultural production and ecological space.

Orderly withdrawal and transformation of rural homesteads is the key to solving these problems (Kong et al., 2018; jiali et al., 2021; Zhang et al., 2018). In order to guide this process and promote rural transformation and development, realize urban and rural integration, and improve the quality of life of rural residents, the state and relevant departments have introduced a series of policies and measures, including the construction of a socialism new countryside, the construction of beautiful countryside, the separation of rights, the reform of the three plots of land, and rural revitalization (Long et al., 2009; Tian et al., 2014; Alcock, 2019). Local governments have also explored the feasibility of withdrawal of rural homesteads on a large scale. However, in practice, due to insufficient consideration of the needs of farmers and one-sided pursuit of political achievements, farmers were having to live upstairs in some areas and there was limited space for rural production development, as well as other problems, which is not conducive to the sustainable development of rural areas.

Rural homesteads have long been a focus of academic studies (Naldi et al., 2015), involving the rural human–land relationship (Dahms, 1995; Amcoff and Westholm, 2007; Chi and Ho, 2018; Cai et al., 2020), the structure and function of rural homesteads (Jiang et al., 2016; Qu et al., 2017; Yang et al., 2020; Cáceres -Feria et al., 2021) and the withdrawal of rural homesteads (Wu et al., 2018; Song et al., 2020; Liu et al., 2021). "Population decrease and land area increase" is a common phenomenon in China's rural areas, but there are also the phenomena of "population decrease and land area decrease", "population increase and land area decrease" and other types (Song and Liu, 2014; Zhu et al., 2020; Dong et al., 2021). Although from the perspective of land use, "population decrease and land area increase" is not conducive to the efficient use of land resources, from the perspective of human welfare, however, increase in land area for residential, industrial and public management services in rural areas is conducive to improving people's livelihoods and the quality of the living environment (Qu et al., 2021a).

Rural homesteads have social security, benefit and retaining functions, and show obvious spatial differentiation (Qinglei et al., 2019). The social security function is strongest in the economically backward mountainous areas, and the benefit function is most prominent in the economically developed plain areas. With the development of both society and the economy, the function of rural homesteads has also changed (Zhu et al., 2014; Ma et al., 2018; Qu et al., 2021b). The production function has weakened, while the life function has strengthened (Jiang et al., 2016). The withdrawal of rural homesteads is affected by factors such as peasant household differentiation, generational differences and compensation methods (Chen et al., 2017; Liu et al., 2020). Pilot areas have begun to explore different modes of rural homestead withdrawal, but the long-term interests of farmers are often ignored (Kong et al., 2018).

The above studies have drawn a large number of enlightening conclusions, providing a scientific reference for guiding the processes of the withdrawal and transformation of rural homesteads, which is of great importance. However, there are few studies on rural homestead withdrawal and transformation based on supply–demand balance analysis (Ma et al., 2019). Rational analysis of rural homestead supply and demand is the premise for the process of rural homestead withdrawal and transformation. In view of this, this study selected the traditional agricultural areas with a large potential for withdrawal of rural homesteads as the research area, evaluated the supply and demand of rural homesteads by means of field investigation based on high-resolution remote sensing images and participatory mapping, and then discusses the withdrawal and transformation of rural homesteads based on the supply–demand balance. We believe our results and conclusions will provide a scientific reference for orderly withdrawal of rural homesteads, improve the living standards of farmers, and protect the rural production development space.

TABLE 1 | Internal spatial structure and functions of a rural homestead.

Rural homestead function		Internal spatial structure of a rural homestead
First-level function	**Secondary function**	
Living function	Residential function	Bedroom
	Life service function	Living room, dining room, kitchen, bathroom, toilet
Production function	Agricultural production function	Colony house (chicken shed, hog house), vegetable plot
	Agricultural production service function	Storage room
	Nonagricultural production function	Concession stand, oil shop
Ecological function	Eco-aesthetic function	Green planting space
Other potential functions	Potential functions	Courtyard

2 THEORETICAL FRAMEWORK AND METHODS

The conceptual framework employed in this study included four aspects: 1) analysis of the supply of rural homesteads; 2) analysis of the demand for rural homesteads; 3) analysis of supply–demand of rural homesteads; and 4) analysis of rural homestead withdrawal and transformation utilization based on the supply–demand balance.

2.1 Supply Analysis

The supply of rural homesteads is characterized by type, scale and quality. The interiors of rural homesteads are not homogeneous spaces, but are heterogeneous spaces divided up by farmers according to their particular needs. They are multifunctional compound units closely related to farmers' lifestyles, livelihoods and social science and technology levels. According to system theory, function is the external representation of structure, and structure is the internal basis of function; that is, structure determines function (Ma et al., 2019). Therefore, according to the internal spatial structure of a rural homestead, we can identify the function it carries and then analyze the types and scale of rural homestead supply. The quality of rural homestead supply can be evaluated on the basis of architectural quality, perfection of and independence of the functional space.

According to field research, a typical rural homestead in traditional agricultural areas usually includes the following: bedrooms, living room, dining room, kitchen, bathroom, toilet, courtyard, storage room, colony house, vegetable plot and green planting space, carrying four first-level functions of living, production, ecology and other potential functions. It also includes six secondary functions, specifically residential function, life service function, agricultural production function, agricultural production service function, nonagricultural production function, and eco-aesthetic function. The relationship between the internal spatial structure of a rural homestead and its carrying functions is listed in **Table 1**.

The bedroom is the most basic spatial structure in a rural homestead, is the rest space for farmers, and carries the residential function. The living room is the space for farmers' daily recreation, meeting guests and making friends, and carries the life service function. The dining room, kitchen, bathroom and toilet are the necessary spaces for daily meeting with others, and bear the life service function. The vegetable plot is the space for farmers to grow vegetables in the courtyard to facilitate daily life and reduce living expenses, while the colony house, comprising such buildings as the chicken shed and hog house, is the space for farmers to carry out agricultural production activities in order to enrich food sources and increase income, both of which reflect the agricultural production function. The storage room is a place for farmers to store food and agricultural production tools and carries the agricultural production service function. Some rural homesteads also carry the function of multifunctional utilization, setting up a room to open a concession stand or oil shop, forming the nonagricultural production function. With improvements in living standards and yearning for a better life, farmers plant flowers and plants in their courtyards to beautify the environment, enhance sentiment and improve the quality of life, which carries the ecological aesthetic function. The courtyard is a flexible space, carrying other potential functions.

2.2 Demand Analysis

According to Maslow's theory of the hierarchy of needs, humans have five levels of need, arranged in a pyramid structure, which are, from the bottom up, physiological needs, security and safety needs, social needs, esteem and self-actualization (Maslow, 1943). Of these, physiological needs and security needs are low-level needs, while social needs, esteem and self-actualization are high-level needs. When the low-level needs are satisfied at least to a certain extent, the high-level needs then arise.

Farmers' need for rural homesteads also conforms to Maslow's hierarchy of needs theory, and there is a hierarchical need pyramid from low to high (**Figure 1**). When social and economic development is backward and materials are scarce, the rural homestead should first meet the physiological needs of farmers, that is, residential needs and the most basic life service needs. With social and economic development, in order to support the family, maintain and improve living standards and achieve sustainable development, a rural homestead should not only meet the physiological needs of farmers but should also meet the production needs of farmers, namely, their security needs. In addition, human beings are social animals, with a basic human need to contact and communicate with each other. Rural homesteads should meet the social needs of farmers, that is, the need for social space. When the problem of food and clothing is solved and people's material needs are basically satisfied, they begin to pay attention to the location and quality of rural homesteads and pursue a better quality of life, resulting in a

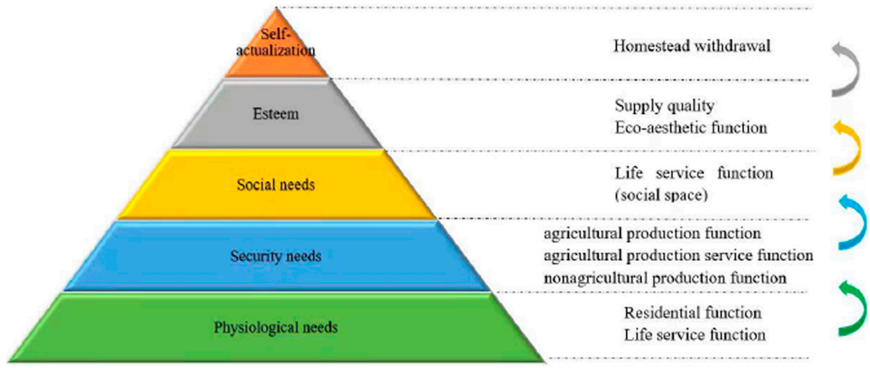

FIGURE 1 | Maslow's hierarchy of needs applied to farmers in rural homesteads.

TABLE 2 | Evaluation index of the supply–demand balance of rural homesteads in use.

Function	Space	Indicator	Calculation methodology and description	Relation between supply and demand
Residential function	Bedrooms	Number of bedrooms per capita	Number of bedrooms/(resident population − 1)	1: Supply and demand in balance >1: Supply exceeds demand <1: Supply is less than demand
Living service function	Living service space	Degree of perfection of living service space	X = M/N; N is 5; M is the number of central rooms, dining rooms, kitchens, bathrooms and toilets	1: Supply and demand are in balance >1: Supply exceeds demand <1: Supply is less than demand
Production function	Production space	Number of production space transformation uses	X = N; N is the number of production space transformations and utilizations, such as vegetable plots, colony houses and storage	0: Supply and demand in balance >0: Supply is less than demand
Ecological function	Eco-aesthetic space	Degree of space perfection	X = N; N is whether there is eco-aesthetic space; yes is 1, no is 0	0: Supply is less than demand 1: Supply and demand in balance

need for esteem and ecological aesthetics. The need for self-actualization can only come about when the levels of social and economic development and of farmers' self-awareness are both high. At present, this level of need is reflected mainly in voluntary withdrawal from idle, abandoned and over-occupied homesteads in response to government policies.

2.3 Supply–Demand Balance Analysis

Rural homesteads are built by farmers according to their production and living needs, and are divided into different internal spaces accordingly. Therefore, when rural homesteads are first built, the supply–demand relationship can be regarded as being in a state of balance. At this time, a rural homestead is both the embodiment of demand and the representation of supply. With the transformation and development of the social economy, the progress of science and technology, and changes in farmers' production and lifestyles, farmers' needs will also be upgraded or will generate new demands, breaking the initial balance between supply and demand, prompting farmers to actively transform their homesteads, forming new spatial structures and utilization states, and then realizing a new dynamic balance between supply and demand. Therefore, the utilization status of rural homesteads, that is, idle, abandoned, multifunctional utilization or transformation utilization, is a direct reflection of the relationship between supply and demand.

Idle and abandoned rural homesteads indicate that supply is greater than demand. When the internal space of rural homesteads is transformed and utilized, or new functional space is created through reconstruction or new construction, the original balance between supply and demand is broken and the supply of the new functional space is less than the demand for it. Based on field research, according to the changes in the internal structure and function of rural homesteads in traditional agricultural areas, and referring to relevant studies, indicators—such as the number of bedrooms per capita, the degree of improvement in living service space, and the degree of transformation and utilization of agricultural production space—were selected in order to evaluate the supply–demand relationship of rural homesteads in use (**Table 2**).

Bedrooms bear the residential function. According to current family structures and living habits in China, in general, parents need one bedroom and each child needs one bedroom. Therefore, the number of bedrooms per capita [number of bedrooms/(number of residents in household − 1)] can be used to represent the supply–demand relationship of residential functions. If the number of bedrooms per capita equals 1, the residential function is in balance with supply and demand. If the number of bedrooms per capita is greater than 1, supply exceeds demand. If the number of bedrooms per capita is less than 1, supply is less than demand.

Restricted by construction age, construction cost and other factors, there are mixed uses and a lack of life service spaces in rural homesteads, and the degree of improvement in life service spaces can be used to reflect the supply and demand relationship of the life service function. If the life service space is complete, supply and demand are in balance. If a certain life service space is missing, supply is less than demand. If the life service space is complete and the number of some spaces is greater than 1, supply is greater than demand. Due to changes in livelihoods, production and lifestyles, the internal space of rural homesteads is often transformed. This shows that the supply of space before the transition is greater than the demand, but the supply of space after the transition is insufficient. Therefore, the quantity of production space transformation can be used to reflect the perfection of the production function. If the amount of transformed space is 0, supply and demand are in balance. If the amount of transformation space is greater than 0, supply is less than demand.

At present, China is implementing a rural revitalization strategy, and ecological livability is one of the basic requirements. Therefore, the perfection of ecological function can be measured by the perfection of ecological aesthetic space. If the latter exists, the relationship between supply and demand is in balance. If there is no ecological aesthetic space, supply is less than demand.

2.4 Withdrawal and Transformation of Rural Homesteads

The supply of idle and abandoned rural homesteads is greater than the demand for them, and should be given priority for withdrawal. For the rural homesteads still in use, the supply-demand balance and supply quality of rural homesteads should be comprehensively considered, and a supply-demand adjustment strategy for rural homesteads should be formulated by classification. If supply is less than demand, farmers' needs cannot be met. The balance between supply and demand should be realized through the transformation utilization of internal space, followed by withdrawal and resettlement. If supply is greater than demand, priority should be given to exiting in order to avoid waste and inefficient use of resources. From the perspective of supply quality, rural homesteads of low quality should be withdrawn first.

3 STUDY AREA AND DATA SOURCES

3.1 Study Area

Qianpozi village is located to the northeast of Changling Town, in Juxian County, Rizhao City, Shandong Province, approximately 0.5 km to the west of 225 Provincial Road, 1 km from Changling Town and 13 km from the county seat (**Figure 2**). Qianpozi village is flat, fertile and has a long history of farming. It is a typical representative of traditional farming villages in China. In 2018, the total population was 820. Most of the farmers were engaged in agricultural production, and the main crops were peanuts, corn and wheat. As a traditional agriculture-oriented village, the livelihoods of farmers there have evolved from agriculture-oriented to a combination of agricultural production and migrant work, gradually becoming nonagricultural and diversified, but with economic instability and poor risk-resistance. The main livelihoods of farmers include farming, migrant work, truck transportation, sole trader, and greenhouse planting, with a net per capita income of approximately 5,000 yuan.

Since the 1930s, Qianpozi village has experienced extensive and continual building of houses. The houses built in different periods witnessed the transformation and reconstruction of rural homesteads driven by demand and supply. The earliest still-existing houses in the village were built in the 1960s and 1970s, and the building materials were mainly adobe bricks (a building material of sun-dried earth and straw), so that the houses were known as adobe houses. The village experienced a house-building boom in the 1990s as productivity and the population both grew. The location and size of this new housing were arbitrary due to the lack of relevant construction standards, village planning and supervision. The building area was generally large, mostly about 280 m^2, and the building material was mostly mud brick, which is why they are known as mud-brick houses. In 2005, driven by the construction of a socialism new countryside, the village experienced another house-building boom. In this period, according to the requirements of a "clean village appearance," the locations of houses were demarcated and the building scale was unified. The footprint of each house was 182 m^2, and the construction materials were upgraded to brick and concrete. The insulation and quality of construction of the houses were greatly improved, and these are known as brick houses. In 2011, the village committee developed and constructed a number of buildings, with a footprint of 162 m^2 and reinforced concrete construction materials, which were called buildings.

3.2 Data Sources

Between January 2019 and January 2021, our research group visited the research area in order to carry out several field investigations. With the help of the Two-step Road Outdoor Assistant software application (https://www.2bulu.com), research

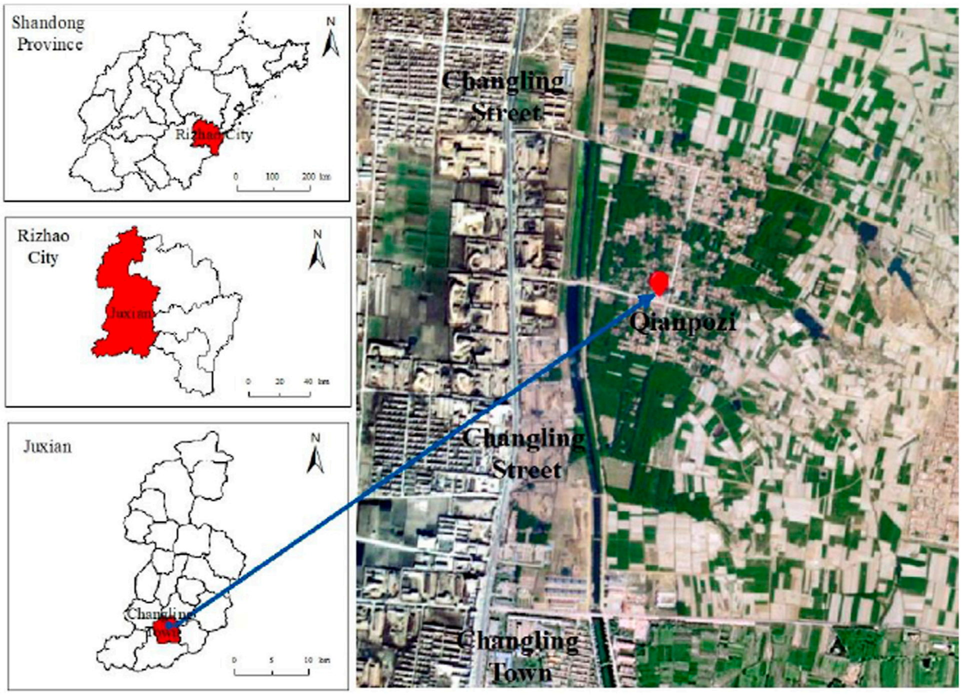

FIGURE 2 | Location of Qianpozi village.

routes, photos, house usage and spatial locations were recorded. Social and economic data related to village development were collected through discussions with village leaders, secretaries, accountants and farmers' representatives familiar with the village development, including middle-aged and senior people. Household investigations were conducted in order to collect data about household structure, income structure, employment structure and other micro-data, as well as internal spatial structure, architectural form, construction age and the building materials used in rural homesteads.

4 RESULTS

4.1 Internal Structural Changes and Functional Transformation of Rural Homesteads

4.1.1 Adobe Houses

Adobe houses are small in area, simple in their internal spatial structure, mixed and imperfect in function and poor in quality (**Figure 3A**). The area of this type of house is typically no more than 50 m^2, composed of four main types of space: living room, kitchen, colony house and courtyard. Of these, the areas of the living room and courtyard are large, 20 and 22 m^2, respectively, and the area of the kitchen and colony house are small, both approximately 4 m^2. During this period, no independent bedroom or dining room was built. The living room is a comprehensive space for living, eating, making friends and receiving guests, carrying the residential and life service functions. The kitchen is used mainly for cooking, thus carrying the life service function. The colony house is used mainly to raise chickens, ducks and other poultry, thus carrying the agricultural production function. In summary, adobe houses are intended to serve mainly the residential and living service functions.

4.1.2 Mud-Brick Houses

The area of a mud-brick house is significantly larger than that of an adobe house, the internal space structure is richer, the independence of functional space is enhanced, and the degree of perfection and the quality of construction are both improved (**Figure 3B**). The area of a mud-brick house increases to approximately 280 m^2. In contrast to the internal structure of the adobe house, the bedrooms in a mud-brick house are separated from the living room to form an independent space. In addition, planting and storage space are added, forming seven types of space altogether. Of these, the area of the courtyard is the largest, approximately 94 m^2. The bedroom and living room are also relatively large, 58 and 56 m^2, respectively, and the areas of the storage space and kitchen are 24 and 16 m^2, respectively. The area of the colony house and planting area are the smallest, both 12 m^2. From the perspective of the functions carried by each space, the living room no longer has the residential function, but carries the living service function only. The bedroom becomes an independent space, carrying the residential function. Planting space is used mainly for planting fruits and vegetables, carrying the agricultural production function. Storage space is used mainly for grain storage and stacking agricultural machinery and tools, and carries the agricultural production services function. The

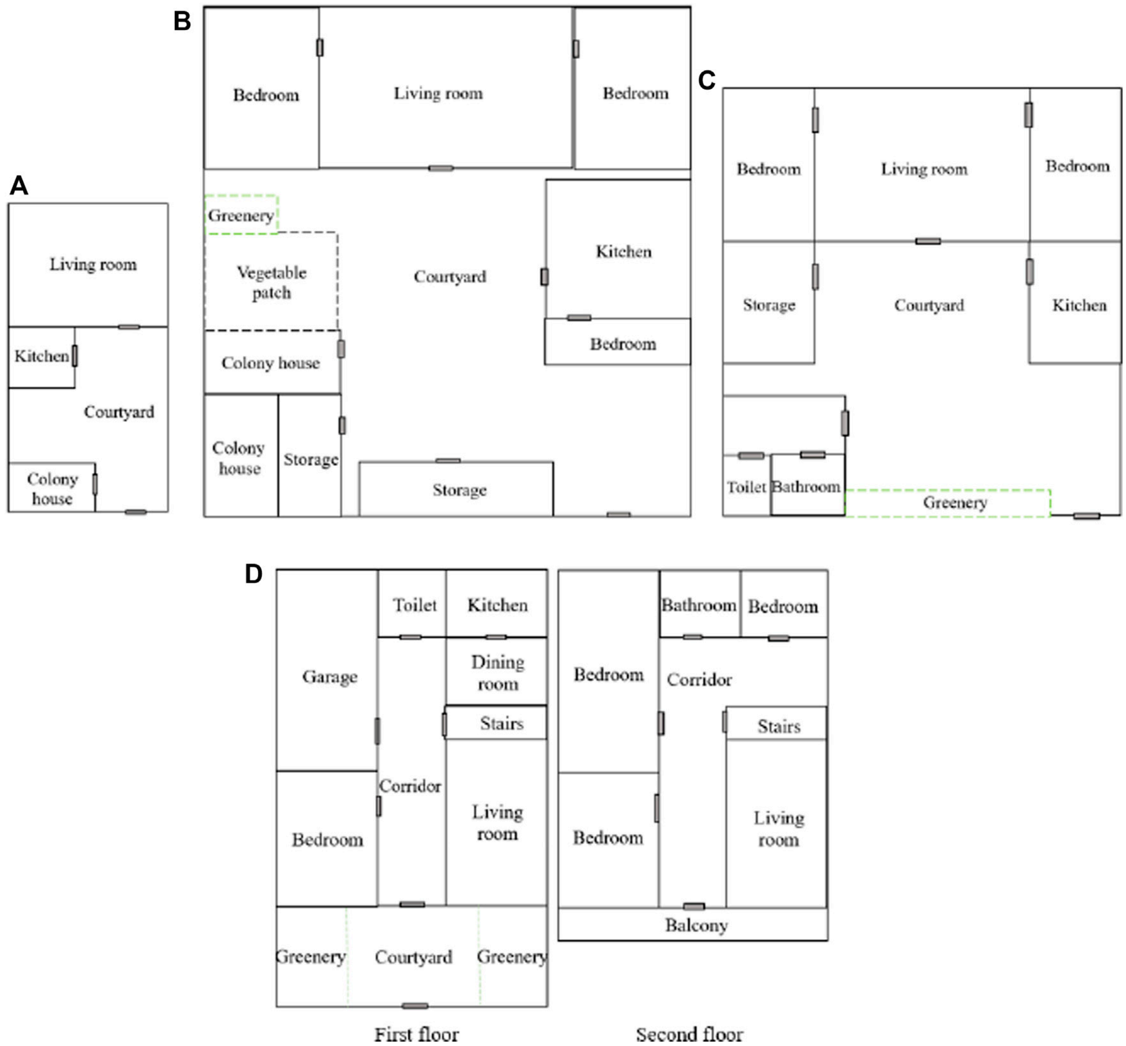

FIGURE 3 | Internal structure of different types of rural homesteads: **(A)** adobe house; **(B)** mud-brick house; **(C)** brick house; **(D)** building; dotted lines represent unfixed, open space.

kitchen, colony house and courtyard are all used, and carry the same functions as before.

4.1.3 Brick Houses

Compared with mud-brick houses, the area of brick houses is significantly reduced, but the internal spatial structure is more reasonable, the functional zoning is more perfect, and the quality of construction is further improved (**Figure 3C**). The area of this type is uniform and reduced to approximately 182 m^2, including seven main types of space, namely living room, bedroom, kitchen, storage room, bathroom, toilet and courtyard. Of these, the courtyard area is the largest, at 74 m^2. The living room and bedroom are 35 and 30 m^2, respectively. The kitchen and storage area are both 12 m^2, and the bathroom and toilet areas are both 4 m^2. Due to the reduced size, this type of house no longer has space for agricultural cultivation inside, which is transferred to the outside of the house. A separate bathroom and toilet are created to support living services. The uses and functions of the living room, bedroom, kitchen and storage room remain unchanged.

4.1.4 Buildings

The floor area of a building is further reduced, and the internal spatial structure and function are further optimized (**Figure 3D**). The building type is a two-story villa with a loft, covering an area of approximately 105 m^2. A separate living room, dining room, toilet, bathroom and garage are added. Of these, the living room area is 50 m^2, the bedroom area is 48 m^2, the dining room and kitchen areas are both 6 m^2, the bathroom and toilet areas are both 4 m^2, the garage area is 18 m^2, and the courtyard area is 44 m^2. During this period, the separation of the various functional spaces was the most perfect, including the residential, living service, agricultural production, production service and ecological aesthetics functions.

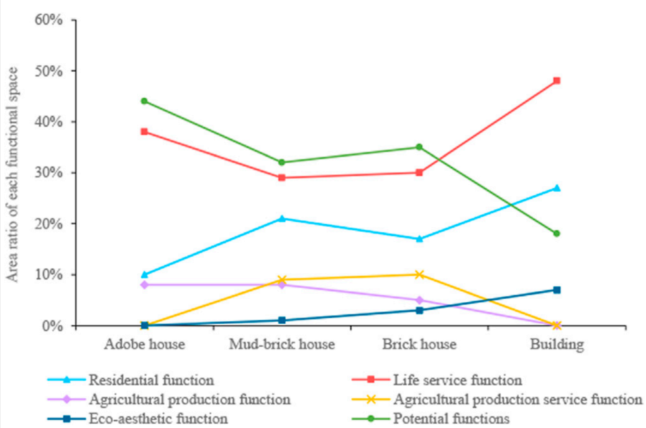

FIGURE 4 | Differences in the proportions of the functional spaces of different types of rural homesteads.

In summary, the area of the rural homestead experienced a process of first increasing and then decreasing from single-layer to multilayer three-dimensional utilization. In terms of spatial structure, the bedroom, dining room and living room are independent, as well as the separation of living space and production space. In terms of spatial proportion, the proportions of the living, living service and ecological aesthetic functions all increased, while the proportions of the potential, agricultural production and agricultural production service functions all decreased (**Figure 4**). In terms of functional changes, the dominant space of the rural homestead has changed from the living service function space and potential function space to the living space, and the ecological aesthetic function has emerged. It can be seen that the rural homestead is more efficient in use, with a more reasonable internal structure, more perfect functions and a better quality of construction.

4.2 Demand Analysis

Farmers' demand for rural homestead structure and function is closely related to the social and economic development level, farmers' livelihoods, income levels and other factors, with obvious differences in different periods (**Table 3**). Adobe houses were built in the 1960s and 1970s. Due to backward social and economic development, low production capacity, lack of materials and limited funds, rural homesteads were limited to meet the most basic needs of farmers for living, life services and simple agricultural production. Therefore, the main demand space includes bedroom, living room, dining room, kitchen and colony house.

Mud-brick houses were built in the 1990s, following 10 years of reform and opening up, during which China's social and economic development improved greatly. The implementation of the household contract responsibility system in rural areas has liberated productive forces, stimulated the enthusiasm of farmers, greatly improved agricultural productivity, promoted the vigorous development of agricultural production and the rural economy, and generated a demand for the storage of food and agricultural production tools (Zhou et al., 2020). In addition, the livelihoods of farmers during this period were dependent mainly on agricultural production. In order to facilitate living, enrich food sources and reduce living expenses, farmers are now growing vegetables in their courtyards, and colony house breeding has also now expanded from chickens and ducks to pigs, cattle and sheep. Therefore, the rural homestead in this stage should meet the needs of farmers for residence, life services and agricultural production, and the main spaces needed include the bedroom, living room, dining room, kitchen, colony house, storage room and green planting space. It is worth mentioning that, in recent years, farmers have generally placed or planted green plants in the courtyard, which increasingly fulfills the need for ecological aesthetics.

In the 21st century, with the development of social and economic transformation, changes in urban and rural factors is accelerating, and the livelihoods of farmers are gradually becoming more diversified and nonagricultural. As a result, the demand for agricultural production from rural homesteads has gradually decreased, and more attention has been paid to the perfection and quality of construction of the residential and life service functions of rural homesteads. During this period, the main spaces required included bedrooms, living rooms, dining rooms, kitchens, storage rooms, toilets and bathrooms. Like mud-brick houses, this type of rural homestead has also included ecological aesthetic space in recent years.

The buyers of buildings are mainly young people and farmers with better economic circumstances, and their need for rural homesteads is basically the same as that for urban housing. Agricultural production space is no longer required as part of housing, and living space has taken the lead, as well as the quality of living space. Due to better economic circumstances, private

TABLE 3 | Differences in the internal space demands of rural homesteads in different periods.

Demand space	Adobe house	Mud-brick house	Brick house	Building
Living space	Bedroom, living room, dining room, kitchen, toilet and bathroom	Bedroom, living room, dining room, kitchen, toilet and bathroom	Bedroom, living room, dining room, kitchen, toilet and bathroom	Bedroom, living room, dining room, kitchen, toilet, bathroom and garage
Production space	Colony house, storage	Colony house, storage and planting space	Storage and planting space	—
Ecological space	—	—	Green planting space	Green planting space
Other space	Courtyard	Courtyard	Courtyard	Courtyard

cars have become an important means of transportation, and the garage has become a necessary space. Therefore, the main spaces needed include the bedroom, living room, dining room, kitchen, toilet, bathroom, garage and green planting space.

4.3 Analysis of the Supply–Demand Balance of Rural Homesteads

4.3.1 Long-Term Idle and Abandoned Rural Homesteads

Long-term idle and abandoned homesteads are in a state of oversupply. Qianpozi village has a large number of the latter, mainly adobe houses, but also some brick houses, distributed mainly in the central and northern parts of the village. As many as 71 rural homesteads are idle or abandoned, accounting for 18.93% of the homesteads, including 51 adobe houses and 20 brick houses, with a total area of 7,700 m^2. Adobe houses are occupied mostly by the elderly. Due to the demise of the latter and to improvements in the living conditions of new houses, most of the adobe houses are now idle or abandoned. Brick houses have not been built for a long time, and some of the remaining ones are of good quality. However, as homeowners settle in cities and towns as a result of educational or employment needs, these houses have been idle and are scattered throughout several villages.

4.3.2 Multifunctional Use of Rural Homesteads

Multifunctional utilization of rural homesteads reflects the fact that the supply of some functions is less than the demand for them. There are only four multifunctional homesteads in Qianpozi village, accounting for only 1% of the total number of houses, scattered along the main street, all of which are brick houses. Of these, three are mixed use of concession stands and homesteads, with homogeneity and competition. The total area is 728 m^2, and the total area engaged in business activities is approximately 260 m^2. One homestead has mixed use of an oil workshop and a homestead, with a total area of 182 m^2 and an oil workshop activity area of 80 m^2. Concession stands and oil workshops are newly built or rebuilt by farmers in the original homestead according to their production and development needs.

4.3.3 Other Rural Homesteads in Use

Adobe houses are small in scale, poor in quality and low in comfort level, and are generally occupied by the elderly. The relationship between supply and demand mainly shows that the supply of living space is less than the demand for it, functional space is not independent, and living space and production space are mixed. The degree of improvement in living space is 4/6. The living room is a complex of bedrooms, living room and dining room, bearing the corresponding functions of the three, but each functional space co-exists in a large space, lacking independence. The living space lacks a toilet and bathroom, and the corresponding functions are realized through the mixed use of a colony house and a courtyard. With increasing age, the health of farmers decreases and their ability to work also decreases, so that they only raise poultry in the colony house. As a result, production space is balanced between supply and demand.

The mud-brick houses are large but poorly laid out, and are mostly occupied by middle-aged people. The relationship between supply and demand mainly shows that the supply of living space is less than the demand. The degree of independence between functional spaces within the living space and between living space and production space has been improved. The degree of perfection of living space is 4/6. There is still a lack of toilets and bathrooms, the toilets are still mixed with the colony house, while the bathrooms are made possible by a subsequent extension. Although the demand for agricultural production space increases due to increases in productivity, the courtyard space is large, and farmers have opened up part of the space in the courtyard in order to grow vegetables. At present, there is no transition utilization, and the relationship between supply and demand of agricultural production space is balanced.

The scale of brick houses is moderate, their layout is more reasonable, and are mostly occupied by young people. The relationship between supply and demand mainly shows that the supply of production space is less than the demand, but the degree of independence of each functional space is significantly enhanced, and the separation of living space and production space is realized. Independent bathrooms and toilets have appeared in the living space, and the demand for living space has been met, realizing the balance between supply and demand. Due to the small scale of houses built in this period and the hardening of the ground inside the homesteads, the demand for vegetable planting could not be met, prompting farmers to transfer the function to the outside of the homestead. In addition, farmers generally grow green plants in the courtyard to beautify their environment.

Buildings are improved housing with the highest levels of quality and comfort, and lived in mostly by young people with better economic circumstances. The supply-demand relationship is manifested mainly as supply being greater than demand. The building type has shown the appearance of independent bedrooms, living room, dining room, the separation of space, the addition of a garage, the living space is perfect and independent, but their supply is greater than the demand for them, resulting in part of the space failing to be fully used. Agricultural production space disappears, but a special space is set up in the yard for planting and raising green plants, so that the supply and demand of ecological aesthetic space is balanced.

4.4 Withdrawal and Transformation of Rural Homesteads Based on Supply-Demand Annlysis

The supply of idle and abandoned rural homesteads is greater than the demand for them, with a total area of 7,100 m^2, and therefore their occupants should be given priority for exiting. For rural homesteads in use, the balance between supply and demand, spatial independence, building quality, scale and layout should all be comprehensively considered in order to formulate appropriate withdrawal and transformation strategies by classification.

The supply of adobe houses is less than the demand for them, the degree of spatial independence is poor, the construction quality is low, the scale is small, the layout is scattered, and thus priority should be given to exit strategies and, through centralized resettlement, improving the quality of living. The supply of some of the living space of mud-brick houses is less than the demand, and the related functions are realized through the mixed use of other spaces. The quality of supply and demand balance is low, and there is supply and demand dislocation. However, the scale of mud-brick houses is very large, and the balance of supply and demand can be realized and optimized through internal modification or transformation. When farmers have the intention to withdraw from rural homestead, they should give priority to withdraw to improve land use efficiency. The brick houses lack mainly space to grow vegetables. However, with the nonagricultural and diversified development of livelihoods, this demand will gradually weaken, and supply and demand will achieve balance. Moreover, the architectural quality and the degree of separation of functional space are both relatively high. Therefore, brick houses can be kept in their current state of use and can be withdrawn when farmers decide to withdraw. The supply of buildings is greater than the demand for them, part of the space is not reasonable to use, and should be combined with actual demand, reasonable configuration and transformation utilization. For example, use existing space to set a study. Although there is a certain level of waste incurred by this type of building, they have a short construction time, achieving high quality and complete functionality. Therefore, the current state of utilization should be maintained.

For the rural homestead in use, even if the supply of its internal space is greater than the demand, farmers cannot be forced to withdraw from the rural homestead as long as the demand of farmers still exists. Rural homestead withdrawal should not be too hasty. A natural exit, though slow, can be a safe measure if properly guided by the government.

5 DISCUSSION

5.1 Factors Affecting the Supply–Demand Balance of Rural Homesteads

The balance between the supply and demand of rural homesteads is a dynamic process, which is the result of many factors. Population size, farmers' incomes, livelihood, lifestyle and social and economic development level are the main factors affecting demand, while supply is affected by social and economic development level and the system used for homestead management.

Population size directly affects demand for rural homesteads: the greater the population, the greater the demand. Household income is also an important factor affecting demand. As farmers' incomes rise, so does their need for improved housing. The scale, structure and function of rural homesteads are closely related to farmers' livelihoods. Before 2005, the latter were derived mainly from agricultural production, so demand for grain storage was high, and storage space in rural homesteads was large. With the differentiation, diversification and nonagricultural nature of farmers' livelihoods, the demand for storage room gradually decreased, while ecological aesthetic space increased. Lifestyle also has a great impact on the demand for farmers' homesteads. At present, many young people from the countryside have accustomed themselves to an urban lifestyle and have bought apartments in cities instead of building rural homesteads. The level of social and economic development has a profound impact on rural homestead demand. When the level is low, demand becomes the most basic demand of living. With improvement in social and economic development, homestead demand shows diversified characteristics. In recent years, farmers have been increasingly pursuing a higher standard of living, paying more attention to quality of life, and thus rural homesteads have gradually regained their living function.

The level of social and economic development affects not only demand but also supply. If the level is backward, the development of productive forces becomes insufficient, and the supply is therefore insufficient. With improvement in social and economic development, productivity develops rapidly, and the supply is sufficient. At present, China implements a rural homestead management policy of "one family, one house, legal area," which defines the quantity and scale of homestead supply.

5.2 Implications of Rural Homestead Withdrawal

Rural nonagricultural industries in traditional agricultural areas are underdeveloped, and there is insufficient endogenous driving force for development. Under the push and pull of urban and rural areas (Zhang et al., 2019), the rural population has been greatly reduced. However, rural homesteads themselves are immovable assets. Changes in the state of rural homesteads have the characteristics of lag, consumption and passivity. Therefore, farmers' willingness to withdraw is weak, and the motivation for vacating rural homesteads is also weak. Idle and abandoned homesteads are a helpless and rational choice for farmers (Kong et al., 2018; Dong et al., 2021).

The key to realizing an orderly withdrawal from homesteads is to stimulate, guide and increase farmers' willingness to withdrawal from them (Chen et al., 2017; Zhang et al., 2018; Cao et al., 2019). A combination of rewards and punishments should be adopted to guide farmers to gradually withdraw in an orderly fashion from idle and abandoned homesteads. On the one hand, collecting fees for idle resources forces farmers to withdraw from idle and abandoned homesteads. On the other hand, by referring to the pilot experience of separating the three rights to homesteads, we guarantee farmers' homestead qualification rights, reward farmers who voluntarily withdrawal, and persuade remaining farmers to voluntarily withdrawal idle and abandoned homesteads.

The structure and function of rural homesteads are the result of a dynamic balance between supply and demand against the specific background of social and economic development, which is appropriate for farmers' lifestyles and livelihoods. Therefore, the withdrawal of rural homesteads should fully consider the needs of farmers and not be carried out too hastily. According to the relationship between supply and demand, rural reconstruction needs to be established, and then rural homesteads should be withdrawn in a classified, orderly and timely manner. Demand by farmers for rural homesteads in traditional agricultural areas is based mainly on basic living needs, living services and agricultural production, while demand for nonagricultural production is relatively low. The construction of rural homesteads needs to combine changes in farmers' lifestyles and livelihoods, employ forward-looking and diversified design, and meet the production and living needs of farmers now and in the future.

There are few multi-functional rural homesteads in traditional agricultural areas, and the service content and scope are limited, which means that rural vitality is low. Therefore, strengthening the cohesion of rural population, improving the attractiveness of rural areas and inspiring rural vitality are effective ways to solve the problem of idle and abandoned of rural homestead.

5.3 Limitations and Future Research

In this paper, a typical village in China's traditional agricultural area is selected to analyze the structure and function evolution of rural homestead and its supply-demand relationship. Although this is a common approach in rural geography (Wang et al., 2016; Yao and Xie, 2016; Zhang et al., 2017; Su et al., 2019). However, China's traditional agricultural area is vast, and a typical village is taken as the representative of the study, which inevitably leads to the problem of under-representation. Plenty of case studies are still needed in the future. In addition, it is an interesting study to compare a typical Chinese village with a typical foreign village, which may provide more valuable information.

6 CONCLUSION

Based on changes in the internal structure and function of rural homesteads, this study analyzed the evolution of rural homestead supply by taking typical villages in traditional agricultural areas as case studies. Using Maslow's theory of needs as a reference point, combined with the internal structures of different types of houses when they were initially built, the changes in rural homestead demand were clarified. Finally, according to the current situation of rural homestead utilization, the relationship between supply and demand was evaluated and countermeasures and suggestions for rural homestead withdrawal and transformation were proposed. The main conclusions are as follows:

(1) From the 1970s to the present, rural homesteads in traditional agricultural areas have experienced four periods of changes in construction: from adobe house to mud-brick house to brick house and, finally, to building. The scale of rural homesteads changed from small to large and then to intensive use. Their internal structure has changed to "simply-enriched-simply-optimized." The independence of each functional space within the overall living space has gradually been enhanced, and the separation of living space and production space has been realized. The living function has gradually been enhanced, the production function has gradually been weakened, and the ecological aesthetic function has emerged.
(2) Demand by farmers for rural homesteads is the result of the combined effects of the levels of social and economic development, lifestyles and livelihoods.
(3) There are a large number of idle and abandoned homesteads in the study area, accounting for 18.93% of the total number of homesteads, and showing obvious hollowing characteristics. The number of multifunctional rural homesteads is small, only four. The service scope is limited to the residents of the village, the service content is mostly limited to farmers' living and production activities, and homogeneity is obvious. This shows a lack of vitality in the countryside. There are obvious differences between the supply and demand of rural homesteads in use.
(4) In traditional agricultural areas, idle and abandoned homesteads should be given priority for withdrawal. For those rural homesteads still in use, withdrawal strategies should be formulated according to the supply–demand balance, construction quality, spatial independence, combined with farmers' wishes.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, GD; methodology, GD and HC; formal analysis, GD and HC; data curation, HC and YG; writing—original draft preparation, GD and HC; writing—review and editing, GD and RZ; visualization, GD and RZ; supervision, GD and RZ. All authors have read and agreed to the published version of the manuscript.

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Feature Recognition of Urban Industrial Land Renewal Based on POI and RS Data: The Case of Beijing

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Urban renewal has increasingly become a hot topic in international urban sustainable development management, and many countries have also carried out a lot of practice. However, there is still a lack of fast and effective methods for how quickly identifying the spatial characteristics of urban renewal to dynamically grasp the renewal effect. The purpose of this study is to identify the renewal characteristics of urban industrial land based on the POI (Points of Interest) data and RS data of the Internet map, and to provide an innovative method for better understanding the renewal effect of urban industrial land and its spatiotemporal evolution characteristics. The results show that: 1) Since the decentralization of non-capital functions in Beijing, industrial development has spread from a high degree of agglomeration to the whole area. The number of high-density areas has decreased from nine to five, and the number of medium-density areas has increased significantly.2) Land-use types in the six districts of Beijing have changed, warehousing and logistics land and industrial land have been reduced greatly, and the number and area of park green space have greatly increased.3) The level of matching between RS image interpretation and POI data is uneven. RS interpretation is accurate for large-scale feature recognition, and POI data are sensitive to small-scale industries. In conclusion, In the process of identifying the renewal feature of urban industrial land, POI and RS data can respectively obtain certain results. The integration of POI and RS can better identify the temporal and spatial changes of the industry.

Keywords: non-capital function decentralization, industrial decentralization, RS interpretation, POI, construction land extraction, urban renewal

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1 INTRODUCTION

Throughout the development process of domestic and foreign metropolises, most developed cities have experienced the "big city disease". The centrality of large cities occupies a dominant position, and radiation drives the flow of people, logistics, capital, and information in the region to form an obvious polarization effect. This condition presents the problems of a large population, overconcentration of industries, traffic congestion, and environmental pollution (Ewing et al., 2002). To alleviate the pressure on the city center and promote the coordinated development of the city, domestic and foreign scholars have investigated related issues such as decentralization of capital functions (June 2007; Kuang et al., 2018; Tian et al., 2019), polycentric development (Champion, 2001; Lan et al., 2019; Sporna and Krzysztofik, 2020), urban renewal (Hyra, 2012; Swensen, 2012; Krabben and Jacobs, 2013), industrial upgrading (Azadegan and Wagner, 2011; Pan and Song, 2017;

Tian et al., 2019), old city reconstruction (Tolle, 2010; Wu, 2016), and brownfield development (Thomas, 2002; Frantal et al., 2015; Green, 2018). The urban renewal strategies of the United States (Clark et al., 2009; Hyra, 2012), Spain (Muiz and Garcí, 2017), Germany (Lang, 2012; Ahlfeldt et al., 2017), France (Duvernoy et al., 2018), Brazil (Costa and Lee, 2019), Britain (Longo and Campbell, 2017), Japan (Martinez-Fernandez et al., 2012), and other countries also have important reference significance for other countries.

As a part of urban renewal theory, industrial land renewal has been discussed in many Western academic circles. In many countries, industrial land is mainly provided by the public sector, not only in countries with public ownership of lands such as China, but also in some countries with private ownership of land such as the Netherlands, France, and Germany. As governments want to ensure an adequate supply of industrial land for employment opportunities and taxation of industrial development, some countries are even considering open leasing of industrial land rather than selling it as a way to solve the problem of industrial land development (Erwin and Buitelaar, 2011; Needham et al., 2013). For example, Canary Wharf in London has been transformed from a decaying port industry site to a world-renowned central business district through a public-private partnership (Zhou and Zhou, 2013). As one of the largest manufacturing countries in the world, China also has a very high proportion of industrial land. With the trend of economic transformation and industrial upgrading, a large amount of industrial land in China needs to be updated. Taking typical urban fringe areas such as Panyu District in Guangzhou as an example (Wang et al., 2018), the practice of industrial land redevelopment created by the three renewal policies is shown. In addition, based on the relevant data of all industrial land urban redevelopment projects from 2010 to 2018, some scholars use a spatial perspective to investigate the transformation of industrial land in Shenzhen (Lai et al., 2020). Based on qualitative research, questionnaire surveys and in-depth interviews, taking Shenyang Tiexi Workers Village as a case study (Dong et al., 2020), the characteristics and driving forces of community renewal in old industrial shantytowns were analyzed.

China is in a period of rapid urbanization. Cities in China have exploded in size, population, and impact during the last three decades (Schneider et al., 2015). This rapid expansion has caused frequent problems such as traffic congestion, environmental pollution, and urban development imbalance (Huang et al., 2016). Some related studies have shown that there is a positive correlation between the urbanization efficiency and agglomeration level of megalopolis (Jin et al., 2018). As the capital of China, Beijing has greatly increased its urbanization level and low-end industries. The population is rapidly agglomerated, and the scale of the city continues to expand, which has led to the occurrence of a series of urban diseases. Under realistic conditions that the intensity of land development and utilization has approached the resource ceiling, the decentralization of Beijing's non-capital functions is the inevitable way to improve the quality of the capital's development at this stage. Beijing's non-capital function decentralization work started in 2014, in which industrial decentralization is the physical content and key support (Li et al., 2019). Beijing has gathered an excessive number of non-capital functions, such as housing manufacturing, regional logistics bases, and wholesale markets (Rao et al., 2015), which are the deep-seated causes of "big city disease". Gao, Liu, and Dunford discussed that Beijing's industries have gradually decentralized moving from the center, and the process of industrial decentralization involved not only relations between the government and firms but also between different levels of government (Gao et al., 2014). Escalona-Orcao analyzes the process of industrial relocation in Spain and introduces the impact of urban system structure and urban development policies on industrial decentralization (Escalona-Orcao and Climent-Lopez, 2012). Li identifies the decentralization industry category and potential decentralization undertaking place from the three dimensions of policy, economy, and resources and environment. He pointed out that a decentralization strategy is a promising approach for promoting regional sustainable development (Li et al., 2019). Although differences exist between domestic and foreign systems, the urban remediation experience of foreign developed countries can be a reference for China's non-capital function decentralization strategy. Beijing's decentralization path can also guide other areas facing big-city diseases.

The continuous emergence and development of Internet data and artificial intelligence methods have provided effective data and methods for the evacuation of urban industries and extraction of construction land, which has greatly helped identify the industrial reforms in Beijing. Satellite remote sensing and GIS technology have been increasingly used in examining land use and land cover change, especially change-related urban growth (Wu et al., 2006; Sarvestani et al., 2011). Using remote sensing technology to extract the scale of urban construction land is a more objective technical method to accurately grasp the current situation of urban construction, understand the direction of urban development, evaluate the implementation of urban planning, and guide urban development and construction. Many scholars have studied the expansion and extraction of urban built-up areas by employing remote sensing. Most of them use methods such as supervised classification, unsupervised classification, and cluster analysis. The imagery data used are mainly concentrated in traditional remote sensing, high-resolution remote sensing, and luminous remote sensing imagery data. (Masek et al., 2010), (Ma and Xu, 2010), (Zhang et al., 2018), (Al-Bilbisi, 2019), Shen and others used traditional remote-sensing data to qualitatively and quantitatively analyze the changing characteristics of urban expansion (Shen et al., 2020). (Sawaya et al., 2003), (Gray et al., 2018), (Li et al., 2016), (Huang et al., 2018), (Zeng et al., 2015), and others used high-resolution remote-sensing images to extract multiple types of urban construction land. Most studies rely on satellite imagery to analyze urban expansion on a large scale. The current automatic interpretation technology of remote sensing still encounters many problems in extracting the refined status of the construction land in the city. Due to their labor-intensive and costly nature in some cases, remote-sensing images cannot be easily applied to study urban expansion for all the cities in a timely manner (Liu et al., 2010). In addition, remote sensing analysis emphasizes the physical perspective of urban development without considering other dimensions (Long et al., 2018). Therefore, we need to find a method to make up for the limitations of these images on the basic of remote sensing analysis. With the rise of Internet big data, relevant scholars have conducted a series of studies and applications of urban development through POI, promoting the development and application of GIS, computers, and other fields. POI data have been widely used in studying of urban spatial structure, the spatial distribution of commercial facilities, the improvement of land use classification, division of urban functional areas, and the optimization of public services. Jiang demonstrated a complete process, including the collection, unification, classification, and verification of online points of interest (POI), and develop methods to utilize such POI data to estimate disaggregated land use (Jiang et al., 2015). Sparks, Thakur, and Pasarka used POI data combined with hierarchical clustering of temporal characteristics to establish geosocial temporal patterns for the business hours of retailers and restaurants in more than 100 cities in 90 countries around the world (Sparks et al., 2020). Xia et al. (2020) used POI data, night-time light data, and small catering business data to analyze the spatial relationship between urban land-use intensity and urban vitality. Xue et al. (2020) used the location information of manufacturing units and automobile sales outlets extracted from POI to perform spatial statistical analysis and analyze the spatial relationship between the two industries as spatial complementary integration, weak spatial correlation, and coordination with scale dependence and spatial heterogeneity.

The two kinds of data have been applied in the extraction of urban construction land and analysis of industrial changes. Related studies also combine remote sensing interpretation with POI data. Hu et al. (2016) developed a protocol that uses open street maps, POIs, and remote sensing images to identify large-scale urban land use functions, which showed an overall high accuracy of the land use maps generated. Liu et al. (2017) focused on urban land use classification with features extracted from high-resolution remote sensing images and social media data; they integrated probabilistic topic models and support vector machines to identify dominant urban land use types at the level of the traffic analysis zone. Song et al. (2019) integrated POI with social attributes and ultra-high-resolution remote sensing images with natural attributes to monitor the finer-scale population density in urban functional zones. Shi et al. (2020) combined nighttime light data, digital elevation model (DEM), normalized differential vegetation index (NDVI), and POI data to develop a comprehensive poverty index (CPI), thereby accurately and effectively identifying poverty-stricken areas to determine the spatial distribution of poverty. The traditional remote sensing interpretation to obtain LUCC changes can only capture some information on land use, especially land cover changes, but for urban industrial land, especially the functional update information of industrial land characterized by “vacating the air for birds”, it cannot be used effective extraction. Other researches based on poi put more emphasis on the spatial characteristics of various industries, which cannot be accurately matched to the actual space, and it is difficult to reflect the spatial scope and area of urban renewal. This research innovatively matches the two together effectively, and provides a new solution for more accurately revealing the functional transformation of LUCC and industrial land brought about by urban renewal. Studies on the spatial relationship and comparative analysis of the two types of data are also limited. Given the achievements and the direction of Beijing’s non-capital function decentralization, this study combines remote sensing information extraction technology with GIS spatial analysis technology by using POI data and high-resolution remote sensing images to conduct the fine extraction of urban construction land and description of industrial reform, to analyze the temporal and spatial changes of industrial decentralization and evacuation. The research idea is shown in **Figure 1**.

2 MATERIALS AND METHODS

2.1 Study Areas

Six districts of Beijing are selected as the study area, namely, Dongcheng, Xicheng, Haidian, Chaoyang, Fengtai, and Shijingshan. The concept of “City Six Districts” was formed after the fifth administrative division of Beijing in 2010. These districts have a total area of 1,381 sq. km., accounting for 8% of the total area of Beijing. As of 2019, their population was 12.828 million, and they accounted for 60% of the population, 70% of industries, 70% of grade 3A hospitals, and 70% of colleges and universities. The six districts of Beijing are shown in **Figure 2**. The six districts are not only the main bearing areas of the core functional areas of the capital, but are also important in the construction of an international first-class harmonious livable capital and are key areas for decentralizing non-capital functions. Evaluating this area is necessary to improve the service guarantee capacity of the six districts and decentralize their non-capital functions. This study selects the six districts as the analysis object and analyzes the changes in land types and industries through two phases of remote sensing images and POI data in 2013 and 2019.

2.2 Data

2.2.1 POI Data Correction

POI mainly refers to geographical entities that are closely related to people’s lives, such as educational institutions, financial service facilities, supermarkets, and others. In this study, the POI data are obtained by programming based on the electronic navigation data of Beijing produced by AutoNavi in July 2013 and September 2019. Combining the “Classification of Land Use Status in the Third National Land Survey” and “Urban Land Classification and Planning and Construction Land Standards” comprehensively integrate the types of non-capital functional decentralization in Beijing. In this study, nine types of POI data are extracted from industry, wholesale market, warehousing and logistics, education, medical and health, government agencies, park green space, cultural facilities, and transportation facilities as the research

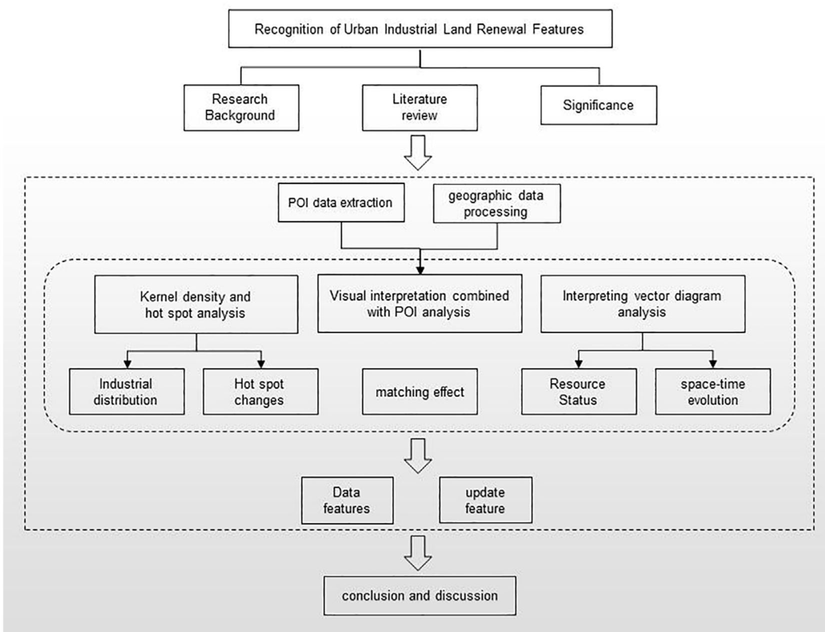

FIGURE 1 | Technology roadmap.

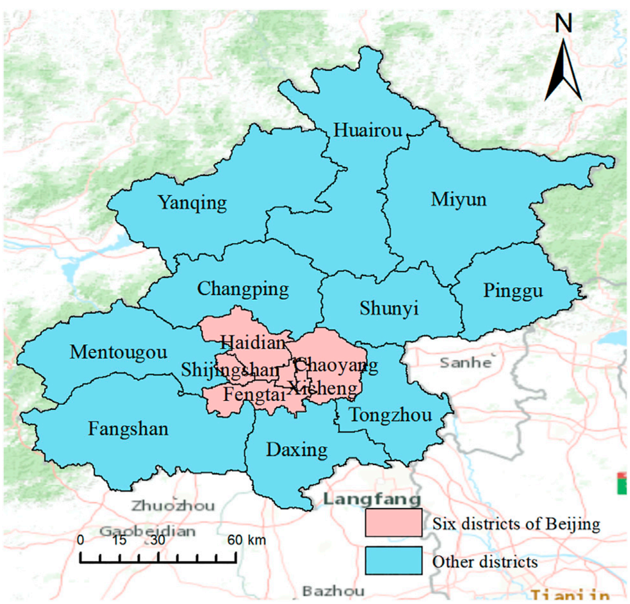

FIGURE 2 | Study areas.

object. The initial data in the six districts of Beijing in 2013 and 2019 were 426,044 and 588,523, respectively. The data were cleaned by spatial matching and deduplication. After selecting according to the nine categories we needed, we collected 74,180 and 76,594 data points. Details are shown in **Table 1**.

2.2.2 Basic Geoprocessing

Basic geographical data includes map data such as the boundaries of Beijing's administrative divisions, and satellite images of the six districts. The data used is based on Google Earth imagery without satellite orbit information, and the imagery data were mainly obtained from the QuickBird satellite of DigitalGlobe and EarthSat in the United States. The spatial resolution of global geomorphic images can reach up to 0.5 m. The Google Earth imagery has a spatial resolution of 1.88 m, which includes the six districts of Beijing. Analysis and correction of multiple sampling points in the image were conducted to meet the requirements for the identification of various types of land. This study is based on "Urban Land Classification and Planning and Construction Land use Standard" combined with the "Beijing New Industry Prohibition and Restriction Catalog (2018 Edition)". In response to research on Beijing's non-capital function decentralization, the land division standards of the six districts of Beijing are determined according to the actual demand. These are divided into eight categories: residential, administration and public services, commercial and business facilities, industrial, road, street and transportation, green space and square, logistics and warehouse, and other land types. Using the ArcMap10.2 software platform, we compare the image features of the remote sensing imagery with Google Maps and AutoNavi Maps to determine the interpretation signs as shown in **Table 2**. Compared with the interpretation marks, the basic features of the satellite imageries were visually interpreted, and the vector map data of the six districts of Beijing in 2013 and 2019 were obtained.

TABLE 1 | POI data collection in 2013 and 2019.

Category	Subclass	2013	2019
Industry	Factory, machinery and electronics, minerals, metallurgy, chemical industry	2511	1346
Wholesale market	Wholesale market, wholesale and retail, professional wholesale	31607	23842
Warehouse logistics	Warehousing, logistics, express delivery, distribution centers, transshipment centers	3174	3536
Education	Kindergartens, elementary schools, middle schools, colleges and universities, vocational education, training institutions	10764	15218
Medical and health	Emergency centers, clinics, general hospitals, specialist hospitals, health centers	4289	6445
Government agencies	Governments, public security agencies, Administrative agencies, foreign-related agencies, social organizations, party organizations	17085	17551
Park green space	Parks, street parks, squares, zoos, botanical gardens	832	2197
Cultural facilities	Library, museum, exhibition hall, science and technology museum, cultural center, youth palace, archives, memorial hall, art gallery	2884	3160
Transportation facilities	Bus station, subway station, railway station, airport, bus station, high-speed service area, port terminal, overpass	1034	3299
Total		74180	76594

TABLE 2 | Interpretation marks of different types of land under remote sensing imagery.

Category code	Category name	Interpretation mark
R	Residential	Land for low, high, medium, and high-rise residential areas, as well as land for dilapidated houses, shanty towns, and temporary housing. Most of them are concentrated and contiguous, with high building density and cluster distribution
A	Administration and public services	Land for education and scientific research, medical and health, administration, culture, and other purposes, with landmark objects such as playgrounds and first-aid places, which cover a large area and are mostly identified by map data
B	Commercial and business facilities	Low-rise buildings are densely packed with clothing, small commodity markets, restaurants, and others. High-rise buildings are comprehensive office land with a large area and are mostly close to traffic arteries
M	Industrial	Production workshops, warehouses, and ancillary facilities of industrial and mining enterprises occupy a large area, with darker colors and uniform tones forming obvious clusters and clear boundaries
S	Road, street, and transportation	The land for urban roads, passenger and freight stations, and transportation depots has obvious shapes and clear maps
G	Green space and square	Park green space, square land, and others, are mainly green with obvious colors and are mostly close to residential areas or main roads
W	Logistics and warehouse	Material reserve, transfer, distribution, and other lands are indicated by a light yellow color, sandwiched with blue. Distribution is concentrated or no obvious rules apply, boundaries are blurred and are mostly close to the transportation hub
	Other lands	Free land, bare land, and others, are scattered and covered with blue woven nets, thereby facilitating their distinction

2.3 Methodology

This study mainly uses spatial analysis method to analyze the distribution of POI data and interpretation of remote sensing images. Kernel density estimation (KDE) is performed to measure the spatial distribution density of nine industries in the six districts, and grid density method is used to analyze the hot spots. Based on the interpretation of the land class, the area of land class change is identified by using the ArcMap platform, SQL language, and Python code. The POI data are spatially connected with the interpreted vector graph and the data are counted.

KDE is used to calculate the density of elements in their surrounding fields. The density is largest at the center position and attenuates with distance, and the density is zero at the limit distance. KDE is used to express the distribution data of various network points in a continuous graph, and study the overall spatial distribution characteristics of various network points in service facilities. The expression is as follows:

$$f(x) = \frac{1}{\mathbf{n}\pi\mathbf{r}^2}\sum_{j=1}^{\mathbf{n}}\mathbf{k}_j\left(1-\frac{\mathbf{d}_{ij}^2}{\mathbf{r}^2}\right)^2$$

where k_j is the weight of the research object j, d_{ij} is the distance between the spatial point i and research object, and r is the bandwidth of the selected area.

3 RESULTS

3.1 Kernel Density and Hotspot Analysis of POI

Judging from the 2013 and 2019 data, the nine types of facilities used in the study have obviously increased or decreased, but their total number is not much different. We import the collected POI data into the GIS, use the WGS1984UTM projection, and merge the various POI data. The selected nine types of data are almost all over the districts of Beijing, in Dongcheng, Xicheng, southeast of Haidian, southwest of Chaoyang, northeast of Fengtai, and the east of Shijingshan show obvious agglomeration patterns. To effectively identify the spatial distribution structure of the six urban districts, KDE shows the distribution of POI data intuitively. The natural breakpoint method is used to reclassify the results of KDE. We selected four search radii of 500, 1,000,

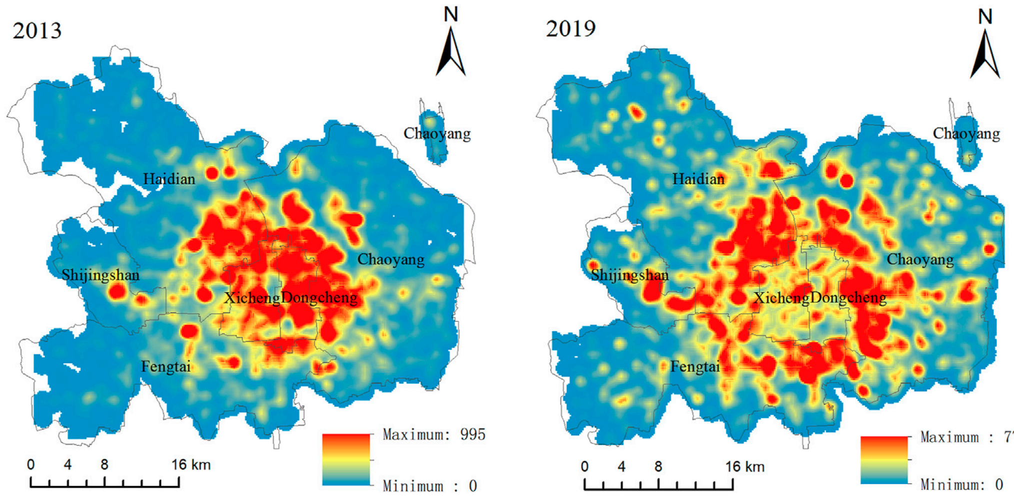

FIGURE 3 | POI kernel density plots of 2013 and 2019.

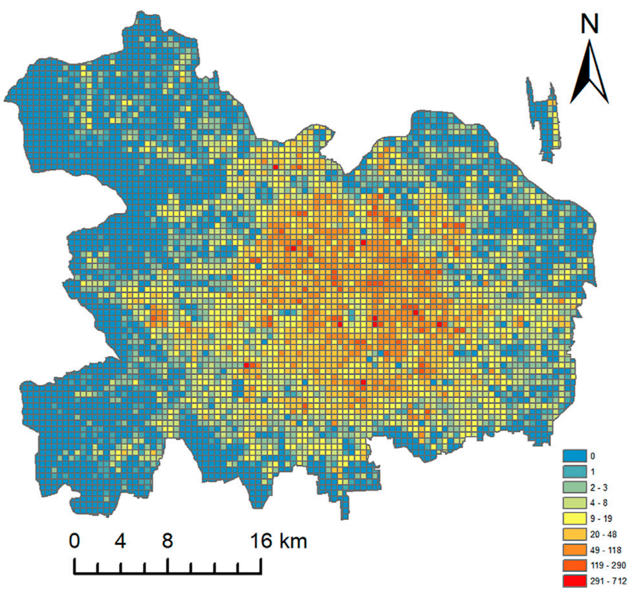

FIGURE 4 | POI content in fishing nets in 2013.

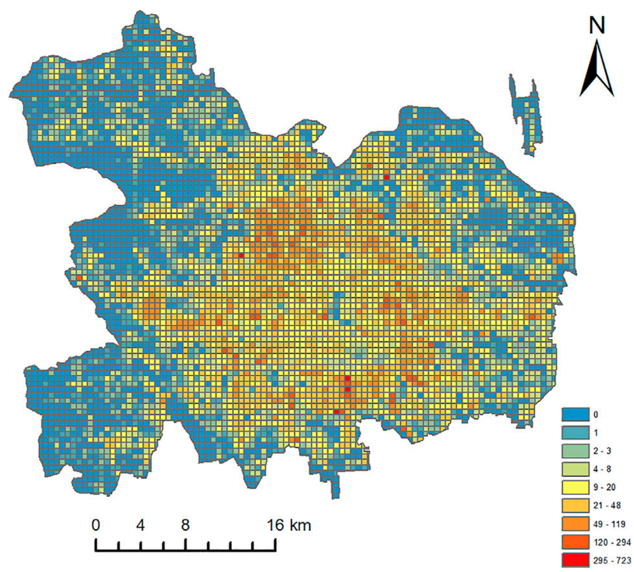

FIGURE 5 | POI content in fishing nets in 2019.

1,500, and 2,000 m for display. After comparison, we found that the search radius of 1000 m can better identify spatial morphological changes. The results are presented in **Figure 3**.

As shown in **Figure 3**, the six districts of Beijing are in a state of agglomeration. Comparing the changes in kernel density in 2013 and 2019, we can observe that in 2013, the industries of the six districts were concentrated in Dongcheng and Xicheng, supplemented by the western part of Chaoyang and the southeast of Haidian, forming a central clustering state. In 2019, the agglomeration of industries in the six districts expanded to the surrounding area, and high-density agglomeration points showed a discrete state. Multiple small agglomeration points are formed throughout the six districts, and medium-density agglomeration points have increased significantly. Overall, after a series of decentralization and retreat policies, industries in the central urban area have been evacuated significantly. The kernel density across the six districts is more balanced and the industrial distribution is more extensive.

To show the distribution of POI data clearly and quantitatively, we evenly divided the entire area of the six districts into 500 m × 500 m fishing nets, and a total of 5,807 fishing nets were obtained. The overlap area is obtained by intersecting overlay analysis of POI data and fishing nets. The

TABLE 3 | Statistics of number of fishing nets and POI points in each density area.

Density zone type	Number distribution	2013				2019			
		Number of grids	Percentage (%)	POI number	Number ratio (%)	Number of grids	Percentage (%)	POI number	Number ratio (%)
high-density area	295–723	9	0.15	3979	5.36	5	0.09	2571	3.36
Medium-high density area	120–294	56	0.96	9939	13.40	39	0.67	6157	8.04
medium-density area	21–119	966	16.63	43927	59.22	1149	19.78	48844	63.77
Low-medium density area	4–20	1457	25.09	14127	19.04	1655	28.50	16822	21.96
Low-density area	0–3	3319	57.16	2208	2.98	2959	50.96	2200	2.87
Beijing		5807	100.00	74180	100.00	5807	100.00	76594	100.00

geometric interval method is used to reclassify by quantity, and a dBase (dbf) table is exported for statistical analysis. The results can be obtained as shown in **Figure 4** and **Figure 5**.

The highest number of fishing nets contains 723 points, and the least contains no points. According to the statistical analysis of the frequency of point distribution in GIS, the average value in 2013 is 12.59, the standard deviation is 30.37, the average value in 2019 is 13.18, and the standard deviation is 27.10. These results show that the distribution of point data in 2019 was closer to the average value and less affected by the extreme value. We define different density areas according to the number of points contained in each fishing net, where 0–3 points are defined as low-density areas, 4–20 points are defined as medium-low density areas, and 21–119 points are defined as medium-density areas, 120–294 points are defined as medium-high density areas, and 295–723 points are defined as high-density areas. According to this standard, the number of fishing nets and number of POI points occupied in each density area in 2013 and 2019 were counted. The results shown in **Table 3** were obtained.

According to **Table 3**, the number of fishing nets in high-density, medium-high-density, and low-density areas in 2013 was higher than that in 2019, while the number of fishing nets in medium-density and medium-low-density areas increased significantly in 2019. These results show that after decentralization, the extremely high-density or extremely low-density areas have decreased. The industry in the high-density area has been greatly improved through decentralization. Low-density areas have obtained development opportunities through industrial transfer. The number of medium-density districts most suitable for urban development has greatly increased. Urban development has spread from dot and cluster agglomerations to the periphery, and the phenomenon of industrial agglomeration has been improved.

Through location selection, we compared the corresponding geographical locations of fishing nets in high-density areas in 2013 and 2019. The nine high-density districts in 2013 correspond to Guanyuan Wholesale Market, Yuegezhuang Wholesale Market, Peking University, Renmin University of China, Peking University People's Hospital, Xinglong Lighting Wholesale Market, Beijing Book Wholesale trading Market, Tsinghua University, and Beijing Foreign Studies University. The five high-density fishing nets in 2019 correspond to the geographical locations of Peking University, Renmin University of China, Beihang University, Haidian District

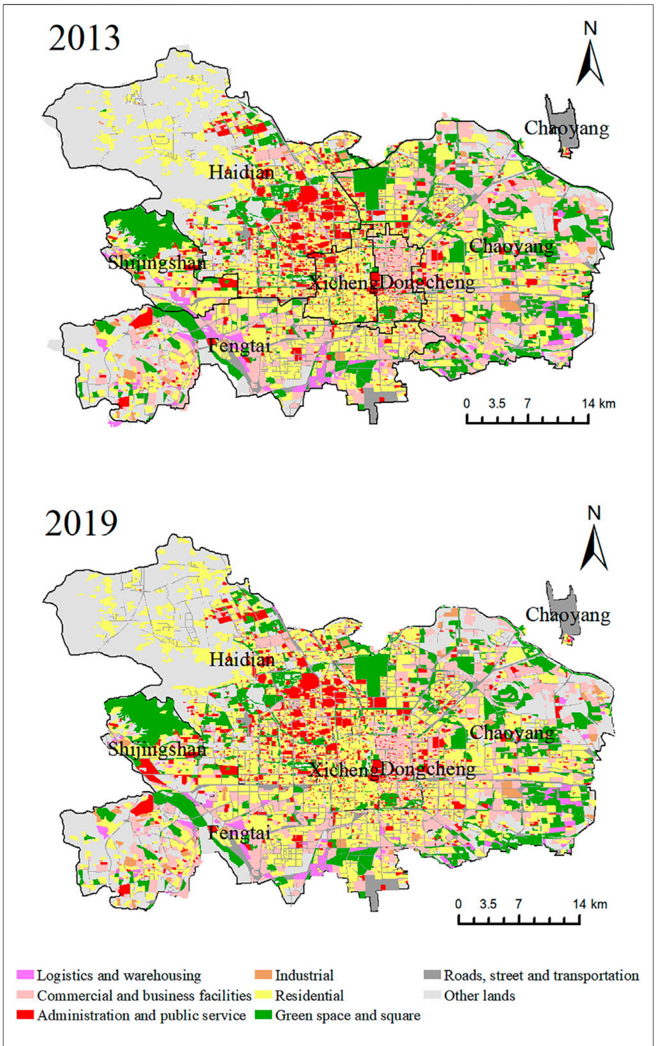

FIGURE 6 | Interpretation vector diagram of eight types of land in six districts of Beijing in 2013 and 2019.

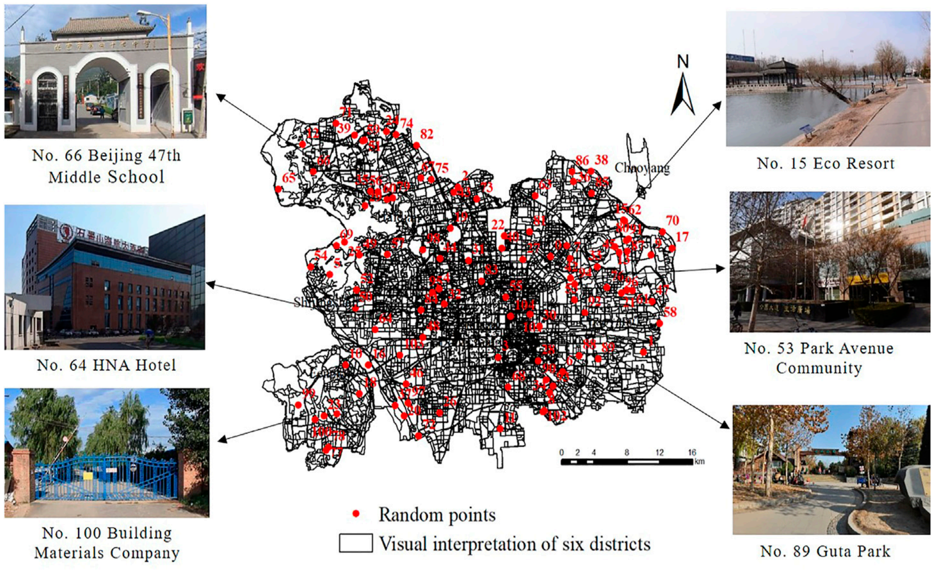

FIGURE 7 | Accuracy detection of interpretation results and presentation of some cases.

People's Hospital, and Peking Union Medical College Hospital. The four areas of Guanyuan Wholesale Market, Yuegezhuang Wholesale Market, Xinglong Lighting Wholesale Market, and Beijing Book Wholesale Trading Market no longer exhibit high-density agglomeration. This condition corresponds to the retreat of some tertiary industries such as regional logistics bases and regional professional markets in the decentralization strategy, which has significantly improved the phenomenon of industrial agglomeration in these regions.

3.2 Interpretation Vector Analysis

According to the interpretation marks and methods introduced, this study visually interprets the 2013 and 2019 images of six districts in Beijing. The results are shown in **Figure 6**.

According to the vectorization results of the two phases of remote sensing images, small-scale land-use changes can be observed in the six districts. The reason is that the six districts have undergone mature development, and large-scale changes in land types cannot occur within a few years. However, according to Beijing's strategic model of decentralizing and promoting development, there will be accompanied by renewal models such as industrial evacuation, demolition and new construction, and renovation and improvement. This condition will bring about small-scale or group-type land changes. We can observe from the data of the two periods that 10,673 visually interpreted plaques existed in 2013 and 10,518 in 2019. From the two issues of data, 10,673 plaques were visually interpreted in 2013 and 10,518 in 2019.

To test the accuracy of patch division results, a random point selection method is used to select points in GIS. Thus, 106 and 105 plaques were randomly selected from 2013 to 2019, respectively, and each plaque was assigned a number. The detailed spatial distribution is shown in **Figure 7** (which takes 2019 as an example). Due to the impact of the COVID-19 epidemic, on-site calibration is dangerous and difficult, and the real scene function on the Baidu map can achieve a good 3D display. Therefore, this study uses the Baidu map to conduct inverse point query and real-time comparison and combines the field data in the process of previous research to test the accuracy of the results. The results show that 89 parcels are of the same type in 2013, and the accuracy of the division result is 84.0%. In 2019, 94 parcels had the same type, and the accuracy of the division result was 89.5%. The accuracy test result was good. **Figure 4** shows some cases of the inspection area. No. 66 is Beijing 47 Middle School, and the patch type is administration and public services. No. 100 is a building materials company in Fengtai district, and the patch type is industrial land. No. 89 is Guta Park, and the patch type is green space and square.

To appropriately show the relationship between industrial and land type changes in the six districts, we gather statistics on the area and the quantity of all types of land patches. As most of the commercial service facilities are within the buildings, the land types can be easily confused with other types of land use, so we put commercial and business facilities aside for area and quantity statistics in this study. Finally, we selected seven types of land for residential, administration and public services, industrial, road, street and transportation, green space and square, logistics and warehouse, and other lands for statistical analysis. The results are presented in **Table 4**.

As shown from the statistical results, the patches of warehousing and logistics land have decreased by 16, and the area has been reduced by 28,400 sq. km. The quantity and area of patches on both industrial and public land have decreased. The area of green space and square and transportation facilities has been increased. The quantity and area of patches of residential land and other lands changed minimally. This result shows that since Beijing's decentralization strategy, the general manufacturing industry, especially the high-consumption industries

TABLE 4 | Statistics of patch quantity and area of seven types of land.

Land class name	Quantity of plaques			Statistical area (10,000 sq. km.)		
	2013	2019	Variation	2013	2019	Variation
Logistics and warehouse	151	135	−16	24.65	21.81	−2.84
Industrial	97	95	−2	20.2	18.55	−1.65
Administration and public services	1884	1769	−115	188.74	180.90	−7.84
Green space and square	956	1024	68	120.68	164.59	43.91
road, street and transportation	1474	1466	−8	68.69	76.42	7.73
Residential	2581	2528	−53	386.00	376.45	−9.55
Other lands	387	328	−59	39.55	36.23	−3.32

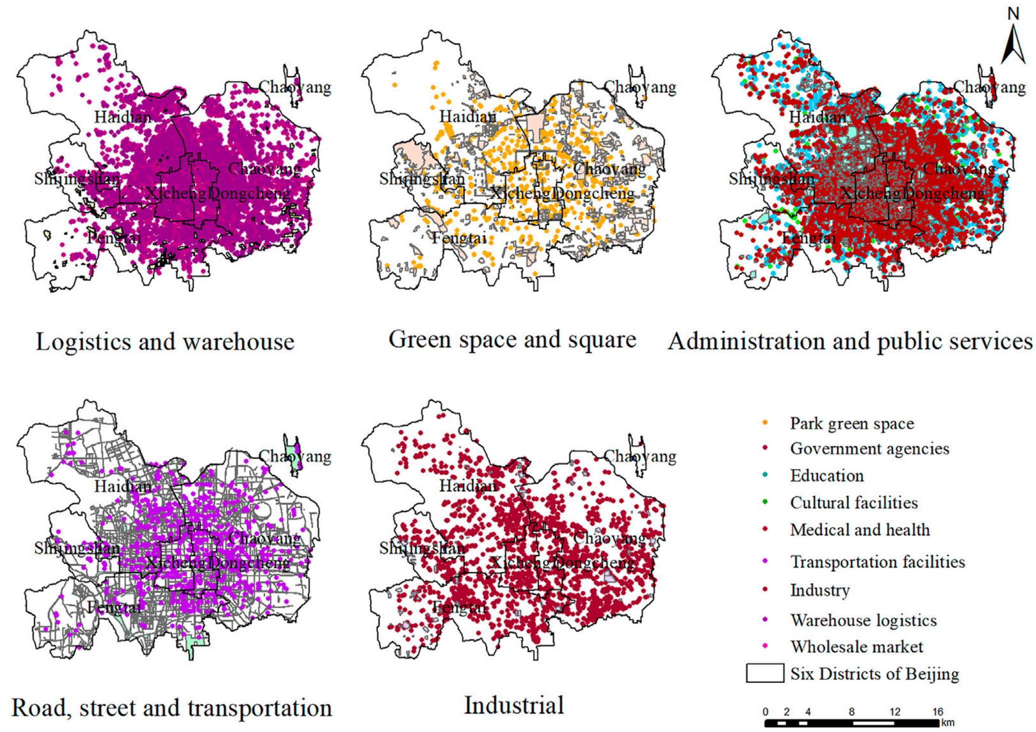

FIGURE 8 | Combination of various types of POI and land type interpretation maps in 2013.

(such as industrial land in this study), regional logistics bases, regional professional markets and other tertiary industries (such as logistics storage land in this study), and some social and public service institutions such as education, medical and training institutions (such as public land in this study) have been improved. Their distribution has become scattered and their area has been reduced. The number and area of patches of park green space have increased significantly, and they are more widely distributed and larger in area. However, the change of residential and other land types is not obvious in a mature city such as Beijing.

3.3 Analysis of Combination of Visual Interpretation and POI

From the preceding analysis, we can observe that both the POI data and visual interpretation results can show the progress of decentralization work in the six districts of Beijing and the changes in the region. To better analyze the point-to-surface multi-dimensionality and ensure the authenticity and availability of the two types of data, this study overlays the POI data on the vector map to determine the relationship between various POI data and land types. Among them, the POI type is “wholesale market,” and “warehousing logistics” is equivalent to the “logistics and warehouse” land type. “Education,” “medical institutions,” “cultural facilities,” and “agency groups” are equivalent to “administration and public services” in land type. Thus, five types remain. In this paper, various POI data and interpretation vector diagrams are spatially connected, with point data as the target element, interpretation vector diagram as the connection element, and “intersect” as the matching option. The results are shown in **Figure 8**; **Figure 9**.

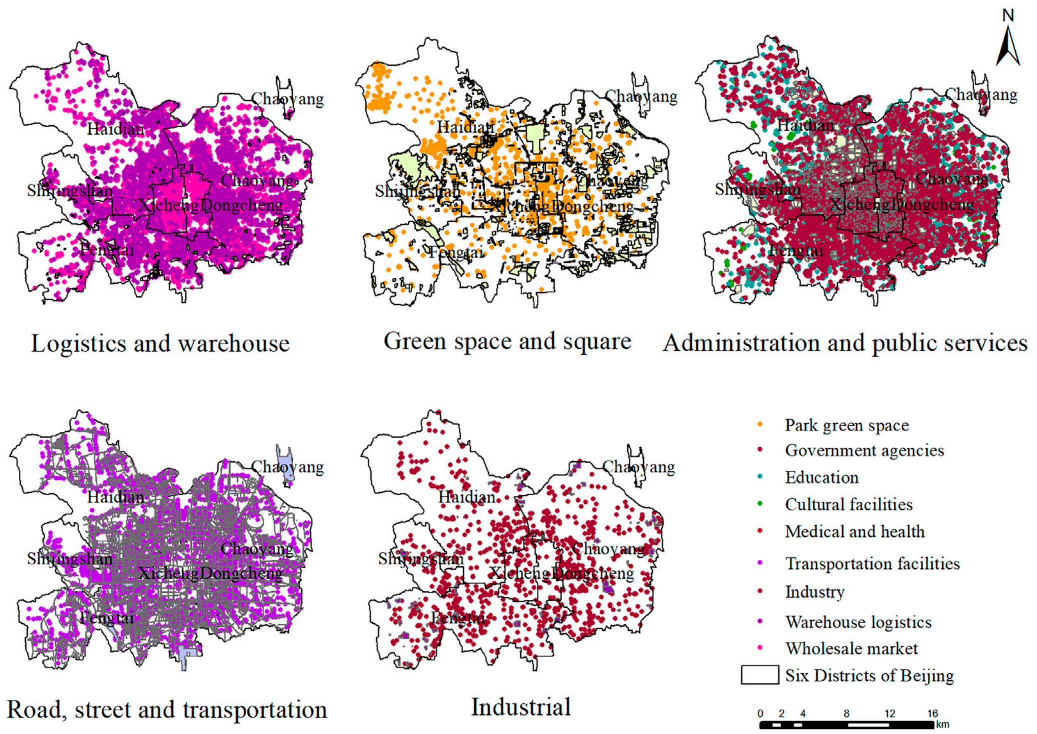

FIGURE 9 | Combination of various types of POI and land type interpretation maps in 2019.

TABLE 5 | Comparison between POI data and interpreted land types.

Type	2013			2019		
	Same quantity	Different quantity	Proportion of same quantity (%)	Same quantity	Different quantity	Proportion of same quantity (%)
Logistics storage land	10642	24139	30.60	9964	17414	36.39
Park green space	569	263	68.39	1606	591	73.10
Public land	12438	22584	35.51	14263	28111	33.66
Transportation facility land	822	212	79.50	2486	813	75.36
Industrial land	1246	1265	49.62	582	764	43.24
Total	25717	48463	34.67	28901	47693	37.73

We open the attribute table after the spatial connection, and use SQL language to judge the POI and land types. According to the corresponding method, the similar parts of the POI type and land type are called "same" fields, and the different parts are called "different" fields. After selecting all kinds of POI data according to attributes, we count the number of "same" and "different" fields. The results are shown in **Table 5**.

As shown in **Table 5**, the matching effect between POI type and land type of warehousing and logistics land is poor at approximately 30%. The two types of data on park green space are well-matched, with the same amount accounting for approximately 70%. The matching effect of the two types of data between public management and public service facilities land is poor at approximately 35%. The matching effect of the two types of data for transportation facilities is high at approximately 80%, and the matching degree of industrial land is in an intermediate state. The reason is that the POI data in warehousing and logistics include not only large wholesale warehouses but also many small express points and post offices, most of which are located in residential and public land types, which are not easy to extract in the land interpretation process. By the same token, a large number of points are found in public management and public service facilities, including not only large hospitals, schools, and libraries but also many training institutions, clinics, and organizations. These structures occupy a small area and are easy to confuse with the image. The park green space is clear in the remote sensing image, which facilitates the land type interpretation and has a high accuracy rate. However, when POI is used to identify park green space, a certain area of this space often has only one or a few POIs to indicate that the area and scale cannot be effectively displayed. The accuracy of transportation facilities' land in visual interpretation is also relatively high, but when expressed by POI, it often only shows the bus stop, subway station, and other parts, ignoring the content of the road section.

Another important factor that can explain the poor matching effect is that, since the decentralization policy, the decentralized area has been transformed from the original traditional manufacturing enterprise into a high-end industrial park. The nature of the original land has not changed but brought about an industry upgrade, which leads to no change in the land type but a change in the industry. For example, the BBMG Intelligent Manufacturing Factory is located in the Haidian district, and its predecessor was BBMG Tiantan Furniture Factory. After decentralization, the existing industrial plants were revitalized and upgraded, but their land properties and factory property rights did not change. However, the location has been built into an innovative science and technology industrial park with intelligent manufacturing as the core industry, thereby achieving an organic combination of transforming and upgrading the traditional manufacturing industry and replacing the industrial space.

4 DISCUSSIONS AND CONCLUSIONS

4.1 Discussions

This study uses POI data to analyze the distribution and changes of industries in Beijing. The current resource status and spatial and temporal evolution characteristics can be seen by using remote sensing image interpretation, and the combination of visual interpretation and POI can show the matching effect and the difference between the two data, so that we can deepen our understanding and application of the two data. In addition, this study also shows that the current status of the evacuation of Beijing has obvious changes in terms of industries and land types. These changes show the effectiveness of the evacuation, but at a deeper level, we also realize that the promotion work after the evacuation is not yet in place, and how to strengthen the reuse and optimization of the vacated space is the focus of future research.

Most studies in the past took remote sensing images mostly to study large scale land use changes or qualitative descriptions. In this paper, we use easily accessible remote sensing images and visual interpretation methods to quantitatively describe land use types on a qualitative basis, which has a more intuitive display of the quantity and area changes of various types of land, and is more convenient for land use and management. In addition, the random point selection function is used in GIS to determine the coordinates of the changing area, and the actual geographic attributes of the parcel are corresponded to by the method of coordinate inverse selection, and the changing area can correspond to the actual point location after the location selection is made, and the geographic location can be accurately identified. In the process of checking the accuracy of remote sensing image interpretation, due to the impact of the COVID-19 epidemic, it is not easy for us to conduct field research, and the real-world function of Baidu Map can achieve a good three-dimensional display, which brings us great convenience. As the current level of modern technology continues to develop, more and more data and resources can be accessed and used. In the face of the high cost of data unavailability, inconvenient field research due to unforeseen circumstances, and other uncontrollable reasons, the adoption of these open resources can bring greater benefits to our research. In future scientific research and social development, good use of Internet technology will increasingly become a skill. The method applied in this study can not only identify the spatial and temporal changes of urban industrial land, but also provide a great help for the fine-grained extraction of urban construction land. In addition, it also provides ideas for the rational layout of various public service facilities in cities.

In addition, visual interpretation is mainly used for vectorization in this study, which is subject to a certain degree of subjectivity and may cause data distortion. This study takes the evacuation of Beijing as the background, and only considers the land types and industries related to this, but does not explore and study other industries, these shortcomings will be further improved in future studies.

4.2 Conclusions

Urban renewal has increasingly become a hot topic in international urban sustainable development management, and many countries have also carried out a lot of practice. China has implemented a large number of urban renewal projects, but there is still a lack of fast and effective methods for how quickly identifying the spatial characteristics of urban renewal to dynamically grasp the renewal effect. This study effectively combines remote sensing imagery, GIS technology, and Internet POI data to closely delineate the land and industrial uses in the six districts of Beijing. This condition realizes the refined extraction of various urban land types and clarifies the temporal and spatial changes of industrial development. Based on the remote sensing image data and POI data in 2013 and 2019, the research carried out refined extraction of construction land in the six urban districts of Beijing and research on industrial temporal and spatial changes, and compared and analyzed the results generated by the two data. The results show:

(1) Since Beijing carried out the decentralization of non-capital functions, industrial development has spread from a highly concentrated state to the whole area, with the number of high-density areas decreasing from nine to five and the number of medium-density areas increased significantly. 2013 industries in Beijing's six urban districts were concentrated in the east and west urban areas, supplemented by the western part of Chaoyang District and the southeastern part of Haidian District, forming a central agglomeration state, while in 2019 the industrial agglomeration state in the six urban districts expanded in all directions, with high-density The number of fishing nets in high-density, medium-density and low-density areas in 2013 is larger than that in 2019, while the number of fishing nets in medium-density and medium-low density areas in 2019 has increased significantly, and the phenomenon of industrial clusterings such as regional logistics bases and regional professional markets has improved significantly, and the number of too-high or too-low density areas have been reduced. The industries in the high-density areas have been greatly improved by the decentralization,

which liberates part of the land in the central city and increases the opportunities for high and precise development in the central city. The low-density areas have been given development opportunities through industrial relocation, improving the utilization of land, which is also beneficial to the production and living standards of people in low-density areas. The number of medium-density areas is greatly increased, which can guarantee the production and living standards as well as protect the ecological health, which is conducive to the stable development of the region. Urban development from point and cluster clusters to the periphery of the spread of the industrial clustering phenomenon has been improved, which is important to alleviate the "big city disease" and promote the healthy and stable development of the city. In general, after a series of decentralization policies, the industry in the central city has been significantly decentralized, and the industry in the six districts is more balanced and widely distributed, which is also conducive to industrial upgrading and urban development;

(2) The type of land use in the six urban districts has changed significantly, with storage and logistics land and industrial land being significantly reduced and the number and area of park green areas greatly increased. The visual interpretation of remote sensing images of two phases in 2013 and 2019 has completed the fine extraction of various types of land use in the six urban districts of Beijing. From the extraction results, it can be clearly seen that the number and area of patches of storage and logistics land and industrial land have decreased, public land and park green space have been increased, and the number and area of patches of transportation facility land and residential land have changed less. This indicates that since the decommissioning of Beijing, general manufacturing industries, especially high-consumption industries (e.g., industrial land in this study), some tertiary industries such as regional logistics bases and regional professional markets (e.g., logistics and warehousing land in this study), and some social and public service institutions such as education, medical and training institutions (e.g., public land in this study) have been improved, and their distribution points have been reduced and dispersed, and their areas have also The distribution points and area have been reduced. In contrast, the change of land for transportation facilities and residential land is not obvious in cities with mature development. The number and area of parkland patches have increased significantly, which corresponds to the "increasing white and green" advocated since the evacuation;

(3) The combination of remote sensing interpretation and POI data can better identify the spatial and temporal changes of industrial land. Remote sensing interpretation is accurate in identifying large features, while POI data is sensitive to the perception of small industries. The combination of the two can show that the two kinds of data have better matching effects on park green areas and transportation facility sites, and poorer matching effects on small courier points, training institutions, clinics, etc., indicating that the two data have different research focuses. Remote sensing image visual interpretation has the disadvantage of strong subjectivity, and there are cases of small buildings being wrongly mentioned, omitted or incompletely extracted, but it has better recognition for park green areas, transportation facilities, large regional industries and large storage and wholesale bases. POI data has strong timeliness and redundant classification, often only a relatively small number of points are distributed in the same type of land in a certain area, which has a barrier for identifying area and the POI data are time-sensitive and categorically redundant, and often only a small number of points are distributed in the same type of land in a certain area, which is a barrier to the identification of area and scale. Combining remote sensing image interpretation with POI data can cover large, medium and small multi-level urban land type changes, which can provide quantitative descriptions of area and scale as well as analyze industrial changes and land type changes. At the same time, the two data can supervise each other as mutual correspondence, which ensures the authenticity and credibility of the results, and also enables qualitative and quantitative multidimensional analysis, which brings greater convenience to the research on urban development and evacuation and vacating. From the study, it can also be seen that some aggregated points with a poor matching degree are industries that are not completely evacuated and need further strengthening of evacuation, and some zones with a poor matching degree need spatial reuse and optimization for quality improvement according to the actual point situation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZH: The overall framework and ideas of this paper are proposed. LR: Process the data and complete the text. YC: Assist in data processing and paper revision and finalization. YH: He has made acertain contribution to the data processing of this article.

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A Spatial Patterns Identification Method of Rural Residential Land Change Integrating Dynamic and Multi-Scale Information

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Affected by rapid urbanization, the spatial layout of rural residential land (RRL) is facing urgent reconstruction and adjustment. The study of spatial change patterns of RRL can provide a basis for optimization and adjustment. The Pinggu of Beijing was chosen as the study area. Taking into account the layout characteristics of RRL from 2005 to 2015, a combination matrix method was developed to identify the spatial change patterns. The distribution characteristics of the change patterns under different environmental gradients were further analyzed. The study shows that the layout types of RRL in Pinggu in 2015 were dominated by the dispersion-regular-large scale cluster type and concentration-regular-large scale cluster type. The area of RRL patches in Pinggu increased by 686.89 hm^2 from 2005 to 2015, which was approximately 12%. The main spatial change patterns of the RRL are the cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern. The distribution of the pattern of RRL shows a decreasing trend under the topography and location gradients set in this paper. And the spatial patterns of RRL are changing at an accelerated rate due to the advanced production environment represented. Our study analyzes the changing pattern of RRL from multiple environmental gradients and provides a basis for the formulation of RRL layout optimization strategies.

Keywords: rural residential land, spatial pattern, environmental gradient, dynamic and multi-scale, pinggu

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1 INTRODUCTION

Rural residential land (RRL) is a central expression of rural human-land relations (Ottomano Palmisano et al., 2016), referring specifically to land that is primarily used for farmers' residences or associated with nonagricultural activities. As rural development has become a global issue in recent years, the spiraling downward trend of rural development elements (e.g., farmers' livelihoods, educational resources, and labor resources) has become a growing concern (Li et al., 2014; Turner et al., 2014; Liao et al., 2019; Tao et al., 2021). In developing countries represented by China, the movement of the population between urban and rural areas and the reorganization of regional socioeconomic development factor allocation have been accelerating (Elshof et al., 2017; Long et al., 2018; Tu et al., 2018). The layout of RRL is also undergoing drastic changes (Hoggart and Paniagua, 2001; Chen et al., 2017; Long et al., 2018). Villages and cities are an organic whole, and both must be sustainable to support each other (Bai et al., 2014). Liu and Li (2017) encourage the use of scientific methods such as big data monitoring and analysis to monitor rural communities and the environment and find solutions to local problems. Compared to the initial top-down strategy of insufficient public participation (Zhang et al., 2019), bottom-up initiatives can act as "social glue" (Elshof and Bailey, 2015; Li et al., 2016). Therefore, it is crucial to identify the changing patterns of RRL from the rural reality to understand the human-land interaction and its systemic effects.

RRL is an open system with an "element-structure-function" (Wu et al., 2016; Tu et al., 2018), and along with rural evolution, rural restructuring, or rural development transformation, and the layout of RRL is undergoing important changes (Wilczak, 2017). RRL in remote and backward areas is gradually declining, while RRL in areas with significant resource endowments is gradually growing, and playing the function of rural centers (Wang et al., 2016). There is a significant life cycle of RRL (Jiang et al., 2006), showing different forms of evolution, such as development, decline, vacancy, and disappearance, and concentration and dispersion are the two basic trends of RRL layout evolution (Xu et al., 2019).

In general, it is difficult to identify rural areas in remote sensing data and analyze their change patterns, especially since the classification of developed land in rural areas is not as accurate as in urban areas (Wickham et al., 2013). Existing studies mostly use image analysis and other auxiliary variables to determine RRL. Conrad et al. (2015) performed multiscale segmentation for the derivation of building contours, followed by random forest classification of spectral and spatial features of objects. Leyk et al. (2014) used auxiliary variables such as topography, road density, and road distance to identify rural development land. The development evolution of RRL layout is characterized by complexity and diversity due to the heterogeneity of regional natural and economic environments (Li et al., 2018; Qu et al., 2018). Therefore, it is necessary to analyze the layout of RRL as a premise to further identify RRL change patterns.

The evolution of RRL is a product of the evolving human-land relationship, which is a combination of spontaneous generative forces within the RRL system and external environmental context factors such as natural and socioeconomic factors (Zhang, 1998). Factors such as rural exodus, increasing rural unemployment, and the establishment of new development relationships between rural and urban areas are important factors in the evolution of RRL, showing both development and decline (Rey and Bachvarov, 1998; Paquette and Domon, 2001). The study of human-land interaction in rural areas and its systemic effects can create favorable conditions for achieving leapfrog development in rural areas (Newburn and Berck, 2011). Li et al. (2019) analyzes the evolution and transformation mechanisms of the spatial structure of RRLs from the perspective of long-term economic and social changes. Ge et al. (2019) construct a conceptual model of coupling farmland transformation and rural transformation development to propose corresponding land use policies based on the coupling relationship. Existing studies focus on the study of RRLs under a certain environmental factor or human-land relationship or mostly embody a combination of environmental factors (Ito et al., 2016; Hirons et al., 2018; Silva et al., 2019; Tebboth et al., 2019), lack a dynamic and comprehensive study of their change elements combined at multiple scales, and present an overall lack of comprehensive consideration of the natural and socioeconomic environment.

To fill this gap, we adopt a new method for identifying RRL change patterns and reveal the role of environmental background elements on the heterogeneous pattern of spatial change of RRL layout to clarify the mechanism of RRL spatial evolution. To study the change pattern of RRL is actually to obtain a black box composed of human-land interaction. The aim is not to identify specific mechanisms. Rather, it derives rules from it, such as managing the RRL and its environment to guide the development of the RRL. Specifically, the following aspects of work will be carried out: 1) analyze the RRL layout characteristics and RRL patch change processes in the village domain based on the RRL data of Pinggu, Beijing, China, in 2005 and 2015; 2) analyze the connotation and key characterization elements of the RRL layout and identify the RRL spatial change patterns; and 3) analyze the distribution pattern of RRL change patterns under the environmental gradients of topography, location, production conditions, public service, economy, and policy. The study provides a new method for the identification of RRL change patterns and integrates the natural and socioeconomic environments to enhance the understanding of human-land interaction and its systemic effects and provides support for RRL spatial optimization strategies, which can promote sustainable rural development.

2 METHODS

2.1 Study Area

Pinggu (40°02′–40°22′N, 116°55′21″–117°24′07″E) is a district 70 km east of Beijing, China (**Figure 1**). It is in the warm temperate monsoon climate zone, with the terrain sloping from northeast to southwest, forming three types of landforms: mountainous, semi mountainous and plain. The plain area is 34,500 hm^2, accounting for approximately 1/3 of the total area. The semi mountainous and mountainous areas account for approximately 2/3 of the total area. The total land use area is 95,000 hm^2, and the proportions of farmland, construction land, and other land areas are 80.15, 11.59, and 8.26%, respectively. Among them, the construction land is mainly RRL land, accounting for nearly 50%, and the scale of land use per capita is much larger than 150 m^2 (the high limit of construction land area per capita stipulated by the Chinese government). The phenomenon of low-utility land, such as "small houses and large yards" and "hollow villages", is more common. Therefore, the degree of intensive land use needs to be further improved. At the same time, due to the variability of the regional natural environment, resource endowment, and socioeconomic development, the regional RRL presents a variety of layout types (Zhang et al., 2015). The socioeconomic development of Pinggu is in a stage of rapid development, with a regional economic gross product of 19.7 billion yuan in 2015, maintaining a 7% rate of growth. The account of three industrial

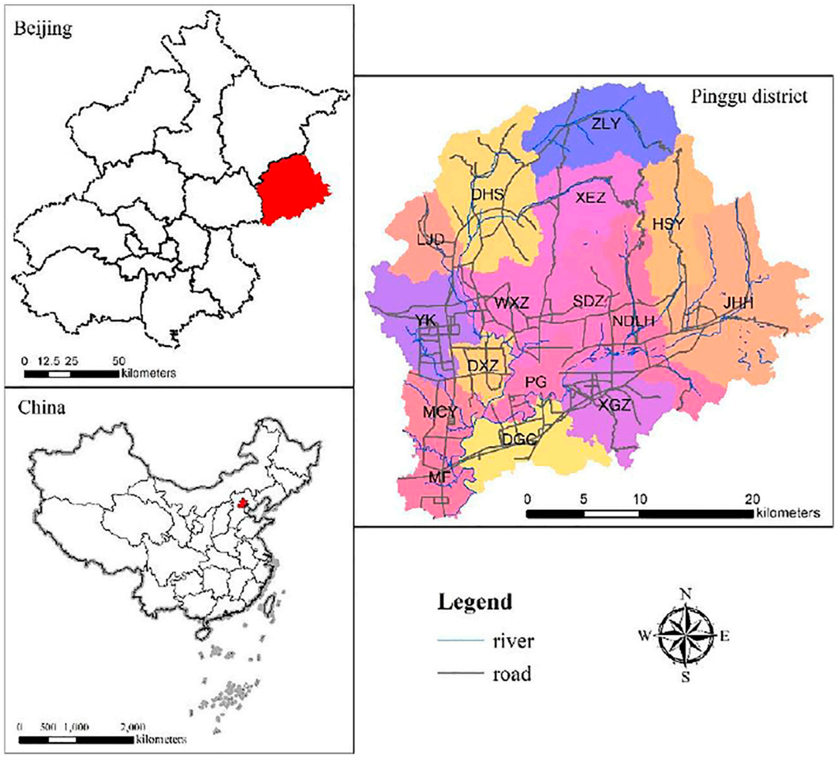

FIGURE 1 | Location of Pinggu, Beijing, China (PG is Pinggu Town, the central town of Pinggu District, which is not the research object of this paper).

TABLE 1 | Explanation of the research data type and source.

Data Type	Data Name	Data Format	Data Resource
Remote sensing image	Remote sensing image	grid	Google earth
Basic geographic data	DEM	grid	USGS
	Administrative zone	shapefile	Pinggu Branch of Beijing Municipal Commission of Planning and Natural Resources
	Land use data	shapefile	
	Agricultural land classification data	shapefile	
	Traffic map	shapefile	
Socioeconomic data	Socioeconomic Statistical Yearbook	electronic forms	Pinggu District Bureau of Statistics
	Rural economic statistics	electronic forms	
	Land Use Planning	text	Pinggu Branch of Beijing Municipal Commission of Planning and Natural Resources
	Rural planning	text	
Village research data	RRL spatial form	picture	on-site research

structures accounted is 9.5, 46.0, and 44.5%. The industrial structure was continuously optimized. The per capita disposable income level for urban and rural residents in that year was 35,000 yuan and 20,000 yuan, respectively, with the steady growth of urban and rural residents' income and continuous improvement of consumption ability and quality of life.

2.2 Data Resources

Land use change research requires a comparative analysis of the change process of specific land use types over a long time series, so the RRL study involves a comparative analysis of data information from different years. The study considers the availability of data, as well as the possible significant impact of regional socio-economic development stages and China's rural development policies on RRL changes. this study identifies 2005 and 2015 as the time node. In 2005, the Fifth Plenum of the 16th Central Committee of the Communist Party of China proposed comprehensive construction of a new socialist countryside. The data required for this study mainly include the following four types, including remote sensing image, basic geographic data, socioeconomic data, and village research data. Remote sensing

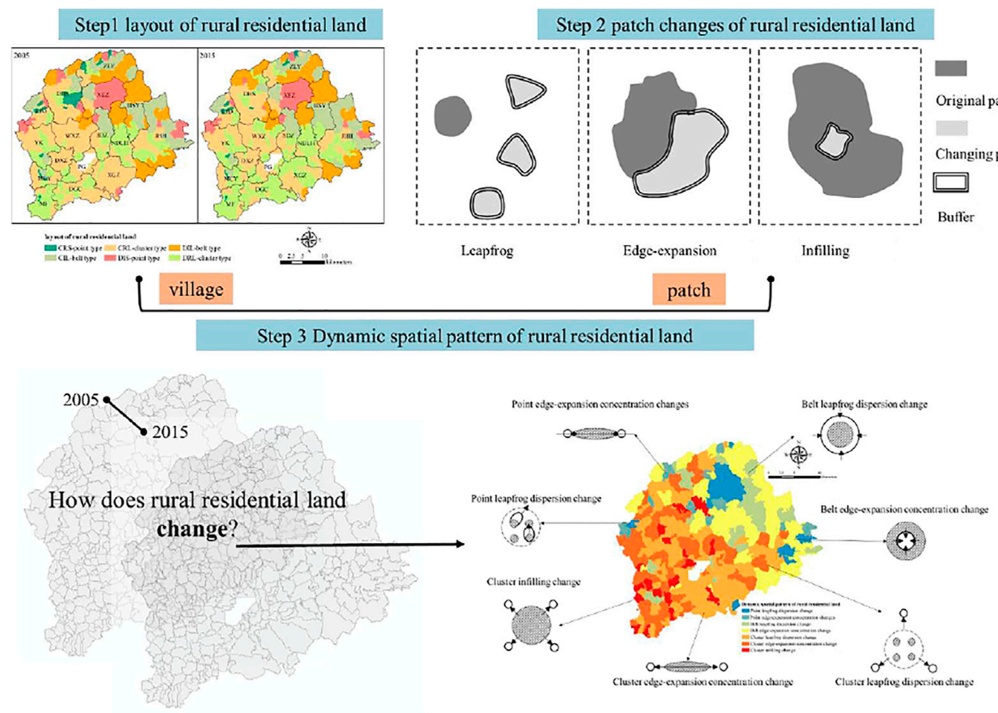

FIGURE 2 | Combination matrix method of the dynamic spatial pattern of rural residential land.

image and DEM belong to grid format data with spatial resolution of 30 × 30 m and 10 × 10 m respectively. Other specific data information is shown in **Table 1**.

2.3 Identification of the Dynamic Spatial Pattern of Rural Residential Land

RRL layout characteristics are an explicit spatial representation, which is the projection of inherent implicit RRL needs in space. RRL bureau spatial change patterns can be understood as a high abstraction and generalization of layout characteristic change information, reflecting the common features and regional differences of the layout change process. Most of the existing studies on RRL layout features and patterns focus only on the descriptive analysis of planar patterns (Yang et al., 2015), lacking in-depth analysis of the static distribution characteristics and dynamic change characteristics of RRLs. Therefore, our study identifies the change patterns of RRL based on the layout characteristics and patch changes of RRL (**Figure 2**).

This combination matrix method is divided into three steps: 1) identify the types of RRL layout; 2) determine the Spatial change process of RRL patches; 3) combine the results of the first two steps to determine the change pattern. It should be noted that the first step is based on the village, and the second step is based on the RRL patch. According to the barrel principle, the final result should be in units of RRL patches with smaller spatial resolution. In other words, the 2015 layout and 2005–2015 patch changes of a certain RRL can be obtained directly through the change mode name.

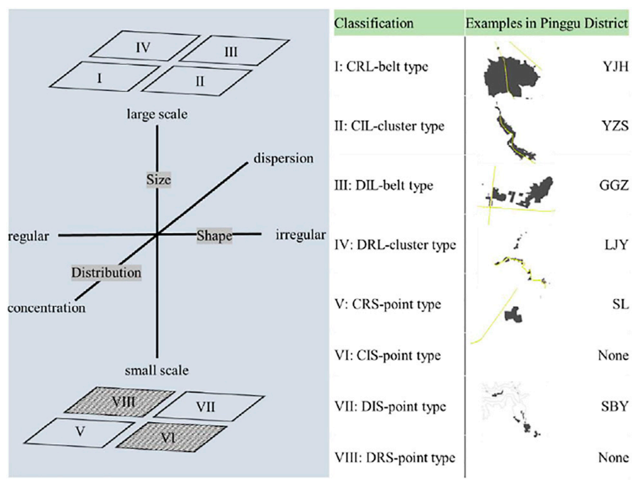

FIGURE 3 | Identification method and layout classification of rural residential land.

2.3.1 Types of RRL Layout

Our study uses villages in Pinggu as the study unit and uses the degree of aggregation and dispersion index, the size characteristic index, and the shape characteristic index to describe the layout characteristics of three dimensions, such as distribution, shape, and size **Eqs 1–3**, and classifies the RRL layout types according to the layout characteristics (**Figure 3**). Among them, the natural

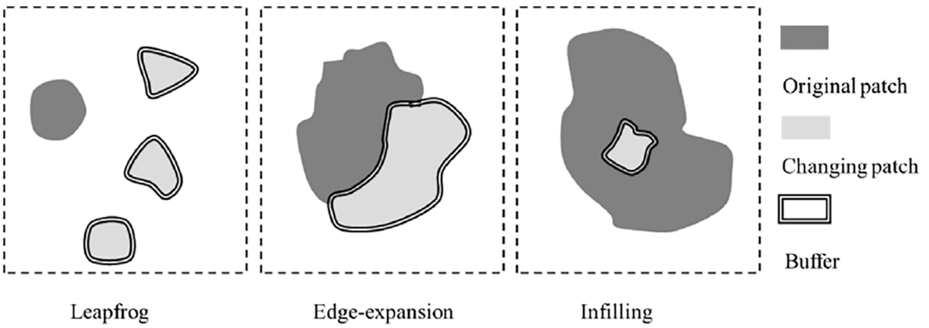

FIGURE 4 | Diagram of RRL patch change process (where "RCI" = 0 means the change patch is separated from the original site, which is leapfrog; "0 < RCI≤50" means the change patch is edge-adjacent to the original site patch, which is edge-expansion; "50 < RCI≤100" means the change patch is in the original site patch, which is infilling).

breakpoint method is used to determine two possible states of each feature, such as whether the distribution feature of each village belongs to the concentration or dispersion based on the size of the WAC.

$$WAC = \frac{1}{2}(WA + C), \quad (1)$$

where WAC is the degree of aggregation index; WA is the degree of aggregation; and C is the degree of proximity.

$$SPI = \sqrt[3]{CIRCLE\_AM \cdot LSI \cdot PAFRAC}, \quad (2)$$

where SPI is the shape characteristic index; $IRCLE\_AM$ is the area-weighted correlation external circle; LSI is the landscape shape index; and $PAFRAC$ is the perimeter-area fractional dimension.

$$SI = \sqrt[3]{A \cdot \rho \cdot AREA\_AM}, \quad (3)$$

where SI is the scale feature index; A is the area of RRL; ρ is the percentage of RRL; and $AREA\_AM$ is the area-weighted average patch area.

2.3.2 Spatial Change Process of RRL Patches

The way in which the urban landscape is expanding can be judged by using the landscape expansion index (Liu et al., 2009). This method is also adapted to the determination of the change process of RRL. The change methods include infilling, edge-expansion, and leapfrog, which are expressed as three topological relationships: inclusion, intersection, and disconnection relationships (**Figure 4**). Based on the formation principle of the landscape sprawl index, a buffer zone of a certain distance is generated with the changing RRL patches as the center. The buffer zone is spatially overlaid with the original patches to determine the spatial topological relationship between the changing patches and the original patches (**Eq. 4**). Considering that most of the RRL are roughly flattened and have high privacy settings, the study uses the psychological distance as the criterion to determine whether the RRL patches are separated from each other and sets the buffer zone radius at 50 m.

$$\mathrm{RCI} = \frac{Ao}{Ao + Av} \times 100, \quad (4)$$

where RCI is the index of the RRL plaque change mode; Ao is the area of the original site in the buffer zone of the change section; and Av is the blank area in the buffer zone of the change section.

2.4 Characterizing Multidimensional Environmental Gradient

RRL is the result of human-land interaction, and the environmental factors affecting its distribution are diverse, mainly from the natural environment, production environment, and socioeconomic, and cultural environment (Sevenant and Antrop, 2007; Wang and Zhang, 2021). The natural environment is the basis for the formation and development of RRL, and topography and rivers are the dominant factors among the natural environmental factors (Tian et al., 2012). The production environment is an artificial environmental system created through conscious social labor, and the production environment that affects the spatial layout of RRL is mainly the agricultural environment (Sevenant and Antrop, 2007), such as the cultivation radius and the richness of surrounding agricultural land (Qiao et al., 2013). Socioeconomic environmental factors give priority to the influence of transportation conditions. As an important transportation corridor in rural areas, the accessibility of roads is a bottleneck limiting the spatial development of rural areas, and the distribution of RRL shows obvious characteristics along roads (Zou and Wang, 2015). Distance from towns is another key factor influencing the land layout of RRL (Liu et al., 2019). In addition, deep-seated sociocultural factors such as neighborhood relations, farmers' ideology, and clan power are also involved (Lotfi and Koohsari, 2009; Beilin et al., 2014; Zachrisson et al., 2021).

Each influencing factor is not isolated from each other but interconnected to influence the land use pattern of RRL (Wang and Zhang, 2021). Considering various environmental factors, five environmental types were selected, such as topography, location, production conditions, public service, and economy and policy (**Table 2**). The spatial change patterns of the RRL layout under different environmental gradients were analyzed. Specifically, the spatial overlay analysis method was used to

TABLE 2 | Grading criteria for major environmental factors.

Type of Environment	Environmental Factors	Five-point Scale (1–5)
Topography	Altitude (meter)	<50; 50–100; 100–200; 200–500; >500
	Slope (degree)	<2; 2–8; 8–15; 15–25; >25
Location	Distance to nearest town (meter)	<2000; 2000–4,000; 4,000–6,000; 6,000–8,000; >8,000
	Distance to nearest road (meter)	<100; 100–500; 500–1,000; 1,000–2000; >2000
Production conditions	Farming radius (meter)	<400; 400–800; 800–1,200; 1,200–1,500; >1,500
	Distance to nearest facility agricultural land (meter)	<400; 400–800; 800–1,200; 1,200–1,500; >1,500
	Distance to nearest rural industrial land (meter)	<400; 400–800; 800–1,500; 1,500–2000; >2000
Public service	Distance to nearest public service facilities (meter)	<250; 250–500; 500–1,000; 1,000–1,500; >1,500
Economy and policy	Rural economic level (thousand Yuan)	<6; 6–8; 8–10; 10–12; >12
	Rural construction investment (ten thousand Yuan)	<20; 20–40; 40–60; 60–80; >80

TABLE 3 | The number and area of pattern types of rural residential land in Pinggu from 2005 to 2015.

Layout of RRL	Number of Villages		Area of Villages		Proportion	
	2005	2015	2005	2015	2005	2015
CRS-point	13	10	2064.49	733.46	2.20%	0.78%
CIL-belt	21	23	14908.97	15309.14	15.88%	16.31%
CRL-cluster	125	102	34534.8	27280.24	36.79%	29.06%
DIS-point	18	13	7623.4	6139.07	8.12%	6.54%
DIL-belt	23	25	15177.69	16071.44	16.17%	17.12%
DRL-cluster	75	102	19561.57	28337.57	20.84%	30.19%

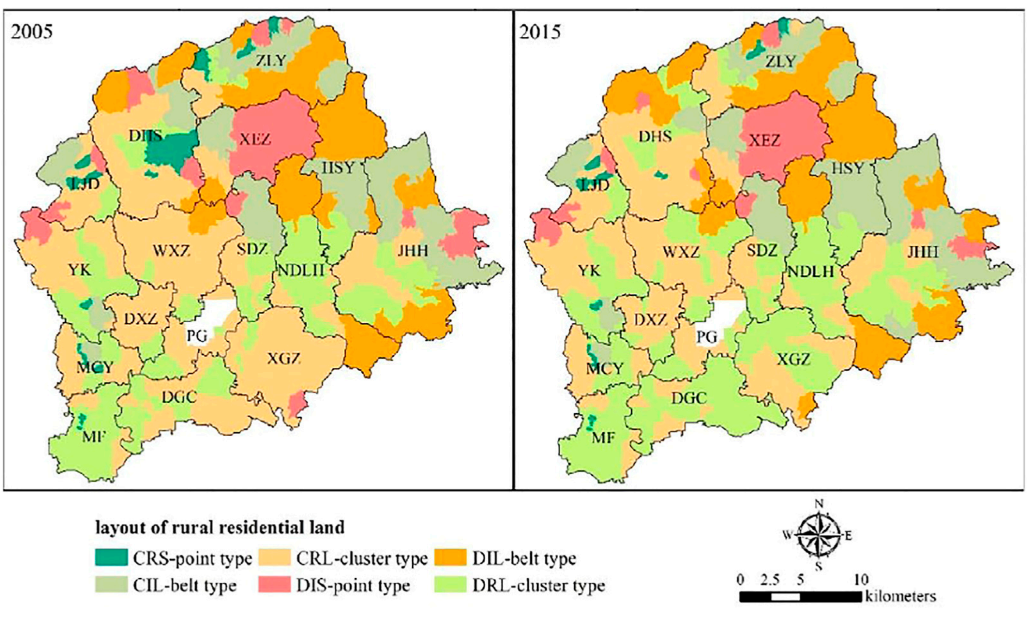

FIGURE 5 | Spatial distribution of pattern types of rural residential land in Pinggu.

spatially overlay the RRL spatial data and the environmental background factor data in the two periods of 2005 and 2015, and then the results of the factor grading were used to count the percentage of the number of RRLs with different spatial change patterns. The grading criteria of each environmental factor was developed based on the actual results of the study area using a

TABLE 4 | Areas and numbers of different changing RRL patches in Pinggu from 2005 to 2015.

Patch Changes	Area/hm^2	Patch Number/pcs	Average Patch Size/hm^2	Scale Growth Contribution/%
Leapfrog	269.55	557	0.57	39.25
Edge-expansion	406.74	1,079	0.48	59.21
Infilling	10.60	38	0.25	1.54
Total	686.89	1,674	0.51	100

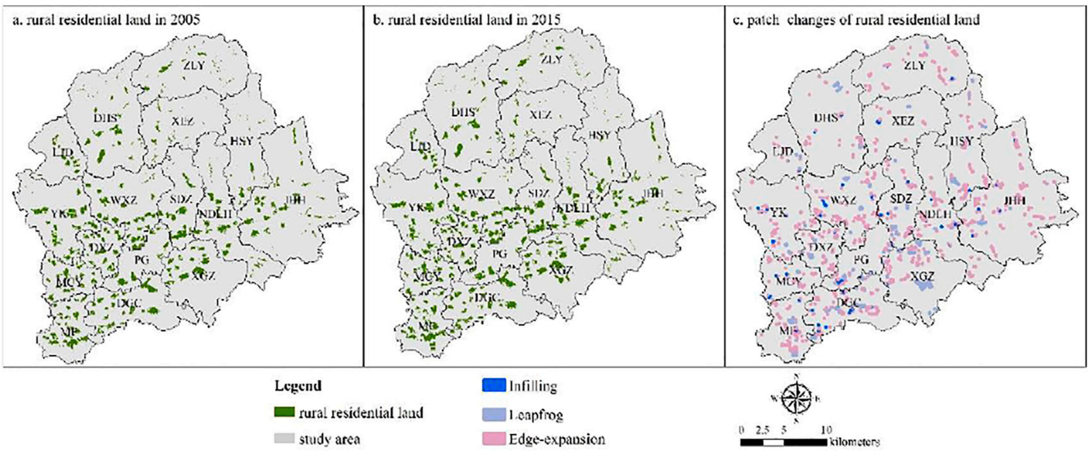

FIGURE 6 | Dynamic modes of rural residential land in Pinggu 2005–2015. the spatial distribution of rural residential land patches and its change processes in Pinggu [**(A)** and **(B)** are the spatial distribution of rural residential land patches in 2005 and 2015; **(C)** is the spatial distribution of the three processes of change in rural residential land patches from 2005 to 2015].

combination of the natural intermittent point method and expert consultation method.

3 RESULTS

3.1 Layout and Patch Change of Rural Residential Land in Pinggu

3.1.1 Layout of Rural Residential Land

The RRL in Pinggu was classified into six layout types in 2005 and 2015, which consisted of 275 villages (**Table 3** and **Figure 5**). The spatial distribution and quantitative characteristics of RRL layout types have some similarities. First, the distribution characteristics are relatively consistent, with DRL-cluster type and CRL-cluster type villages mainly distributed in plain areas. The layout types of RRLs in mountainous and semi mountainous areas are mostly dominated by CRS-point type, CIL-belt type, DIS-point type, and DIL-belt type. This is because in areas where the terrain is suitable for living, the agricultural infrastructure is often superior, which is conducive to the concentration of population and the formation of large-scale group-like and cluster-like RRL. This also reflects the impact of topographic and geomorphological conditions on the formation of RRL layout types.

The differences in the number and scale of RRL layout types in the Pinggu between 2005 and 2015 are also obvious. The layout of RRL in 2005 had the highest proportion and size of the number of CRL clusters (36.79%; 34534.80 hm^2), followed by DRL clusters (30.19%; 28337.57 hm^2). From 2005 to 2015, the number and scale of villages in the layout of the CRL cluster type decreased most obviously. The number and size of villages in the layout of the DRL cluster type increased significantly.

3.1.2 Patch Changes of Rural Residential Land

The specific characteristics of the layout of RRL can be further identified by the different change modes of patches and their combinations, including the total area, number, average patch area, and scale growth contribution of patches with different change modes (**Table 4**). Overall, the RRL scale in the Pinggu increased by 686.89 hm^2 from 2005 to 2015, accounting for approximately 12% of the increase. Among them, the scale growth contribution of edge expansion (59.2%) and leapfrog (39.25%) patches are the main types of site patch changes. There were regional differences in the change process of RRL patches influenced by the heterogeneity of regional environmental conditions (**Figure 6**).

The edge-expansion patches mostly rely on the original spatial base for expansion. The leapfrog patches have a good development base and potential, such as topography, natural resources, and location (in the hinterland of the central city). Leapfrog patches generate new scattered patches around the original RRLs, and this evolution will intensify the decentralized development of the RRL layout. Leapfrog patches are relatively scattered, and the number of distributions is relatively high in the periphery of the central city, which is an important urban function. In contrast, the infilling patches are relatively fragmented. Infilling patches rarely appear in the layout

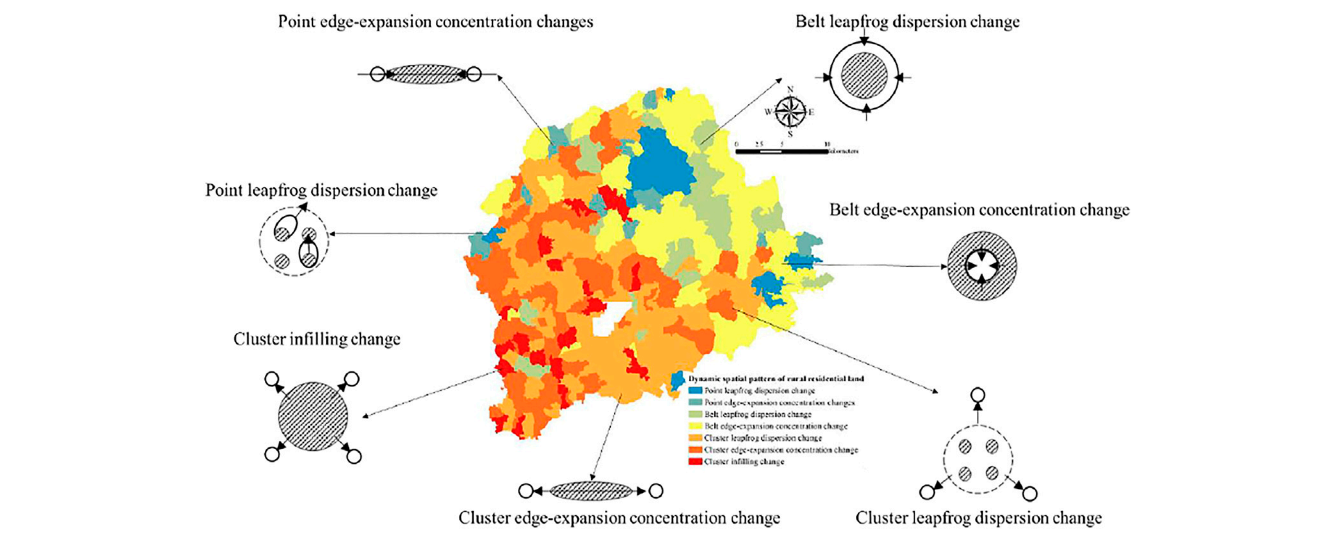

FIGURE 7 | Distribution of dynamic spatial patterns of RRL in Pinggu.

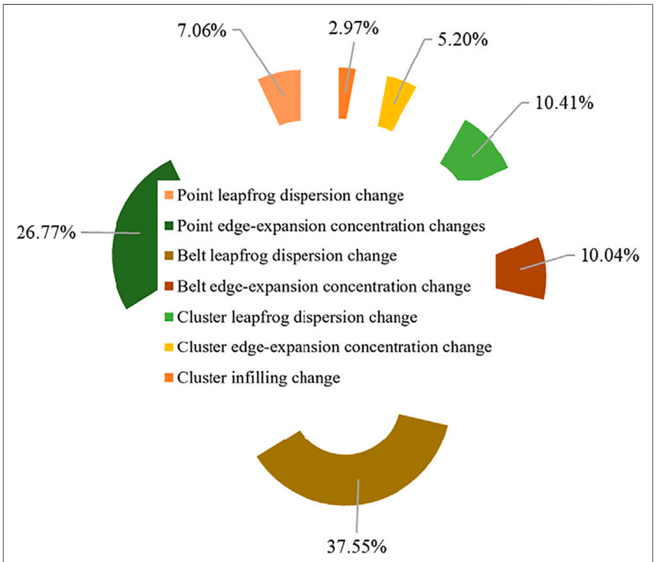

FIGURE 8 | Proportion of dynamic spatial patterns of RRL in Pinggu.

evolution of RRL, and this inward intensive development approach contributes to the clustering development of village layouts. The main location is close to the central urban area, the development of RRL is subject to the requirement of intensification to reduce arbitrariness and disorder, and the requirement of intensification of r RRL layout is significantly enhanced.

3.2 Distribution Characteristics of the Spatial Pattern of RRL

Based on the characteristics of clustering and dispersion evolution of the layout of RRL in the Pinggu, the spatial change pattern of the layout of RRL in the Pinggu is determined by the combination matrix method, which mainly shows the spatial clustering change pattern and the spatial dispersion change pattern (**Figures 7**, **8**), including point leapfrog dispersion change, point edge-expansion concentration changes, belt leapfrog dispersion change, belt edge-expansion concentration change, cluster leapfrog dispersion change, cluster leapfrog concentration change, and cluster leapfrog dispersion change, point edge-expansion concentration changes, belt leapfrog dispersion change, belt edge-expansion concentration change, cluster leapfrog dispersion change, cluster edge-expansion concentration change, cluster infilling change, are seven other modes of change.

The point edge-expansion concentration change pattern is scattered in mountainous and hilly areas, with a large number of land patches and small scale, but there are significant dominant patches. The trend of clustering change is to expand from the center to the edge. Belt edge-expansion concentration change is distributed in mountainous hilly areas, the boundary expansion is constrained by the topography, and the land is continuously extended along the ditches and roads in a linear pattern, resulting in dispersion change. Point leapfrog dispersion change is distributed in mountainous hilly areas in the form of beads, with the road as the axis of a jump-type dispersion change. Cluster infilling change is located near the center of the city, the number of patches is small, the scale is large, and the internal space is used to develop inwardly, resulting in a clustering change in layout. Cluster leapfrog dispersion change mode is located in the plain area, with better location conditions, driven by industrial transformation and spatial renewal, the land use type mainly of industrial enterprises and new communities show jumping dispersion change.

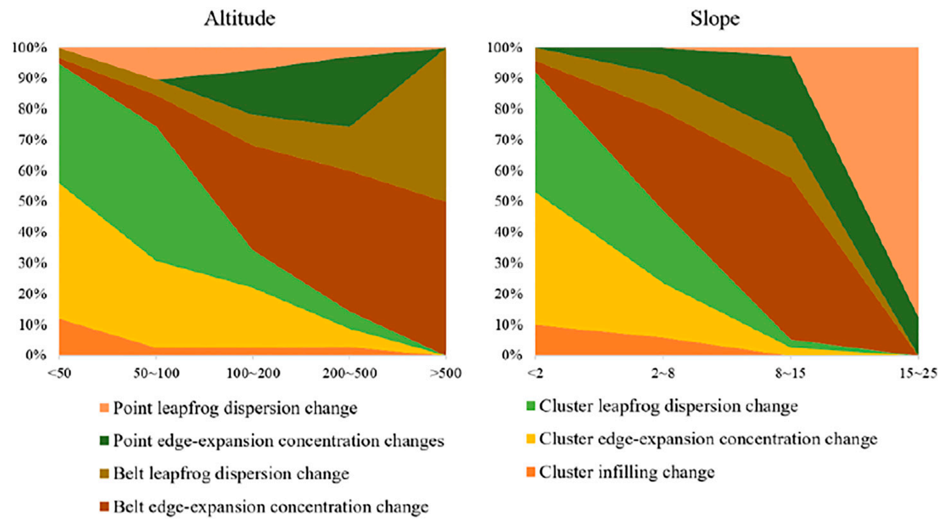

FIGURE 9 | Distribution characteristics of the dynamic spatial pattern of RRL under the topography gradient.

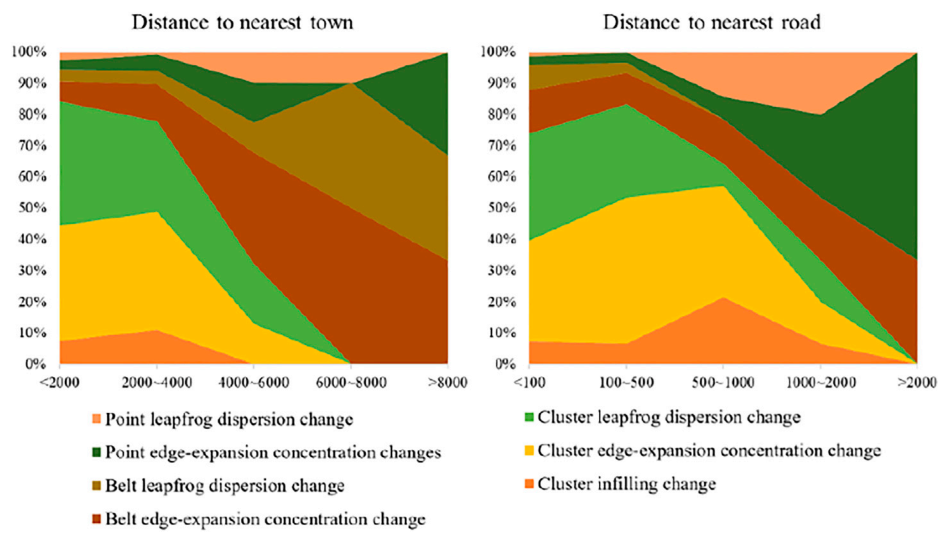

FIGURE 10 | Distribution characteristics of the dynamic spatial pattern of RRL under the location gradient.

3.3 Dynamic Spatial Pattern of Rural Residential Land in Pinggu

3.3.1 Topography

The degree of concentration of the RRL shows an obvious vertically decreasing law as the elevation and slope gradually increase (**Figure 9**). The high-altitude environment determines the prominent characteristics of small and scattered RRL. But due to the strong constraints on its spatial development, the evolution of RRL layouts instead shows concentration development. The number of RRLs with different spatial change patterns on each slope gradient shows that the change pattern of RRL below the 2° slope is dominated by the cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern. The slope size often determines the advantages and disadvantages of agricultural infrastructure, and gentle terrain conditions are conducive to the clustering of large-scale RRLs, while the slope advantage reduces the construction cost of outward development of RRLs, and the outward rough development of RRL is higher, often forming new residential clusters.

3.3.2 Location

The factors selected for the location environment gradient include town proximity and road accessibility (**Figure 10**). In the area less than 2000 m away from the town center, the main change pattern is cluster leapfrog dispersion change and cluster

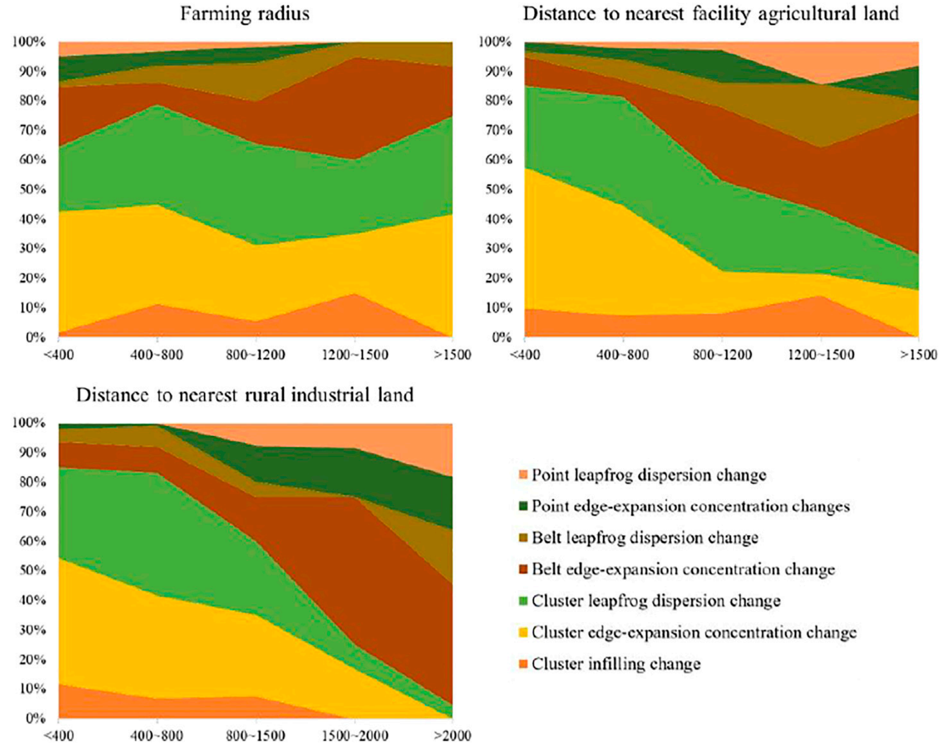

FIGURE 11 | Distribution characteristics of the dynamic spatial pattern of RRL under the production condition gradient.

edge-expansion concentration change. The area is closer to the town, whose spatial development is restricted by the influence of town spatial development and industrial park construction, especially the increased requirement of intensification of RRL. With the gradual increase of the distance from the town, the spatial expansion of RRLs decreases significantly, which to a certain extent foreshadows the potential declining trend of rural spatial development in areas where the influence of town radiation is weak.

The RRL spatial changing pattern is greatly influenced by roads. The RRL near the road still shows a certain spatial accessibility dependence, and the new sites are mostly extended along the road axis on the basis of the original space. As the distance between the RRL and the road gradually increases, the spatial expansion scale of RRL shows a gradual decline. In the range of fewer than 100 m and 100–500 m from the road, the change patches mainly show the characteristics of edge expansion. With a distance of more than 500 m from the road, the RRL changing pattern shows the characteristic of mainly leapfrog. The new sites tend to expand in the direction of the road, which further leads to a more dispersed layout pattern of RRL.

3.3.3 Production Conditions

The RRL is the main settlement place for the population engaged in agricultural production work, so three factors, farming radius, distance to the facility agricultural land, and distance to the rural industrial land, were selected to construct the production environment gradient. From the comparison of changing pattern in 2005 and 2015, the RRL shows a dispersion trend, with the increased distance to the facility agricultural land or the rural industrial land. In the farming radius gradient, the trend is the opposite (**Figure 11**). There is a strong spatial convergence between the concentration of arable land and the clustering of RRLs, and the clustering of RRL layout decreases as the concentration of arable land decreases. The degree of decentralization of the RRL layout evolves and weakens with the decrease in the concentration of farmland. In areas with concentrated arable land distribution, the decentralization of RRL layout evolves to a stronger extent, and the proportion of new RRL patches expanding through leapfrogging is higher.

The range of 400–800 m from the agricultural land of facilities is the area with the largest number of RRL, the RRL layout is dominated by a cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern. The RRL layout is dominated by a cluster leapfrog dispersion change pattern and a cluster edge-expansion concentration change pattern. The cluster change pattern has a good development base of RRLs in general, and the high spatial proximity to rural enterprises makes the layout change very active and easily produces new clusters around rural enterprises. New clusters are easily created around rural enterprises, which in turn leads to the formation of clusters of RRLs. The linear and dotted RRLs attract scattered villages to relocate by virtue of the good location of rural enterprises and the employment and income opportunities they provide, further contributing to the

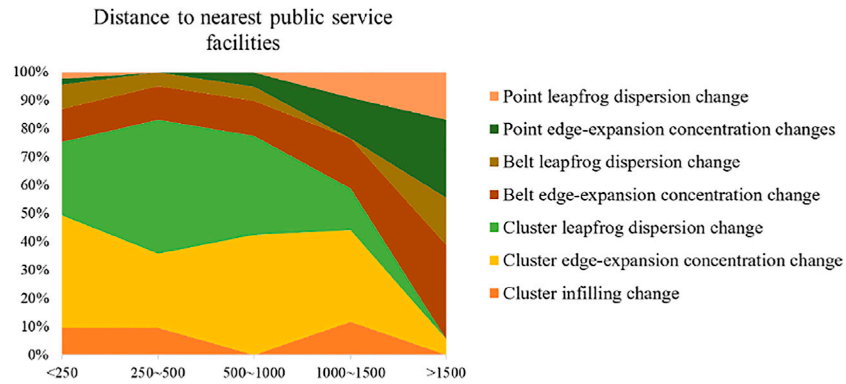

FIGURE 12 | Distribution characteristics of the dynamic spatial pattern of RRL under the public service gradient.

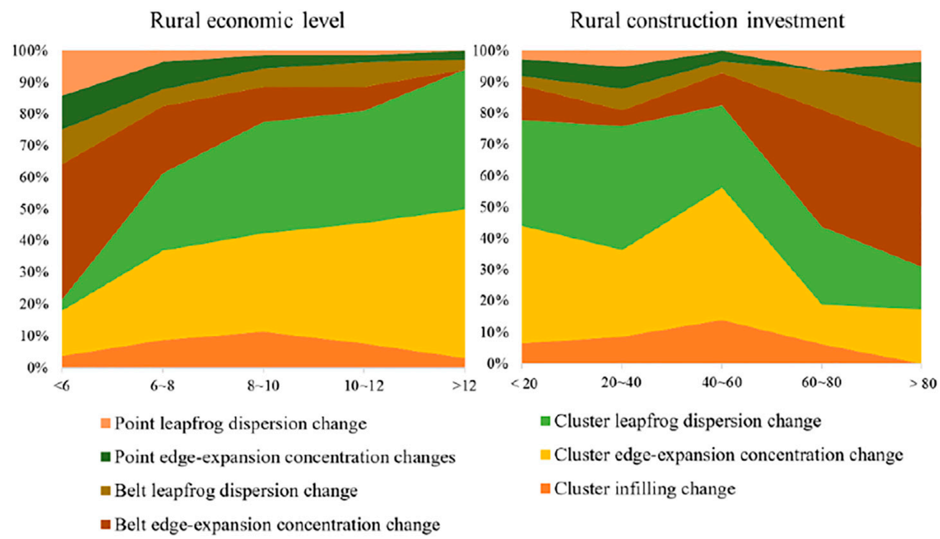

FIGURE 13 | Distribution characteristics of the dynamic spatial pattern of RRL under the economic-political gradient.

development of marginal spatial clustering of linear and dotted RRLs.

3.3.4 Public Service

With the deepening of the social division of labor and the diversification of rural residents' living needs, the supply of public services has become a key element affecting the choice of residence, so the role of the accessibility of RRLs to living service facilities led by educational facilities, medical facilities and commercial facilities on the spatial change pattern of RRL layout is considered (**Figure 12**).

The number of RRLs with different spatial change patterns in each distance class of living service facilities shows that the RRL layout change pattern within 1,000 m distance from living service facilities is dominated by the cluster leapfrog dispersion change pattern and the cluster edge-expansion concentration change pattern, while the point leapfrog dispersion change pattern and the belt leapfrog dispersion change pattern dominate the change in the layout of RRLs within 1,000 m distance from the amenities. The variability was dominated by the point leapfrog dispersion change pattern and the belt leapfrog dispersion change pattern. The reason for this variability may be that the configuration of living service facilities usually takes into account the scale of population served and operational efficiency and is often relatively well developed in town centers and urban areas with relatively high population sizes.

3.3.5 Economy and Policy

This study expressed the rural economic level and rural construction implementation intensity by rural per capita income and rural construction capital investment level, respectively. The level of capital investment and the degree of RRL layout clustering show roughly the opposite relationship. With the increasing per capita income level of villages, the stronger the demand for improving living space, the greater the possibility of changing the land use of RRLs from concentration to dispersion (**Figure 13**). At the same time, with the increase in the level of new rural capital investment, the decrease in the index of the degree of clustering and dispersal of RRL layout gradually shrinks, indicating that new rural construction management further plays a suppressive role in the development of RRL spatial decentralization.

The RRL with a per capita income level higher than 10,000 yuan is dominated by cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern. The layout change pattern of villages with an income level lower than 6,000 yuan is dominated by belt edge-expansion concentration change pattern and point edge-expansion concentration change pattern. This variability indicates that economic activities have an important influence on the spatial change pattern of RRL layout, and the dispersed change characteristics of RRL layout in areas with strong economic activities are obvious, while the RRL layout in economically backward areas is stable and retains more initial natural forms.

There is a correlation between the level of investment in new rural areas and the changing pattern of RRL layout. The RRL layout with a high level of investment in new rural areas is dominated by cluster edge-expansion concentration change pattern and belt edge-expansion concentration change pattern. Policies aimed at rural development and spatial management should not only focus on the improvement of the living environment of remote and dispersed villages but also pay attention to the need for pattern optimization of concentrated villages to prevent them from developing extensive and dispersed development from a regional perspective as a whole.

4 DISCUSSIONS

4.1 Evolutionary Process, Trend, and Possible Influence of RRL Change Patterns

In this study, seven typical RRL change patterns in the Pinggu were identified by considering the layout of different villages and the change process of RRL patches. Different change patterns show different change processes and directions, but most of the RRLs show a change trend from “disorderly” to “orderly.” This is not possible without the administrative interventions implemented by the Chinese government in recent years, such as the new rural construction and rural revitalization strategies. Of course, policy measures do not affect all RRLs to the same extent and in the same direction, which is why the study was able to identify seven typical patterns of change.

The cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern are the main change patterns, the RRLs in these two patterns are usually located in the open plain area, and the expansion space is less restricted by the topography. However, the cluster edge-expansion concentration change pattern is characterized by outward clustering along the edge of villages, which can be interpreted as the “native growth” of villages and is mainly distributed in western YQ, southern MF and MCY. This pattern can be interpreted as the “local growth” of villages. Although they all show cluster changes and are located in the plain area, the cluster leapfrog dispersion change pattern is influenced by the production environment. Specifically, under the influence of both industrial spillover from the central urban area and the increase in the intrinsic development demand of villages, some new communities and industrial enterprise sites are developed in a leapfrog manner, further resulting in the loosening of the layout of RRLs. The number of RRLs conforming to this pattern is the largest, accounting for 37.55% of the total number in the region, mainly distributed in the villages of DX, DG, WX, and XG around the central urban area. The other five patterns are mainly distributed in hilly areas, which also indicates that the RRL change patterns are diversified by the influence of topography, location and production conditions in hilly areas.

Therefore, the RRL in the flat valley area shows orderly development as a whole, the RRL change pattern in the plain area is dominated by the cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern, and the RRL change pattern in the hilly area is more diverse. The RRL change pattern in the plains was dominated by the cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern, while the RRL change pattern in the hills was more diverse. Among the various change patterns, the cluster leapfrog dispersion change pattern is a kind of RRL change pattern driven by the gathering of multiple factors and inherent development demand. In the context of the implementation of a rural revitalization strategy in China, if the factor input strategy can be formulated to guide other change patterns to cluster leapfrog dispersion change patterns, the “high-quality growth” of villages can be promoted.

4.2 Dissecting the Relationship Between Rural People and Land and Its Impact on the Land Use Layout of RRL

Understanding the intrinsic forces driving rural change allows scientific planning to guide the rural revitalization process and achieve sustainable development (Liu and Li, 2017). The environmental factors affecting the spatial distribution and changes in RRL mainly include the natural environment, production environment, and socioeconomic and cultural environment (Wang and Zhang, 2021). In this study, we analyze the relationship between people and land from five environmental gradients, including topographic and geomorphological environment, location environment, production environment, living service environment, and economic policy environment, and analyze the distribution pattern of RRL change patterns. There are significant differences in the regional environmental influences on RRL in different regions (Zou and Wang, 2015). The influence of altitude and slope on the RRL layout shows a relatively obvious vertically decreasing pattern, and the influence of the location environment represented by town proximity and road accessibility on the layout of the RRL shows a significant distance decay pattern. Rural economic development further promotes the active degree of RRL development (Tan and Li, 2013), and the higher the per

TABLE 5 | The 5 stages of China's policy system impact on RRL.

Stage	Description
1949–1980s	Events/policies The implementation of the people's commune system Affect A commune-production team-group type of RRL distribution hierarchy is formed Result The scattered small villages were merged into a wholly residential area
1980s to mid-1990s	Events/policies Rural economic restructuring Affect Due to the loose management policies, the phenomenon of farmers building houses is more prominent. There a considerable amount of farmland is occupied Result The layout of RRL was dominated by loose and disorderly expansion
Mid-1990s to 2005	Events/policies New demands and changes have emerged Affect Construction activities around the villages have increased. In addition to the living function, RRL also carries a production and business function Result The disorderly expansion of rural residential land layout scale intensified
2005 to 2018	Events/policies New rural construction Affect Under the guidance of the development of land-intensive and industrial concentration, the layout of RRL was facing spatial adjustment, and the functions began to be diversified and non-agricultural Result RRL shows the trend of standardization and agglomeration
2018 since then	Events/policies Rural revitalization strategy Affect China's rural revitalization strategy puts forward the general requirements of prosperous industry, livable ecology, civilized rural style, effective governance, and rich life Result RRL further move towards orderly development, and coordinately develop with industrial development and ecological civilization construction

capita income level is, the higher the degree of RRL spatial expansion, while the layout of RRLs with relatively low-income levels remains relatively stable. While improving the rural habitat, the rural development policy plays a great role in restraining its spatially disorderly decentralized development. It should be noted that arable land, as an important production resource, interacts with RRL (Liu et al., 2010; Su et al., 2011; Han and Lin, 2019; Li et al., 2021; Penghui et al., 2021). The traditional agricultural production environment plays an important role in the formation of the RRL layout, but with the transformation and upgrading of rural production methods, advanced forms of the production environment represented by facility agriculture and rural enterprises are accelerating the evolution of the RRL layout. In 2021, the FAO proposed to "ensure world food security and protect the earth", and arable land protection is also an important national policy in China, so it is necessary to consider the production environment of traditional agriculture, facility agriculture and rural enterprises in the layout optimization of RRL to realize synergistic development with arable land protection. The development of RRL should be synergistic with the conservation of farmland (Gao et al., 2020).

4.3 Policy Implication

Throughout the five stages of the influence of China's policy system on RRL (**Table 5**), the practice of village improvement, mainly relocating and merging villages and linking urban and rural construction land, has profoundly changed the layout of RRL. The demand for production and living is the most direct driver of the change in the layout of RRL. Taking the layout changes of the village in JHH and HSY of Pinggu as an example, the villages have become neat and uniform after construction, with a staggered layout of new residential houses, which is in sharp contrast to the original loosely organized villages. The change in village layout is conducive to the transformation from a traditional village mainly for agricultural production to a service-oriented village mainly for tourism reception.

Therefore, the formulation of policies related to the layout adjustment of RRL should take into account both the needs of people and the carrying capacity of the land. In other words, we should fully consider the ecological function, the level of economic development and the carrying capacity of resources and environment, the flow of rural labor force, and the spatial development of land. There is the need to set reasonable "thresholds" and "ceilings." It is necessary for the construction of infrastructure, public service facilities, and other hardware materials (e.g., planning a reasonable radius of agricultural production and living services). At the same time, decision-makers need to deal with the relationship between production and living space, as well as the preservation and protection of ecological and cultural resources. In addition, not only should the linkage between new construction and reclamation in scale be considered, but the coordination and orderliness of spatial patterns should also be considered to avoid aggravating the disorderly development of space.

4.4 Contributions to Research, Limitations, and Future Work

In this study, combining remote sensing data and field research data, the layout types and spatial variation of patches of RRL were used to identify the changing patterns of RRL. It also analyzes their distribution patterns under different environmental gradients and provides a new perspective for analyzing the relationship between rural people and land. Therefore, the methodology and research results of this study provide support for the spatial optimization strategy of RRLs and are of reliable practical significance for promoting sustainable rural development. Compared with the field research data, which can only cover a few villages, and the low accuracy of identifying land types by remote sensing data, the method used in this study covers a wider spatial range, and is more accurate.

However, there are some limitations and uncertainties in this study. The differences in the changing patterns of RRL are formed under the influence of multiple environmental contextual factors that are jointly involved. Therefore, an integrated quantitative model is needed in the future to identify the combined effects of complex environmental factors on the spatial change patterns of RRL. Second, the research conducted in the Pinggu and the discovered RRL change patterns can only provide a direct reference for areas with similar natural and socioeconomic conditions; for different countries and regions, the spatial optimization strategy of RRL should be adjusted according to the specific change patterns.

5 CONCLUSION

This study explores the shape, distribution, size and change characteristics of RLL in the Pinggu and identifies the spatial change pattern of RRL. On this basis, the distribution characteristics of the change patterns under the environmental gradients of topography, location, production conditions, public service, economy and policy are analyzed to reveal the laws of spatial evolution of RRL layout in the area of rapid urbanization and rural transformation and development. The study shows that the DRL cluster type and CRL cluster type are the main types of RRL layouts in the Pinggu, and the area of RRL patches in the Pinggu increased by 686.89 hm^2 from 2005 to 2015, represented by the cluster leapfrog dispersion change pattern and cluster edge-expansion concentration change pattern. The main spatial change patterns of the RRL layout are the belt leapfrog dispersion change pattern and point edge-expansion concentration change pattern. The regional variability of environmental background factors plays a different role in the generation of spatial change patterns of RRL. The distribution of the pattern of RRL shows a decreasing trend under the topography and location gradients set in this paper. The production environment changes the evolutionary tendency of the spatial pattern of RRL. As a next step, the policy should take into account the environmental conditions of villages, move to areas with higher economic strength, high development potential, and good location conditions, and plan a reasonable radius of agricultural production and living services. The retention and protection of ecological and cultural resources should also be done in a manner which contributes to the sustainable development of rural areas.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

GJ: Conceptualization, Methodology, Data curation, Formal analysis, Writing–original draft. TC: Conceptualization, Data curation, Writing–review and editing. RZ: Conceptualization, Supervision, Writing–review and editing. YT: Writing–review and editing. SW: Writing–review and editing.

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Evaluating the Association of Regional and City-Level Environmental Greenness and Land Over Patterns With $PM_{2.5}$ Pollution: Evidence From the Shanxi Province, China

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Ambient $PM_{2.5}$ (fine particulate matter with aerodynamic diameters ≤2.5 μm) is a major threat to human health. Environmental fates and human exposure to $PM_{2.5}$ can be affected by various factors, and environmental greenness have been documented to be significantly associated with the exposure disparities; however, the relationship between the greenness and ambient $PM_{2.5}$ on the region and city levels, and variations across different land cover types remain unclear. In this study, $PM_{2.5}$ changes from 2001 to 2020 varying over different land cover types and cities were analyzed, and discussed for the relationships with environmental greenness, by taking Shanxi province as an example. The results showed in the past 2 decades, the mean annual NDVI (normalized difference vegetation index) of the study area showed a significant increasing trend ($p < 0.01$), and the $PM_{2.5}$ concentration decreased as environmental greenness get better. The same trends were observed across different land cover types and cities. The negative correlation was stronger in the construction land with more frequent human activities, especially in the built-up areas with low vegetation coverage; but limited in the high green space coverage areas. These results provide quantitative decision-making references for the rational development, utilization and management of land resources, but also achieving regional coordinated controls of $PM_{2.5}$ pollution by optimizing land use.

Keywords: land cover, NDVI, fine particulate matter, spatiotemporal patterns, environmental greenness

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1 INTRODUCTION

Along with the fast development of urbanization and industrialization, environmental quality changes rapidly in most areas. Emissions from sources like industry sector, diesel or gasoline vehicles, coal and biomass burning in power plants and residential stoves lead to serious air pollution (Shi Y et al., 2020). In China, air pollution has been recognized as the 4th largest risk factor, following dietary risks, tobacco, and high blood pressure, and causing millions of premature deaths every year. Although efforts have been taken to fight against the serious air pollution issue and many countermeasures effectively reduced pollution levels, fine particulate matter ($PM_{2.5}$) remains a significant contributor to high burdens of disease (Liu et al., 2017). Several large-scale epidemiological studies highlighted significant correlations between exposure to air pollutants and premature mortality (Lu et al., 2015; Fang et al., 2016; Cohen et al., 2017; Huang et al., 2017). The Chinese Longitudinal Healthy Longevity Survey (CLHLS) showed that each 10 μg/m^3 increase in the past 3-years average $PM_{2.5}$ was associated with 8% higher mortality in adults aged 65 years or older, and extrapolated that more than 1.7 million premature deaths among Chinese older adults was associated with exposure to ambient air pollution (Li et al., 2018).

Characteristics, fates and influencing factors of $PM_{2.5}$ that can be affected by many factors have been widely discussed in literature studies. Natural meteorological conditions such as wind speed, temperature, humidity, etc., can affect transport and deposition of airborne particles, and meanwhile, factors associated with human activities, like combustion emissions and land use/cover change (LUCC), especially the deterioration of natural ecological environment such as grassland and woodland being caused by urban expansion and increase of cultivated land, influence $PM_{2.5}$ fates notably (Lin et al., 2014; Shi K et al., 2020). It has been realized that it is necessary to include the LUCC into researches of $PM_{2.5}$ influencing factors from the perspective of environmental geography (Fan et al., 2019). Usually, resident, road and industry lands in urban are associated with high $PM_{2.5}$ intensities as activities like biomass burning and coal combustions in these areas contribute obviously to increased $PM_{2.5}$ concentration (Huang et al., 2014; Zhang et al., 2016), while forest usually acts as the adsorption sink reducing ambient $PM_{2.5}$ concentration significantly (Dzierżanowski et al., 2011). She et al. found that PM concentration was proportional to patch area and patch number of LUCC (She et al., 2017). Different landscape patterns cam also affects the interaction between woodland, water and atmospheric PMs (Wu et al., 2015).

The relationship between land cover patterns and air pollution is complex and usually pattern-process relationships (Lam and Niemeier, 2005; Bandeira et al., 2011; Chen et al., 2013; Zhang et al., 2013). Results primarily focusing on urban land cover types (e.g., urban forests, built-up land) may be not generalized to settings where greenspace largely represents regional woodland, grassland, farmland, and open areas (Taylor and Hochuli, 2017). Vegetation was found to have potentially offsetting effects in increasing $PM_{2.5}$ levels driven by industrial structure and energy-related emissions (Wang et al., 2018). It was suggested that the response of PM pollution to LUCC had obvious differences across different regions, and the correlation between PM pollution and LUCC was weak in coastal areas but strong in inland areas (Sun et al., 2016). According to an investigation of spatial scale effect by Chen et al., the capability for a neighborhood green space to attenuate $PM_{2.5}$ pollution would be vanished when its size smaller than 200 m, and would be maximized when its size within 400–500 m (Chen et al., 2019). Impacts of land cover pattern changes on the spatial distribution of $PM_{2.5}$ from the view of different scales, i.e., regional, city and district levels, is still limited.

In China, Shanxi Province, as the country's main energy base, has vigorously developed the coal industry. Its industrial development, population growth, and urban expansion have caused significant changes in land use patterns and increasingly serious air pollution problems in the past several decades, which directly threaten the physical and mental health of local people and severely hinder its regional sustainability (Bandeira et al., 2011). Development and in-depth study of the relationship between land cover pattern and typical air pollutant $PM_{2.5}$ can enrich relevant research on the impact of land cover pattern caused by human activities on the ecological environment. Taking Shanxi Province as the research area, this study aims at analyzing 1) the land cover pattern and environment greenness characteristics, which has rapidly developed urbanization in the past 20 years; 2) characteristics of the spatiotemporal changes of $PM_{2.5}$ pollution in these 20 years under the background of air pollution prevention and control; 3) how does the environment greenness change affect $PM_{2.5}$ pollution. Carrying out researches on the impact of changes in land cover patterns on $PM_{2.5}$ can not only provide quantitative decision-making references for the rational development, utilization and management of land resources, but also achieve regional coordinated controls of $PM_{2.5}$ pollution by optimizing land use methods.

2 MATERIALS AND METHODS

2.1 Study Area

Shanxi Province (ranging from 110°14′-114° 33′E, 34°34′ -40° 43′N) is in the hinterland of China, with an area of about 156,300 km^2 (**Figure 1**), relying on Taihang Mountain and neighboring Hebei in the east, acing Shaanxi across the Yellow River in the west, and adjoining the Inner Mongolia to the north and Henan Province to the south. There are 11 prefecture-level cities, namely Taiyuan, Datong, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Xinzhou, Linfen, Yuncheng and Lvliang. Shanxi Province has a very complex topography, with mountains, hills, plateaus and basins widely distributed. With the acceleration of urbanization and industrial development, the emission of particulate pollutants is increasing, and the air pollution pressure is becoming more and more urgent, which has become an important constraint factor for the opening-up and sustainable economic development of Shanxi Province.

2.2 Data Source

The land cover data in this study (including 2000 and 2020) were obtained from the 30-m spatial resolution global land cover data (GlobeLand30, http://www.globallandcover.com/). The images used for classification in this dataset are mainly multi-spectral images of 30-m spatial resolution, including TM5 (Thematic Mapper), ETM+ (Enhanced Thematic Mapper), OLI (Operational Land Imager) multi-spectral images of Landsat and HJ-1 multi-spectral images. The selection principle of these images includes the multispectral image of vegetation growth season within ±2 years of the data production base year or the update year, under the premise of ensuring that the image is cloudless (less cloud). The confusion matrix was used to verify the accuracy of GlobeLand30 data, and its overall

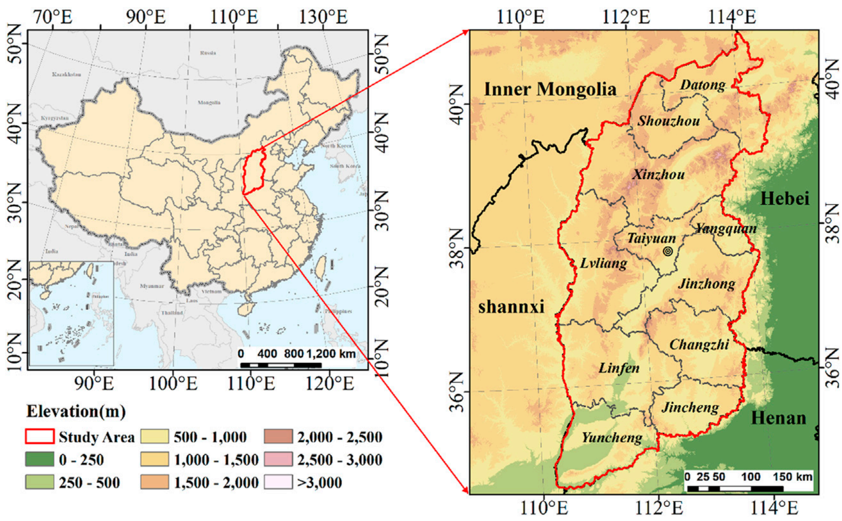

FIGURE 1 | Location of the study area (Shanxi Province).

accuracy reached over 80%. Based on the existing GlobeLand30 classification system, this study divides land cover types into seven categories: cropland, woodland, grassland, wetland, water body, built-up land, and barren land.

In this study, NDVI (normalized differential vegetation index), a symbolic index representing vegetation growth status and coverage, was selected to reflect environment greenness. NDVI is the ratio of the difference between the near-infrared region and red visible reflectance to the sum of these two measures, ranging from −1.0 to 1.0. Negative NDVI values are often thought of as blue space or water, whereas larger values indicate denser green vegetation (Tucker et al., 2020). We measured NDVI values from the Moderate-Resolution Imaging Spectro-Radiometer (MODIS) in the National Aeronautics and Space Administration's Terra Satellite (http://wist.echo.nasa.gov) from 1 January 2001 to 31 December 2020. MODIS has a temporal resolution of 16 days and varying spatial resolution up to 250 m. After the projection transformation, format conversion and splicing processing of the original data set, the annual average of NDVI was calculated for analysis. This calculation process was conducted using Google Earth Engine.

Estimates of ground-level concentrations of $PM_{2.5}$ were obtained from the ChinaHigh$PM_{2.5}$. It is generated from MODIS/Terra + Aqua MAIAC AOD products together with other auxiliary data (e.g., ground-based measurements, satellite remote sensing products, atmospheric reanalysis, and model simulations) using artificial intelligence by considering the spatiotemporal heterogeneity of air pollution. Hourly $PM_{2.5}$ were obtained from the China National Environmental Monitoring Center. Daily $PM_{2.5}$ values were then averaged from valid hourly observations at each monitoring station. Auxiliary data, including meteorological variables, surface conditions, pollutant emissions, and population distributions, that may potentially affect $PM_{2.5}$ concentrations, were collected to improve $PM_{2.5}$-AOD relationships in China. In this study, meteorological variables considered included temperature, relative humidity, precipitation, evaporation, surface pressure, wind speed, and wind direction, as described in detail elsewhere (Wei et al., 2021). Annual $PM_{2.5}$ estimates were calculated from 2000 to 2020, at 1 × 1 km spatial resolution, which was averaged from the Level 2 daily products. Since the data for the year 2000 is averaged from March 2000 to December 2000, we extract the annual PM2.5 data from 2001 to 2020 for analysis. The annual $PM_{2.5}$ estimates are highly related to ground-based measurements (R^2 = 0.94) with an average root-mean-square error (RMSE) of 5.07 μg/m^3, as described in detail elsewhere.

2.3 Data Analysis

2.3.1 Land Cover Change Rate

To analyze and assess the dynamic degree of land cover types objectively, the land change rate (LCR) of each land cover type was calculated, which is expressed as follows:

$$LCR = \frac{U_b - U_a}{U_a} \times 100\%$$

where Ua and Ub represent the area of each land cover type at the beginning year and ending year of the study period, respectively.

2.3.2 Correlation Analysis Between Vegetation Dynamics and $PM_{2.5}$ Change

The Pearson correlation analysis model is used to calculate the correlation coefficient between NDVI and $PM_{2.5}$ from 2001 to 2020, and to study the relationships between environmental greenness and air pollution on the spatial scales and pixel scales. The equation is as follows:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

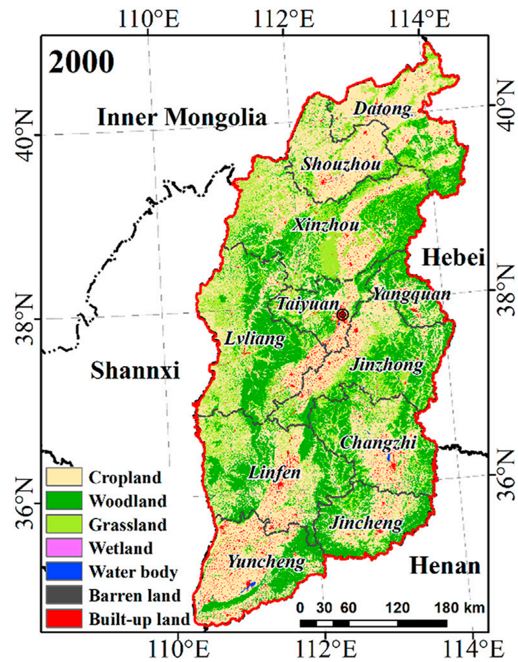

FIGURE 2 | The spatial distribution of land cover types in 2000 and 2020.

where n is the number of years, xi represents the value of variable x in the year i, and y_i represents the value of variable y in the year i. x and y represent means of the two variables, respectively. r_{xy} represents the correlation coefficient between x and y ranging from -1 to 1. If the $r_{xy} > 0$, it indicates variables x and y have a positive correlation. On the contrary, if the $r_{xy} < 0$, it indicates variables x and y have a negative correlation. In addition, if the absolute value of r_{xy} is closer to 1, the correlation between variable x and variable y is stronger. In this study, x and y refer to NDVI, which represents environmental greenness, and PM, which represents air pollution, respectively.

2.3.3 Trend Analysis of Normalized Difference Vegetation Index and $PM_{2.5}$

In this study, we applied a simple linear regression analysis method based on ordinary least squares (OLS) (Jiang et al., 2017) to detect the trend of mean annual NDVI, and $PM_{2.5}$ at the regional or pixel scale from 2001 to 2020. The expression of the slope is:

$$Slope = \frac{n\sum_{i=1}^{n} i \times N_i - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} N_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}$$

where Ni is the value of parameter (NDVI or $PM_{2.5}$) in the year i, and n represents the number of years. If the Slope >0, it means the parameter exhibits an upward trend. Otherwise, if the Slope <

Zero, it means the parameter exhibits a downward trend. In addition, the T-test method was operated to examine whether the trend of the parameter was significant at the basin or pixel scale.

TABLE 1 | Areas and changes of land cover types from 2000 to 2020 in study area.

Land cover type	2000	2020	2000–2020	
	Area/km^2	Area/km^2	Change Area/km^2	LCR
Cropland	70710.4 (44.97%)	65639.9 (41.91%)	−5070.5	−7.17%
Woodland	42747.2 (27.18%)	44295.2 (28.28%)	1548.0	3.62%
Grassland	39042.0 (24.83%)	37245.6 (23.78%)	−1796.4	−4.60%
Wetland	155.4 (0.10%)	234.3 (0.15%)	79.0	50.81%
Water body	386.0 (0.25%)	592.7 (0.38%)	206.7	53.53%
Built-up land	4153.3 (2.64%)	8515.9 (5.44%)	4362.7	105.04%
Barren land	51.3 (0.03%)	93.5 (0.06%)	42.2	82.30%

3 RESULTS

3.1 Land Cover Change Between 2000 and 2020

The distribution of land cover types showed significant spatial and temporal differences (**Figure 2**). Cropland is the most widely distributed type, accounting for more than 40% of the total area, mainly distributed in basin located in the central, northeast and southeast, and southwest in Shanxi Province. Woodland and grassland accounted for 28.28 and 23.78% of the total area in 2020, respectively, comprising two dominant natural land cover

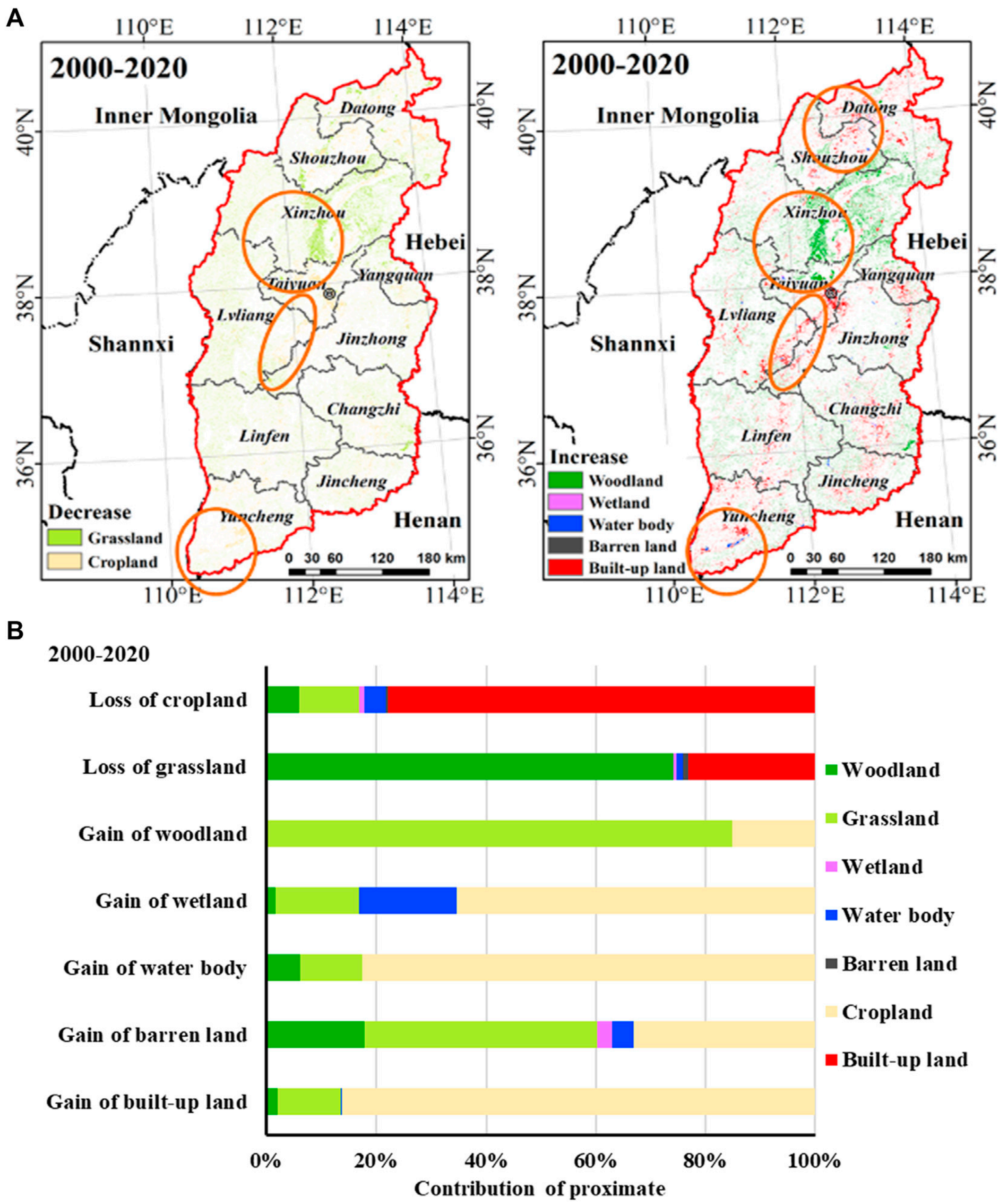

FIGURE 3 | The spatial location **(A)** and contribution of proximate driver **(B)** of decreasing and increasing land cover type.

types. Woodland is distributed mainly along mountain ranges, such as Taihang Mountain, Lvliang Mountain and other mountains. Grassland is mainly distributed in the west and center part. Built-up land is mainly distributed in the central and southeastern basin, accounting for 5.44% of land cover types. The proportions of wetland, water body and barren land in the study area are few, accounting for ~0.15, 0.38, and 0.06%, respectively. The area statistics of different land cover types are shown in **Table 1**.

The statistical area change of land cover types results are shown that areas of cropland and grassland had a decrease rate of 7.17 and 4.60%, respectively. Our estimates showed a 5070.5 km^2 and 1796.4 km^2 net loss areas of cropland and grassland, respectively (**Table 1**). Grassland loss occurred mainly in the forest-grass ecotone of the northern and central parts, with woodland (contribution to 74.13%) and built-up land (contribution to 23.25%) expansion being the main proximate driver. While cropland decrease was also extensive in these regions, decreased croplands occurred mainly in the central and southwestern basins. As can be seen from **Figure 3**, the main proximate driver of cropland reduction is built-up extension (contribution to 77.94%), followed by conversion of

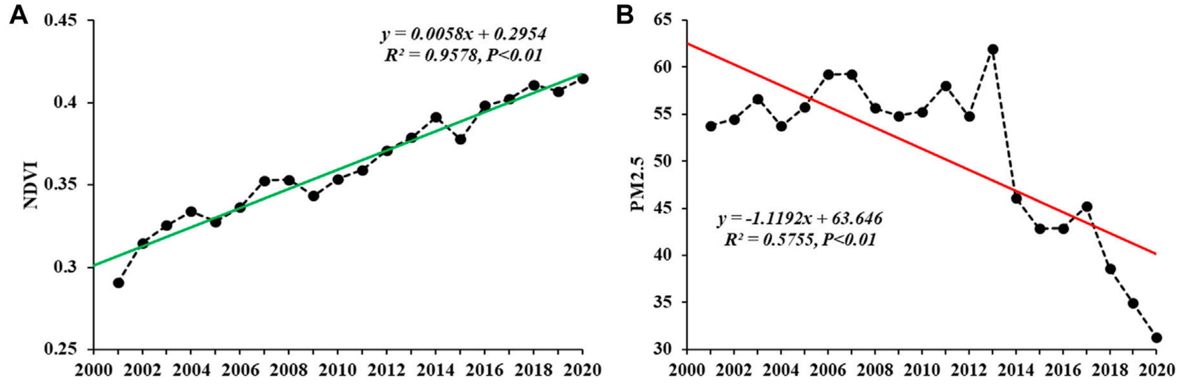

FIGURE 4 | Change trend of NDVI **(A)** and $PM_{2.5}$ **(B)** in the Shanxi Province from 2001 to 2020.

farmland to woodland and grassland (contribution to 16.73%). The area of built-up land increased the most (4362.7 km^2) and the increase rate was the highest (105.04%), followed by the area of woodland, the increase area was 1548.0 km^2. The increase rates of wetland, water body and barren land were high, but the increase areas were very small due to the low distribution area. Expanded built-up lands were mainly due to the occupation of cropland (contribution to 86.34%) and grassland (contribution to 11.5%), with Taiyuan, Datong and Yuncheng as the center, and other cities also expanded. Woodland expansions were mainly distributed in the central part, and returning grassland (contribution to 84.89%) or cropland (contribution to 15.11%) to forest were the main proximate driver.

3.2 Spatiotemporal Patterns of Normalized Difference Vegetation Index and $PM_{2.5}$

At the regional scale, the mean annual NDVI of the study area is 0.36 from 2001 to 2020, which showed significant increasing trends, and the increased rate is 0.0058/year ($p < 0.01$, **Figure 4A**). Of the total pixels, 93.67% of the entire area had significant increase detected, while only 0.97% experienced significant NDVI decreases in the study area, which were detected mainly in the central construction area (**Figure 5**). It indicates that the environmental greenness of Shanxi Province has been improved in the last 20 years. We analyzed the mean annual NDVI changes of four main land cover types (**Table 2**) and found that the mean annual NDVI of Woodland is 0.49, which is the highest value of four main land cover types. The mean annual NDVI of Built-up land had lowest value. Significant increase in mean annual NDVI was found in woodland (0.0064/year, $p <$ 0.01), grassland (0.0065/year, $p < 0.01$), cropland (0.0055/year, $p < 0.01$), and built-up land (0.0029/year, $p < 0.01$). The analysis of the mean annual NDVI in different cities shows that the mean annual NDVI of different cities in Shanxi Province is significantly increased, but the change trends are different (**Table 2**). The mean annual NDVI value of Jincheng from 2001 to 2020 is the highest among different cities in Shanxi Province, with an increased trend of 0.005/year. Shuozhou has the lowest mean annual NDVI from 2001 to 2020, which is 0.27, lower than the mean annual NDVI of the entire region. The city with the slowest increase of the mean annual NDVI is Jincheng, with an increase rate of 0.005/year, and the city with the fastest increase of the mean annual NDVI is Lvliang (0.0073/year).

The annual average of $PM_{2.5}$ concentration in Shanxi Province was 50.77 μg/m^3 from 2001 to 2020, showing a significant decrease trend (over 99% of the entire area), especially in the central and southern regions, whose decrease trend was faster than that of other regions, indicating that the atmospheric environment in Shanxi Province was getting better during these 2 decades (**Figure 4B**, and **Figure 5**). Different decrease trends were observed in four main land cover types (**Table 2**). The annual average of $PM_{2.5}$ concentration of Woodland is 46.59 μg/m^3, which is the lowest value of four main land cover types, and the annual average of $PM_{2.5}$ concentration of the Built-up land had highest value (62.10 μg/m^3). The most significant decrease was found in the built-up land (1.388 μg/m^3year^{-1}) from 2001 to 2020, followed by the cropland and grassland, and the lowest in the woodland. According to the regional statistics of the annual average of $PM_{2.5}$ concentration in different cities, the annual average of $PM_{2.5}$ concentration of different cities in Shanxi Province showed a significant decrease trend from 2001 to 2020 (**Table 2**). More than half of the cities have higher annual average of $PM_{2.5}$ concentration than the average value in Shanxi Province, with Yuncheng having the highest annual average of $PM_{2.5}$ concentration at 69.33 μg/m^3. The city with the slowest decrease of the annual average of $PM_{2.5}$ concentration is Datong, with a decrease rate of 0.882 μg/m^3year^{-1}, and the city with the fastest decrease of the annual average of $PM_{2.5}$ concentration is Yuncheng (1.680 μg/m^3year^{-1}).

3.3 Spatially Different Correlation Between Normalized Difference Vegetation Index Dynamics and $PM_{2.5}$ Variations

The relationship between the NDVI dynamics and $PM_{2.5}$ variations over the period 2001–2020 was analyzed by using the Pearson correlation method in the overall region at Shanxi Province (**Figure 6**). The annual average of $PM_{2.5}$ concentration had significant negative correlation with the

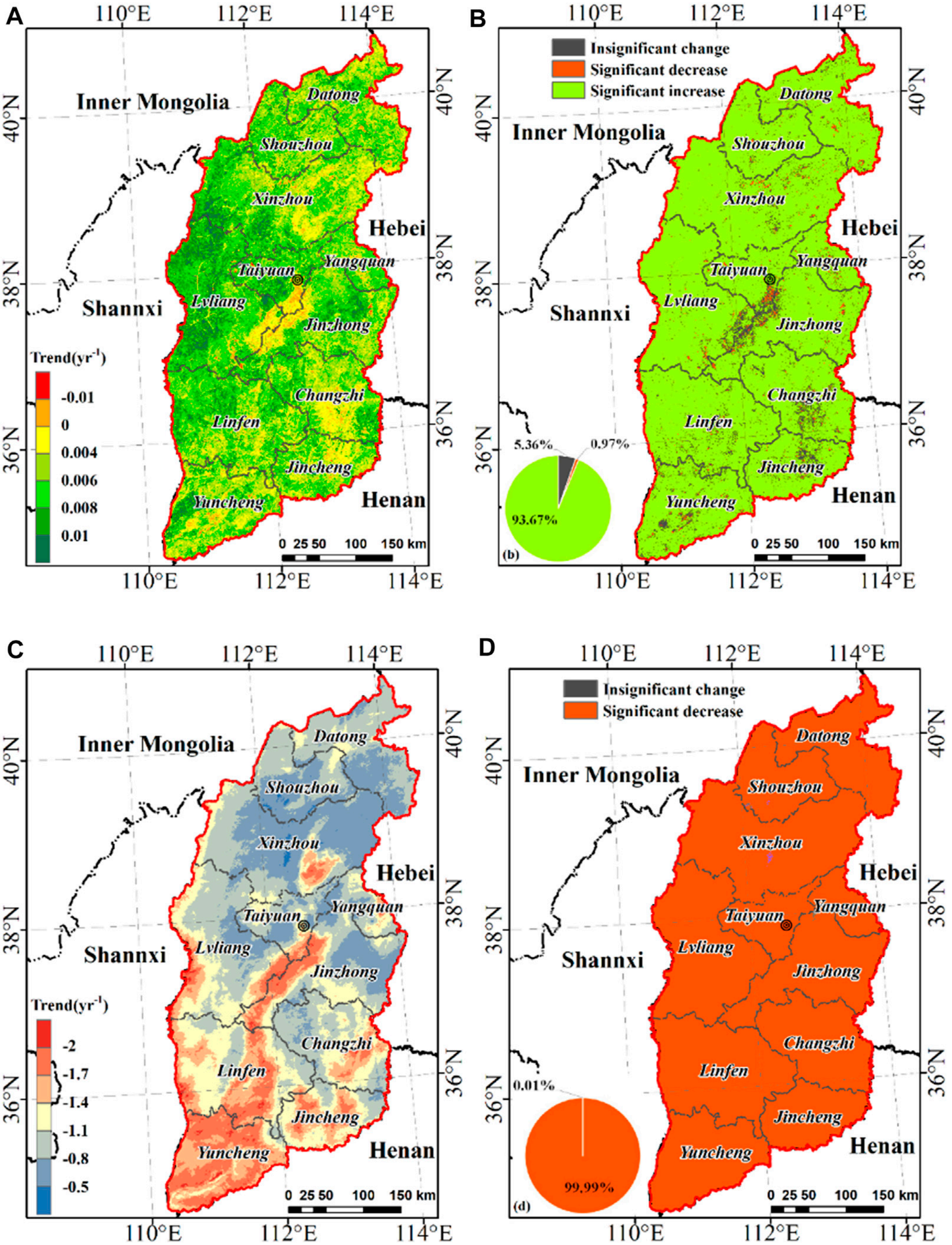

FIGURE 5 | Difference in the NDVI change trend **(A,B)** and $PM_{2.5}$ trend **(C,D)** in Shanxi Province from 2001 to 2020.

mean annual NDVI (R = −0.723, p < 0.01). Thus, environmental greenness was influential in the decrease of $PM_{2.5}$ concentration in this region. Of the total pixels, $PM_{2.5}$ concentration showed significant negative correlation with NDVI in most areas of Shanxi Province, with proportion of 83.77%, which were mainly distributed in vegetated areas. While 15.56% of the entire area showed insignificant correlation between $PM_{2.5}$ concentration and NDVI, and only 0.67% showed significant positive correlation, which mainly occurred in the areas with expansion of built-up land.

The correlations of $PM_{2.5}$ concentration with NDVI by the main land cover types and different cities were also calculated, and listed in **Table 3**. $PM_{2.5}$ concentration of four main land cover types was significantly negative correlated with NDVI. It is important to note that $PM_{2.5}$ concentration had the

TABLE 2 | The changes of mean annual NDVI and $PM_{2.5}$ in main land cover types and different cities.

Main Land cover types	Mean NDVI	Trend NDVI	Mean $PM_{2.5}$	Trend $PM_{2.5}$
Woodland	0.49	0.0064*	46.59	−1.012**
Grassland	0.34	0.0065*	47.28	−1.033**
Cropland	0.31	0.0055*	54.51	−1.218**
Built-up land	0.24	0.0029*	62.10	−1.388**
Different cities				
Datong	0.28	0.0052*	40.53	−0.882**
Shuozhou	0.27	0.0058*	42.65	−0.833**
Xinzhou	0.33	0.0059*	42.24	−0.859**
Taiyuan	0.35	0.0063*	48.99	−0.992**
Yangquan	0.38	0.0055*	51.57	−1.027**
Lvliang	0.35	0.0073*	48.30	−1.128**
Jinzhong	0.39	0.0056*	50.91	−1.092**
Linfen	0.40	0.006*	57.66	−1.370**
Changzhi	0.41	0.0051*	54.28	−1.118**
Jincheng	0.45	0.005*	58.85	−1.350**
Yuncheng	0.40	0.0052*	69.33	−1.680**

*The symbol * meant that the trend NDVI of the four land cover types and different cities had significant increase and the value of* p *is below 0.01. The symbol ** meant that the annual mean decrease value of $PM_{2.5}$ concentration of the four land cover types and different cities and the decrease trends were all significant and the value of* p *is below 0.01.*

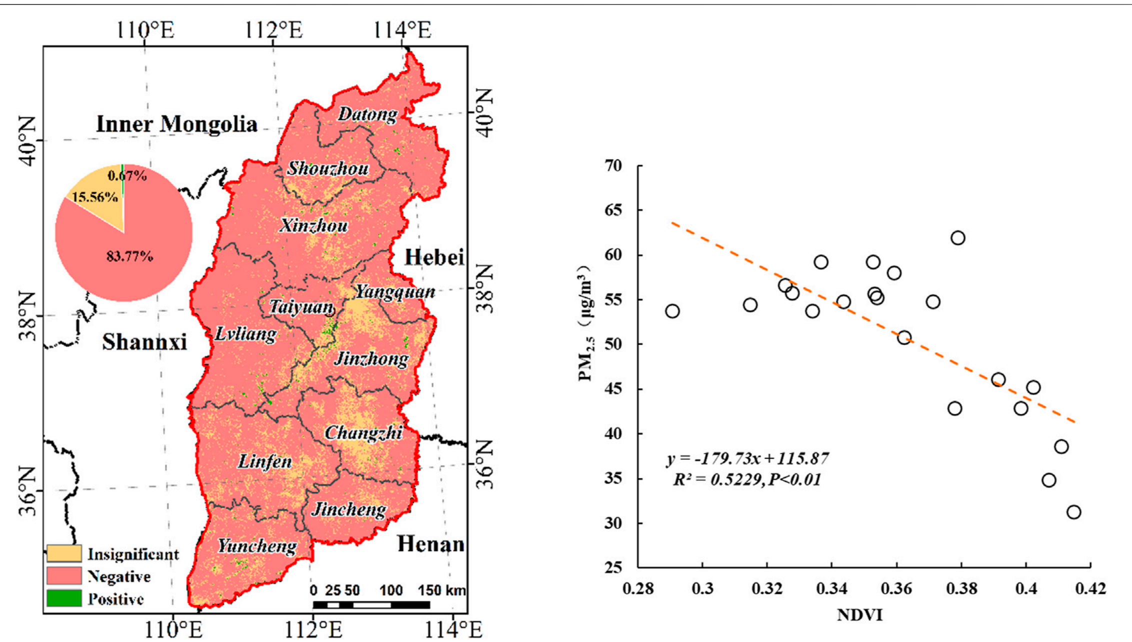

FIGURE 6 | The correlation between NDVI and $PM_{2.5}$. The pie charts illustrate the area percentage of different spatial patterns of the correlations.

strongest negative correlation with NDVI (R = −0.827, $p < 0.01$) in the built-up land, followed by the cropland (R = -0.726, $p < 0.01$) and then the woodland (R = −0.710, $p < 0.01$), and grassland has the weakest negative correlation with NDVI. The relationship between $PM_{2.5}$ concentrations with NDVI in different cities showed similar results (**Table 3**), and the trend of correlation coefficient was different among different cities. $PM_{2.5}$ concentrations were negatively correlated with NDVI for all cities, and the correlation coefficient ranged from −0.626 to −0.817, with Datong showing the strongest significant correlation (R = −0.817, $p < 0.01$), following by Yuncheng (R = −0.772, $p < 0.01$) and then Lvliang (R = −0.743, $p < 0.01$). The weakest negative correlation between $PM_{2.5}$ concentration and NDVI was occurred in Jinzhong.

At the pixel scale, the correlation analysis between $PM_{2.5}$ concentrations and NDVI in the main land cover types and different cities revealed that $PM_{2.5}$ concentrations had

TABLE 3 | Correlations between NDVI and $PM_{2.5}$ in different land cover types and cities.

		Correlation of $PM_{2.5}$ and NDVI		
Main Land cover types	Trend	Negative (%)pixels, $p < 0.05$)	Positive (%)pixels, $p < 0.05$)	Insignificant (%)pixels, $p > 0.05$)
Woodland	−0.710**	91.12	0.26	8.62
Grassland	−0.700**	87.15	0.29	12.56
Cropland	−0.726**	79.57	0.51	19.91
Built-up land	−0.827**	72.58	1.14	26.28
Different cities				
Datong	−0.817**	92.58	0.69	6.73
Shuozhou	−0.705**	86.47	0.45	13.09
Xinzhou	−0.704**	87.24	0.56	12.21
Taiyuan	−0.737**	81.64	1.75	16.60
Yangquan	−0.656**	83.29	0.64	16.07
Lvliang	−0.743**	92.59	0.64	6.77
Jinzhong	−0.626**	71.85	1.21	26.95
Linfen	−0.664**	81.03	0.26	18.71
Changzhi	−0.631**	70.09	0.49	29.42
Jincheng	−0.727**	87.22	0.31	12.47
Yuncheng	−0.772**	83.20	0.92	15.88

*The second column of table meant that the annual mean decrease values of $PM_{2.5}$ concentration of the four land cover types and different cities. The symbol ** meant that the decrease trends were all significant and the value of p is below 0.01.*

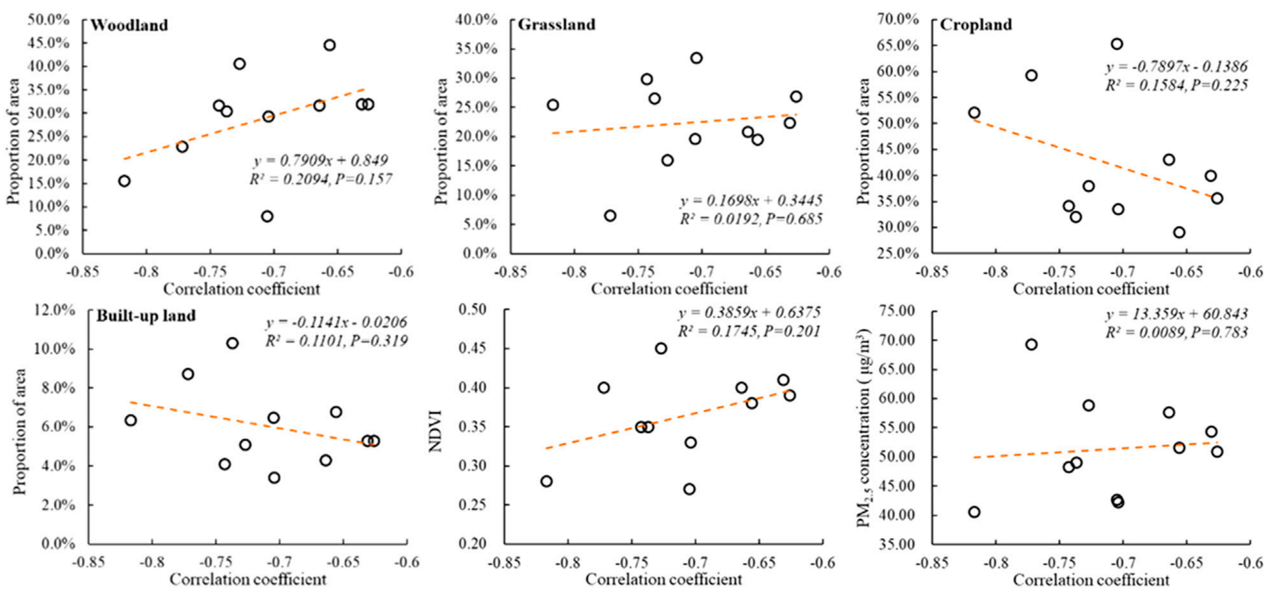

FIGURE 7 | The trends of the correlation coefficient between $PM_{2.5}$ concentration and NDVI with the change of NDVI, $PM_{2.5}$ concentration, and area of land cover types.

significantly negative correlations with NDVI in most areas of woodland, grassland, cropland and built-up land, with proportion of 91.12, 87.15, 79.57 and 72.58%, respectively (see **Table 3**). The insignificant correlation areas are relatively few, mainly in the built-up land (26.28%), followed by cropland (19.91%). Among different cities, Lvliang has the highest proportion of significant negative correlation between $PM_{2.5}$ concentrations and NDVI (92.59%), and almost the same result was showed in Datong (92.58%). The areas that $PM_{2.5}$ concentrations showed insignificant correlation with NDVI mainly occurred in Changzhi and Jinzhong, with proportion of 29.42 and 26.95%, respectively. There are few areas with significant positive correlation between $PM_{2.5}$ concentrations and NDVI in all cities, and the highest proportion occurs in Taiyuan, accounting for only 1.75%. The trends of the correlation coefficient between $PM_{2.5}$ concentration and NDVI were different with the change of NDVI, $PM_{2.5}$ concentration, and area of land cover type (**Figure 7**). The correlation coefficient becomes stronger with the decrease of NDVI. At the same time, the smaller ratios of woodland and grassland area were, the higher the negative correlation coefficient between $PM_{2.5}$ concentration and NDVI is, while the larger the built-up land area is, the higher the negative correlation coefficient between $PM_{2.5}$ concentration and NDVI is. These indicate that in the region with lower vegetation coverage, the increase of environmental greenness has a stronger reduction effect on $PM_{2.5}$ concentration. Thus, increasing environmental greenness has a stronger effect on $PM_{2.5}$ concentration reduction in low-vegetation areas than that in high-vegetation areas.

4 DISCUSSION

Results here are expected to be informative for regional land use planning and ecological environment construction to improve air quality, especially to control $PM_{2.5}$ pollution. With the construction of the *Beautiful China* in recent years, China's ecological environment has improved and air pollution has been effectively controlled. With the implementation of the Air Pollution Prevention and Control Action Plan (APPCAP) since 2013, significant declines in pollutants concentrations have achieved in nationwide of China (Bai et al., 2021); however, there are significant differences in $PM_{2.5}$ concentrations across different regions (Huang et al., 2018). Previous studies revealed that more than 70% of Chinese cities were found to exceed Grade II of the Chinese National Ambient Air Quality Standard, with the highest levels in the North China (Wang et al., 2018). This study found that $PM_{2.5}$ pollution in Shanxi province has decreased significantly since 2013, which is consistent with the overall pollution trend in China.

As an important energy base in China, the economic development of Shanxi Province has been dominated by the energy consumption, which produces large amounts of harmful emissions (Wei et al., 2018). Different from previous studies that mainly discussed the relationship between urban green space and $PM_{2.5}$ concentration, this study explored the impact of environmental greenness on $PM_{2.5}$ concentration from multiple perspectives of different land cover types and different cities at the regional scale (Feng et al., 2017; Chen et al., 2019). The results showed that less vegetation cover has limited ability to deal with high $PM_{2.5}$ concentration, which was consistent with a previous observation showing that higher green space coverage the site had, the lower the $PM_{2.5}$ concentration were there (Yang and Jiang, 2021). It has been recognized that vegetation may play an important role in reducing air pollution and improving air quality. For example, Sun et al. found that the concentrations of pollutants including SO_2, NO_2, CO, $PM_{2.5}$, and PM_{10} all have a negative correlation with the NDVI value (Sun et al., 2019). Some studies pointed out that the vegetation cover and $PM_{2.5}$ concentration correlated negatively (Jin et al., 2020; Kulsum and Moniruzzaman, 2021). The results of this study further confirmed the importance of environmental greenness in mitigating air pollution.

Some scholars studied the mechanism of green vegetation reducing air particulate pollution, and found that plants absorb pollutants through root absorption and leaf absorption pathways, as well as three mitigation mechanisms of green space on particulate matter: deposition, dispersion and modification (Diener and Mudu, 2021). Greenness, on the contrary, can effectively reduce the amount of fine particulate matter in the air. However, in the present study, we found that although environmental greenness has a significant reduction effect on $PM_{2.5}$ concentration, the reduction effect of NDVI on $PM_{2.5}$ is affected by green space coverage and $PM_{2.5}$ concentration level. With the increase of woodland and grassland area, the reduction effect of NDVI on $PM_{2.5}$ is weakened, and with the expansion of built-up area (that is, the area of green space decreases), the reduction effect of NDVI on $PM_{2.5}$ is enhanced. Woodlands may be more effective than grasslands in removing particulate matter, but the ability of green space to reduce $PM_{2.5}$ also has its limitations (Qiu et al., 2018). In high-density urban areas with low vegetation coverage, $PM_{2.5}$ concentration is high and pollution is serious. Improving environment greenness can more effectively control particulate pollution, while in high-density vegetation areas, air particulate concentration is relatively low, and continuously increases of environment greenness will reduce $PM_{2.5}$ reduction efficiency (Chen et al., 2019). In addition, as the concentration of $PM_{2.5}$ in the environment continues to increase, the reduction effect of NDVI on $PM_{2.5}$ is weakened. In the environment with high concentration of $PM_{2.5}$, the absorption of particulate matter by leaves will eventually reach saturation, and then the protection efficiency of particulate pollution is reduced (Hui et al., 2020). This suggests that, in densely populated residential or commercial areas, increasing environmental greenness may offer greater opportunities to improve air quality.

However, the mechanism, process, and outcome of PM mitigation by green space are complex and subjected to various influencing factors. Because of limited sample sites, evidence to quantitatively define the level of influence of green space on PM reduction is insufficient in this study. In addition to the land cover types and environmental greenness, researchers found that the landscape pattern (e.g., Patch area, degree of urban cluster, etc.), can also strongly affect $PM_{2.5}$ concentration (Wu et al., 2015), which was not addressed here due to limited information available. It is also necessary to note that the study did not consider possible time-lag effect, as it was found that the LUCC caused by natural disasters or human activities may have smaller impacts on air pollution in a short period of time, but stronger impacts over a few years (Sun et al., 2016). The time-lag effect is an interesting issue to be investigated in future.

5 CONCLUSION

Based on GlobeLand30, MODIS NDVI and ChinaHigh$PM_{2.5}$ data, this study investigated the spatiotemporal patterns of land cover types and environmental greenness in Shanxi province, and their relationships with ambient $PM_{2.5}$ over a period from 2001 to. This study found that although the vegetation area in Shanxi Province decreased since 2000, the environment greenness did show an upward trend. The $PM_{2.5}$ concentration fluctuated before 2013, and then started to decline continuously. Through the multi-scale analysis, it is found that there is a significant negative correlation between the $PM_{2.5}$ concentration and environment greenness, confirming the important role of regional greenness on $PM_{2.5}$ reduction. The study further demonstrates the multiscale effects of the relationship between $PM_{2.5}$ concentration and environment greenness, that is, $PM_{2.5}$ concentration is negatively correlated with environmental greenness, and the reduction effect of greenness on $PM_{2.5}$ was stronger with the low green space coverage areas than in high green space coverage areas, and higher in the low $PM_{2.5}$ concentration area than in high concentration area. This indicates that the reduction effect of environmental greenness on air particulate pollution is limited, but in construction land with frequent human activities, especially in built-up areas with low vegetation coverage, improving environmental greenness can effectively reduce PM pollution. The results of this study provide a theoretical basis for regional environmental planning and prevention and control of regional $PM_{2.5}$ pollution.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

GG and YD designed the study. GG and LL analyzed and interpreted the results of the data. GG drafted the manuscript. YD revised the manuscript.

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Responses of Land-Use Changes to Drought and its Disparate Impact on Livelihoods of Farmers and Herders in the Agro-Pastoral Ecotone of Northwestern China

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The agro-pastoral ecotone is an ecologically fragile region where drought is the main factor influencing land use and livelihoods. In this paper, we took two farmer villages and two herder villages in Ar Horqin Banner, located in the agro-pastoral ecotone of northwestern China, as the research areas, and where we conducted participatory rural appraisal and questionnaire survey to analyze the responses of land-use changes to drought and its disparate impact on the livelihoods of farmers and herders. Results show that: 1) Under drought, farmers tended to abandon rain-fed land, and herders tended to abandon grassland. 2) The livelihood activities of farmers were more stable than those of herders under drought. Farmers abandoned rain-fed farming, and herders just retained cattle rearing. The per capita net income of each farmer in Pingandi and Fenghuangling in the drought year of 2016 was only 9.27% and 12.52% lower than those in 2012, respectively, which was 132.88% and 128.25% lower than those in 2012 of each herder in Wuriduhubu and Haolibao. 3) Diversified livelihoods, especially non-agricultural ones, are the key to ensuring the sustainable livelihoods of farmers and herders. It is an effective way for farmers to encourage more labor force to emigrate to non-agricultural sectors. Regarding herders, it is urgent to develop artificial pastures and animal products processing industry with the support of government.

Keywords: land use change, livelihood, farmer, herder, drought, agro-pastoral ecotone of northwestern China

1 INTRODUCTION

The agro-pastoral ecotone in northwestern China, a transitional zone between the western desert and the eastern agricultural areas, is an ecologically fragile region with drought as the main stressor on ecology (Meng et al., 2015; Liu et al., 2020). The coexistence of farming and animal husbandry is the main mode of agricultural production, and the inlay of cultivated land within grassland is the main landscape (Yang and Wang, 2019; Liu, 2021). The ecological equilibrium has been broken by the increased intensity of land uses and drought episodes, which aggravates the fragility of ecosystems (Wang F. et al., 2012; Han et al., 2018). Coping with the threat of drought is a major challenge to sustainable development in the agro-pastoral ecotone (Tang et al., 2012; Lei et al., 2016; Martin et al., 2016; Zhao et al., 2019).

TABLE 1 | The socioeconomic status of farmer villages in 2016.

Village	Population	Households	Rain-fed land/ha	Irrigated land/ha	Sheep	Non-agricultural workers
Pingandi	1,377	623	67	600	10,000	500
Fenghuangling	1,389	596	180	340	30,00	550

1) Non-agricultural workers refer to those engaged in non-agricultural sectors.

TABLE 2 | The socioeconomic status of herder villages in 2016.

Village	Population	Households	Sheep	Cattle	Grassland/ha
Wuriduhubu	1,119	428	28,000	6,000	10,667
Haolibao	706	275	13,000	4,500	8,000

In the area, previous research has focused on the temporal and spatial changes of cultivated land or grassland (Zarafshani et al., 2012; Tesfa and Mekuriaw, 2014; Yu, 2016). It is an inefficient approach for determining differences in the changes of the two land use types as well as the socioeconomic effects of these changes by not putting both land use types into a research framework (Wang et al., 2020; Liu et al., 2021; Tao et al., 2021). The main reasons for land-use changes are eco-environmental factors and effects related to climate change and human activities (Ma et al., 2020; Li et al., 2021; Xue et al., 2021). Studies have focused on the livelihoods of rural residents under climate change and their coping strategies (Liu et al., 2012; Song et al., 2015; Wu et al., 2017). The livelihood vulnerability of farmers under climate change declines as their livelihood diversification increases (Wang J. et al., 2012; Chen et al., 2014). Diversified livelihoods can mitigate the impact of climate change on the quality of life of farmers (Paavola, 2008; Liao et al., 2015). In contrast, herders rely on animal husbandry, and their livelihoods severely affected by the degradation of the quality of grassland (Mogotsi et al., 2012; Zhang et al., 2012; Majekodunmi et al., 2014; Beyene, 2016; Tan et al., 2018). Hence, the stability of livelihoods of farmers and herders is different under drought (Roncoli et al., 2001; Yan et al., 2010; Liu et al., 2011). Despite this disparity, current research has mostly focused on the impact of drought on the livelihoods of farmers and herders in the agro-pastoral ecotone of China, collectively, which is not a robust approach when seeking to compare and contrast the different challenges these two groups of rural residents face under ecological stress.

Research has shown that the agro-pastoral ecotone of China is subjected to an increasing trend of interannual drought, and its degree has been aggravated in the past 55 years and is expected to be further aggravated (Guo et al., 2021). Based on the above arguments, we investigated two farmer villages and two herder villages in agro-pastoral ecotone of Ar Horqin Banner (AHB, Banner equivalent to County) with the intention of determining the socioeconomic challenges faced by its farmers and herders under drought. The goals are: 1) To investigate the main land resources of farmers and herders and their changes; 2) to outline and understand the differences of livelihoods between farmers and herders and the challenges they face; and 3) to suggest policies which would promote the improvement of the livelihoods of farmers and herders to resist and mitigate negative impacts of drought.

2 MATERIALS AND METHODS

2.1 Study Area

The AHB is located in the Inner Mongolia Autonomous Region of northwestern China (**Figure 1**), characterized by a mid-latitude, temperate, semi-arid, continental monsoon climate. The geographical coordinates which bound the domain are 119°02′–121°01′E, 43°21′–45°24′N and the annual average rainfall is only 320–400 mm. The AHB is endemic to competition between farming and animal husbandry. The southwest of AHB is farming areas while others are pastoral areas. Grassland and cultivated land are the most important land-use types, covering 777,522 and 138,599 ha in 2016, respectively, accounting for 58.72% and 10.47% of the total area. In terms of being seriously affected than other villages, the villages of Pingandi, Fenghuangling, Wuriduhubu, and Haolibao were selected. The farmer villages of Pingandi and Fenghuangling have residents who are farmers. The herder villages of Wuriduhubu and Haolibao, called “gacha” in Mongolian, have residents who are herders. The cultivated lands of farmers include rain-fed land and irrigated land, and most crops are ripe once a year. The irrigation period is mainly from May to August, while the rain-fed land is completely dependent on precipitation. In addition, farmers engage in non-agricultural employment. For herders, grassland is the main land resource. They engage in animal husbandry, mainly sheep and cattle rearing. The agricultural livelihoods of rural residents in the study areas mainly rely on natural conditions, especially precipitation, causing drought to become the main factor affecting land uses and livelihoods. The AHB experienced a four-year drought from 2013 to 2016, which significantly impacted land uses, flora coverage, and consequently the livelihoods of farmers and herders.

2.2 Data Acquisition and Processing

From 2012 to 2016, the annual precipitation of AHB represented a decreasing trend, with 561.1, 307.0, 313.3, 212.2, and 408.3 mm, respectively. Due to the continuously decreasing precipitation from 2012 to 2015, the degree of drought reached its peak in 2016. The methods of participatory rural appraisal and questionnaire survey were employed to investigate the land uses and livelihoods of both farmers and herders in 2012 (the non-drought year) and 2016 (the drought year). First, we conducted face-to-face

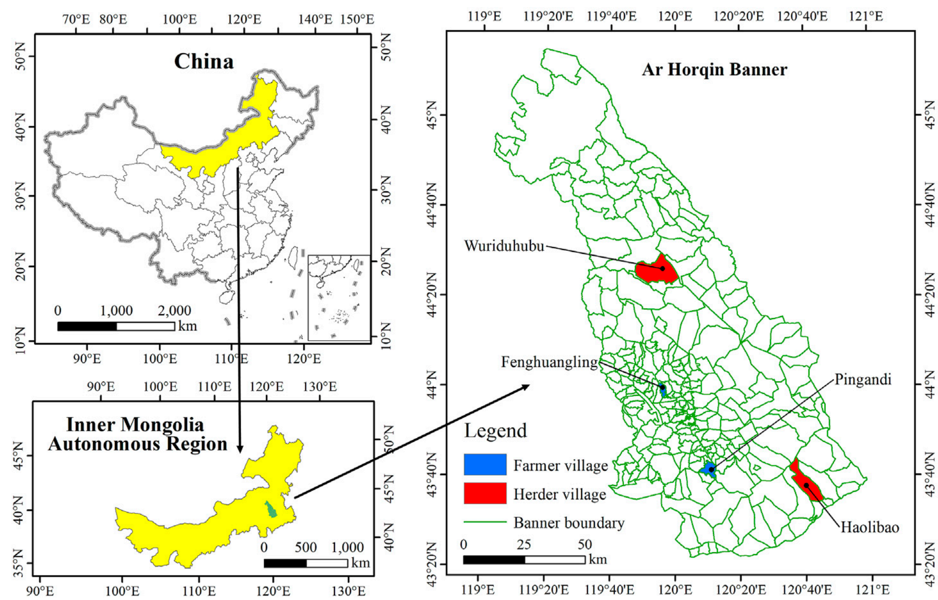

FIGURE 1 | Location of the study area.

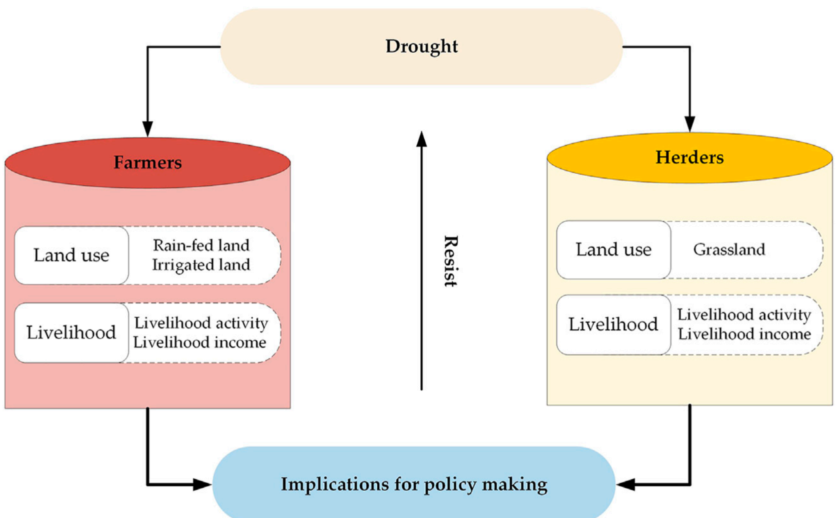

FIGURE 2 | Research framework.

interviews with village managers to acquire data that centered on land-use changes and the state of livelihoods of farmers and herders (**Tables 1**, **2**). Second, with the intent of ensuring data acquisition effectiveness, 30 farmers in Pingandi and Fenghuangling, and 30 herders in Wuriduhubu and Haolibao were selected to conduct a closed questionnaire survey. The recovery rate is 100%. The data mainly included: 1) Individual information of farmers and herders; 2) types of land use of farmers and herders in 2012 and 2016, and their changes; 3) the livelihood activities and incomes of farmers and herders in 2012 and 2016, and their changes; and 4) the causes attributed to differences in livelihoods of farmers and herders. The survey was conducted in October 2016 by a five-member research team. The questionnaire data were then statistically analyzed using the *SPSS* software package.

2.3 Hypotheses

In the agro-pastoral ecotone, the livelihoods of farmers are more diverse than those of herders. Farmers are engaged in farming, as well as in non-agricultural sectors. Herders mainly

FIGURE 3 | Rain-fed and irrigated land of Pingandi in August 2016 (the left is rain-fed abandoned land, the right is irrigated land).

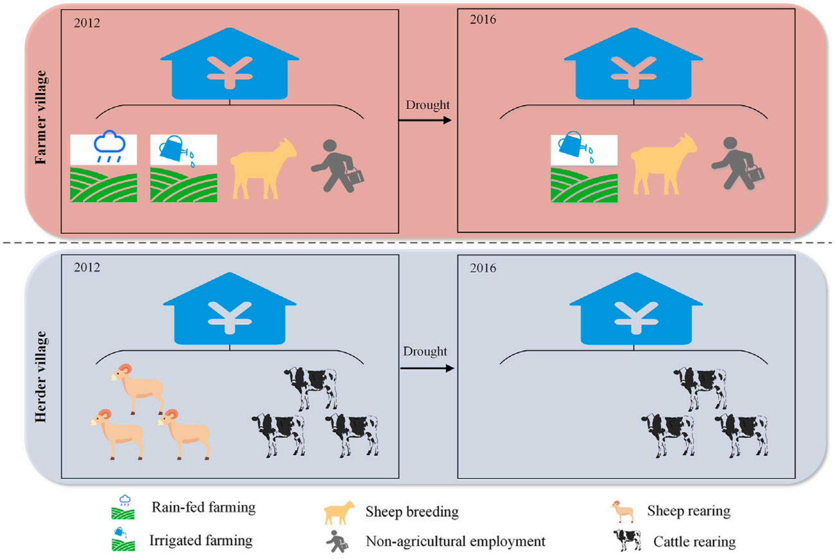

FIGURE 4 | Changes in livelihood activities of farmers and herders in 2012 and 2016.

rely on grassland to develop animal husbandry, which is the main income source for them. Under drought, the quality of rain-fed land and grassland is degraded. The impacts of drought-driven land-use changes on livelihoods (including livelihood activities and livelihood incomes) of farmers and herders are different due to different livelihood structures.

We take the losses in land resources and livelihoods from 2012 to 2016 as indicators to measure the stability of livelihoods of farmers and herders under drought. The research framework is shown in **Figure 2**.

3 RESULTS

3.1 Land-Use Changes Induced by Drought

3.1.1 Rain-Fed Land was Abandoned by Farmers

Both rain-fed and irrigated land were the land resources in the farmer villages. The per capita area of cultivated land of each farmer was 0.48 ha and 0.36 ha in Pingandi and Fenghuangling, of which 0.44 and 0.24 ha was irrigated land, respectively. Therefore, irrigated land was the main land resource of farmers. This area is irrigated with groundwater and hardly threatened by drought due to the stable of group water pumping. As for rain-fed land, it is completely dependent on precipitation. Therefore, under drought conditions, this area suffered serious impact. The rain-fed land was abandoned in 2016 (**Figure 3**).

3.1.2 Grassland was Abandoned by Herders

Grassland was the main land resource in the herder villages. The per capita area of grassland of each herder was 9.53 ha in Wuriduhubu, and 11.33 ha in Haolibao. The quality of grassland is dependent on precipitation. Due to the precipitation decreasing from 561.1 to 212.2 mm from 2012 to 2015, the water demand gap of the grassland reached its peak in 2016, and it was seriously degraded with the quality of grass insufficient for animal husbandry (**Figure 4**). Therefore, herders abandoned grassland in 2016.

FIGURE 5 | Grassland in wuriduhubu (left) and haolibao (right) in August 2016.

TABLE 3 | Livelihood incomes in farmer villages.

Village	Farming			Livestock breeding	Non-agricultural	Per Capita (yuan)
	Year	Irrigated	Rain-fed			
Pingandi	2012	6857.4	343.5	1,270.88	9041.4	17,513.18
	2016	5,577	0	1,270.88	9041.4	15,889.28
Fenghuangling	2012	2660.4	765	377.97	10,043.19	13,846.56
	2016	1,692	0	377.97	10,043.19	12,113.16

1) The cost of livestock breeding in Pingandi and Fenghuangling includes buying lambs and grass, which is no differences in 2012 and 2016. After deducting the cost, the profit of livestock breeding is approximately 175 yuan; the per capita net income of each farmer in Pingandi and Fenghuangling was 1,270.88 yuan and 377.97 yuan, respectively. 2) The average income of non-local and local non-agricultural employment is 3,000 yuan/month and 1,500 yuan/month, and the average work time is 10 and 3 months, respectively. According to the number of non-local and local workers, the per capita income of non-local and local non-agricultural employment was 8,714.6 yuan and 326.8 yuan in Pingandi, and 9, 711.22 yuan and 323.97 yuan in Fenghuangling, respectively.

3.2 Impacts on Livelihoods

3.2.1 The Livelihood Activities of Farmers Were More Diverse Than Those of Herders

In 2012, farming (irrigated and rain-fed), livestock breeding (raising sheep in captivity due to the grazing prohibition policies for farmers in the farming areas of AHB), and non-agricultural employment (non-local refers to those working out of the town, and local refers to those working within the town) were the main livelihood activities of farmers in the farmer villages (**Figure 5**). In 2016, rain-fed farming was abandoned. Unlike herders, sheep breeding in the farmer villages has not been affected because of the pattern of breeding (**Figure 4**). Therefore, the drought had little impact on their other livelihood activities.

In 2012, animal husbandry (sheep and cattle rearing) was the main livelihood activity of herders in the herder villages. In 2016, herders were forced to sell lambs and entrusted other herders to graze their ewes in those Banners influenced slightly by drought because of the degraded grassland quality and the associated decline in the carrying capacity. As a result, only cattle rearing was retained who raised mainly on forage and green stored corn. The livelihood activity of herders was seriously affected.

3.2.2 The Loss in Livelihood Incomes of Herders was Greater Than That of Farmers

Although livelihood incomes of farmers reduced in 2016, the change was slight. Farming and livestock breeding don't require much labor time and their income proportion is relatively low. Farmers are inclined to engage in other livelihood activities to improve their livelihoods. Hence, non-agricultural employment accounts for a major proportion of farmers' livelihood incomes (**Tables 3**, **4**). In 2016, the loss in livelihood incomes was mainly attributed to rain-fed farming. The incomes of livestock breeding and non-agricultural employment were only slightly affected. Hence, the total per capita net income of each farmer in Pingandi and Fenghuangling was 15,889.28 yuan and 12,113.16 yuan, respectively, which was only 9.27% and 12.52% lower than those in 2012.

Herders hardly engage in other livelihood activities. The sheep and cattle rearing were the main sources of their livelihood incomes (**Tables 5**, **6**). In 2016, the cost of sheep rearing was greatly increased, while the income was reduced (the selling price of a lamb decreased from 1,000 yuan to 400 yuan due to the poor quality of lambs). The per capita net income of sheep rearing of each herder in Wuriduhubu and Haolibao decreased by 159.84% and 170%, respectively. The cost of cattle rearing was much higher than in 2012, and there was almost no revenue from catle rearing. Hence, the total per capita net income of each herder was −2,920 yuan and −2,273 yuan, respectively. The livelihood incomes in Wuriduhubu and Haolibao in 2016 were lower than those in 2012 by 132.88% and 128.25%, respectively.

TABLE 4 | Input–output flows of farming in farmer villages.

Village	Year	Crop	Cultivated land	Yield (Kg/ ha)	Price (Yuan/kg)	Cost (Yuan/ ha)	Net income (Yuan/ha)	Per capita area/ha	Per capita net income	Total revenue
Pingandi	2012	Corn	Irrigated	14,250	1.5	5,790	15,585	0.44	6,857.4	7,200.9
		Millet	Rain-fed	3,000	5	3,300	11,700	0.02	234	
		Mung Bean		975	9	3,300	5,475	0.02	109.5	
	2016	Corn	Irrigated	12,750	1.5	6,450	12,675	0.44	5,577	5,577
		Millet	Rain-fed	0	——	——	0	0.02	0	
		Mung Bean		0	——	——	0	0.02	0	
Fenghuangling	2012	Corn	Irrigated	11,250	1.5	5,790	11,085	0.24	2,660.4	3,425.4
		Millet	Rain-fed	2,250	5	3,300	7,950	0.06	477	
		Mung Bean		900	9	3,300	4,800	0.06	288	
	2016	Corn	Irrigated	9,000	1.5	6,450	7,050	0.24	1,692	1,692
		Millet	Rain-fed	0	——	——	0	0.06	0	
		Mung Bean		0	——	——	0	0.06	0	

1) For comparison, the crop price is based on 2016; 2) The costs of corn: fertilizer is 4,500 yuan/ha, herbicide and insecticide is 300 yuan/ha, irrigation is 990 yuan/ha in 2012 and 1,650 yuan/ha in 2016, so the total cost is 5,790 yuan/ha in 2012 and 6,450 yuan/ha in 2016, respectively; 3) The cost of millet and mung bean: fertilizer is 3,000 yuan/ha, herbicide and insecticide is 300 yuan/ha. The total cost is 3,300 yuan/ha.

TABLE 5 | Livelihood incomes in herder villages.

Village	Year	Rearing sheep	Rearing cattle	Per capita net income
Wuriduhubu	2012	4,880	4,000	8,880
	2016	−2,920	0	−2,920
Haolibao	2012	3,247	4,800	8,047
	2016	−2,273	0	−2,273

1) The ratio of mature cattle to calves is approximately 3:2. In 2012, the per-head cost of mature cattle was approximately 3,000 yuan, and that of calves was 1,500 yuan; in 2016, the cost was approximately 4,000 yuan and 2,000 yuan, respectively. Calves can usually be sold after one year for approximately 8,000 yuan/head. 2) The per capita number of mature cattle and calves was 3 and 2 in wuriduhubu, and 3.6 and 2.4 in Haolibao, respectively. In 2012, the cost and income of rearing cattle were 12,000 yuan and 16,000 yuan in Wuriduhubu, and 14,400 yuan and 19,200 yuan in Haolibao, respectively. Hence, the per capita net income of raising cattle was 4,000 yuan and 4800 yuan, respectively. In 2016, the cost and income of rearing cattle were both 16,000 yuan in Wuriduhubu and, and both 19,200 yuan in Haolibao. Hence, the per capita net income of raising cattle was both 0.

TABLE 6 | The cost and income of rearing sheep in herder villages.

Village	Year	Cost of ewes						Cost of lambs			Total cost	Income		
		Per capita quantity	Hay	Concentrated feed	Parasite-killing, washing sheep	Grazing	Total	Per capita quantity	Parasite-killing, washing sheep	Total		Price (Yuan/ piece)	Total revenue	Net income
Wuriduhubu	2012	15	288	45	5	0	5,070	10	5	50	5,120	1,000	10,000	4,880
	2016	15	288	45	5	120	6,870	10	5	50	6,920	400	4,000	−2,920
Haolibao	2012	11	288	45	5	0	3,718	7	5	35	3,753	1,000	7,000	3,247
	2016	11	288	45	5	120	5,038	7	5	35	5,073	400	2,800	−2,273

1) In 2012, herders sold the lambs after fattening. A lamb was born in spring, fattened in summer, and slaughtered in autumn. The cost included parasite killers and washing sheep at 5 yuan/piece; other costs were negligible, and the sales price was approximately 1,000 yuan/piece. Ewes must eat forage in winter. Generally, one ewe needed 288 yuan of hay, 45 yuan of concentrated feed, and 5 yuan for parasite killing and washing sheep, for a total of 338 yuan/piece. 2) In 2016, herders sold the lambs for approximately 400 yuan/piece. The cost of grazing ewes on pastures of other Banners was 20 yuan/piece per month. According to the grazing characteristics in Inner Mongolia, the resting and grazing period was generally six months. Therefore, the grazing time was set to six months; one ewe requires 120 yuan, and the cost was approximately 458 yuan per sheep, including other costs.

3.3 Livelihood Diversification is the Key to Ensure the Stability of Livelihoods

The livelihood activities and incomes of farmers are diverse. Besides farming and livestock breeding, non-agricultural livelihood accounted for a large proportion (**Figure 6**). Although farmers faced the double pressure of abandoning rain-fed farming and the increasing cost of irrigated farming, the net income from farming still remained higher than 7,050 yuan/ha, which was a relatively considerable sum. Moreover, the proportion of non-agricultural income accounted for 51.62% and 72.53% in Pangandi and Fenghuangling in 2012, and 56.9% and 82.91% in 2016, respectively. Farmers can rely on non-agricultural employment to ensuring the stability of livelihoods. Hence, the diversified livelihoods, especially non-agricultural ones enable farmers to resist the threat of drought.

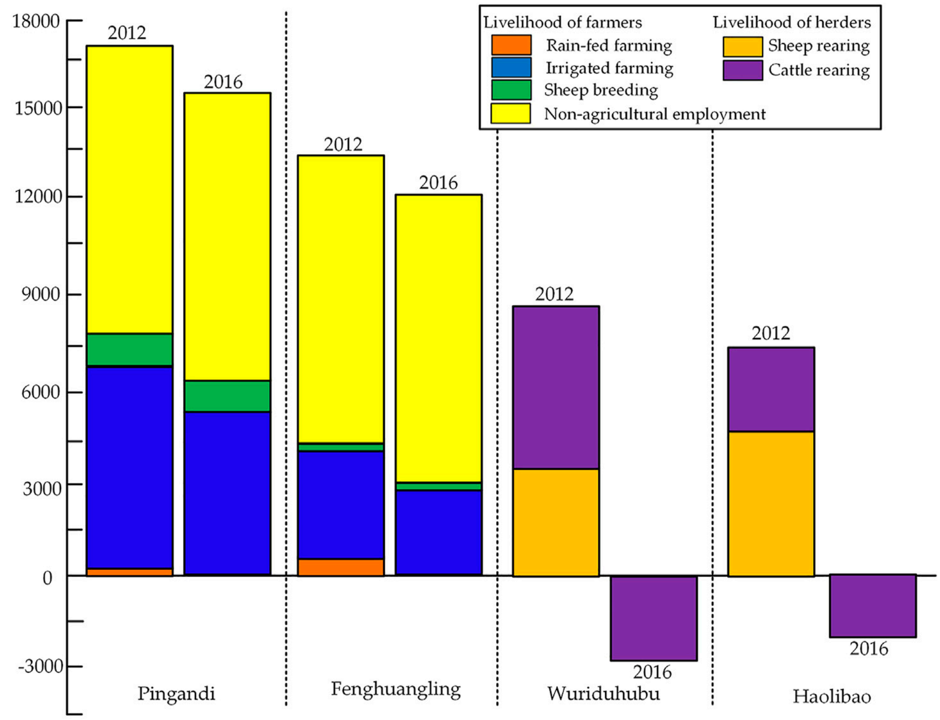

FIGURE 6 | The incomes of farmers and herders before and after the drought.

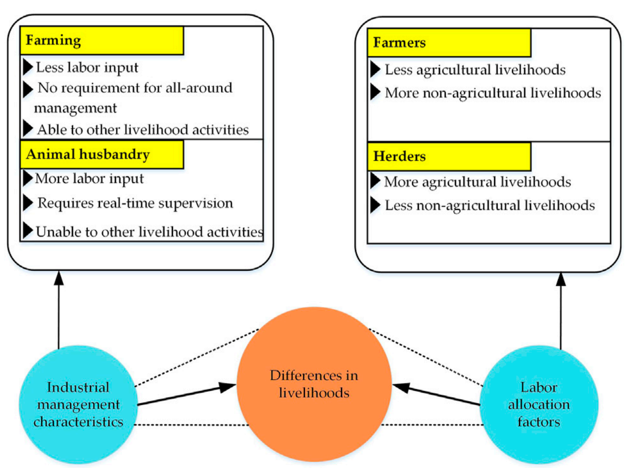

FIGURE 7 | Driving factors of the differences in the livelihoods of farmers and herders.

The livelihood activity of herders is single-dimensional, and more vulnerable than that of farmers under drought. With the continuation of drought, the animal husbandry seriously declined, with the incomes the herders got barely covered their cost in 2016. This makes the livelihoods of herders fragile and unadaptable under drought. Furthermore, herders took out loans to maintain animal husbandry activities during the drought years. According to our survey, the average loan of a herder family was about 46,700 yuan and 54,500 yuan in 2016 in Wuriduhubu and Haolibao, respectively. Hence, it is impossible to compensate for the losses suffered in animal husbandry without other livelihood activities.

4 DISCUSSION

4.1 Causes of the Differences in the Livelihoods of Farmers and Herders Induced by Drought

Farming is less time-consuming than that of animal husbandry (**Figure 7**). For instance, according to our survey, one ha of corn costs no more than 150 working days (plowing, sowing, weeding, and harvesting) in the two farmer villages. The time-consuming of millet and mung bean is less than that of corn. Therefore, farmers can engage in other livelihood activities besides farming (Liu et al., 2017; Liu and Li, 2017). The income from non-agricultural sectors is higher than that of agricultural ones, which incentivizes rural labor force to emigrate to non-agricultural sectors. Hence, the livelihoods of farmers are still diverse even they abandon rain-fed farming under drought.

The major reason that herders are tied to grassland and unable to engage in other livelihood activities is that full-time monitoring is required by animal husbandry. Herders have to spend about six months for grazing. During the rest six months of captivity time, herders also spend about 6 h each day to feeding sheep and cattle. Moreover, grassland is the most important land resource for herders. These make herders hardly engage in other livelihood activities. Besides, most herders in AHB speak Mongolian, which makes it hard for them to engage in non-agricultural sectors dominated by those speaking mandarin. Hence, herders hardly engage in non-agricultural sectors, and the instability of their livelihoods is greatly increased by drought.

4.2 Policy Implications

The income of non-agricultural employment is much higher than agricultural income, which is important for farmers in resisting drought (Long et al., 2016). Hence, encouraging the labor force to emigrate to non-agricultural sectors is an effective way to improve their livelihoods (Liu et al., 2014; Ma and Yang, 2018). Income from rain-fed farming accounts for a very small percentage of their total income; therefore, it is suggested that farmers abandon rain-fed cultivation. By doing this, more labor force can engage in other livelihoods. Additionally, the human disturbance to land will be alleviated, which is a foundational premise for restoring and reconstructing a stable ecosystem in the agro-pastoral ecotone (Liu et al., 2018; Yang and Xu, 2018). Moreover, government should provide funding to establish the water-saving irrigation system to improve irrigated farming.

The livelihoods of herders are highly dependent on animal husbandry, which is vulnerable and unstable under drought. Hence, maintaining the quality of grassland is important for them. To achieve this, herders need to develop artificial pastures for a more stable animal husbandry, government should also build a forage reserve system to prevent the impact of a forage shortage. It is also critical for herder to improve livelihood by developing non-agricultural ones, such as animal products processing industry. The artificial pasture cultivation and animal products processing training system should be provided by government. Government's support for herders to diversify their livelihoods is essential to maintaining livelihood security under drought.

4.3 Deficiencies and Prospects

The agro-pastoral ecotone in northwestern China is an area with frequent drought, and relative poverty of its rural residents. The rural revitalization strategy is being implemented by the Chinese government, which aims to eliminate poverty and achieve common prosperity. The difficult of the strategy is to improve livelihoods of rural residents in this area. Scholars have discussed the livelihoods and land use in this area under drought. For farmers, scholars paid more attention to the stability of livelihoods, the pattern of land use and the type of crop planting, pointing out that farmers with diversified livelihoods have stronger adaptability by returning farmland to forest, adopting water-saving irrigation measures and planting forage crops [7,13,18]. As for herders, scholars indicated that the livelihoods of herders were vulnerable, and they could adapt to drought by building canals [22]. Additionally, herders would give up grasslands under drought [31,42]. However, the study of putting both farmers and herders into a research framework to find out their differences is relatively rare. Hence, the focus of future research is to study the differences in land use and livelihoods of farmers and herders and the driving factors under natural disasters and human activities, and then put forward recommendations to improve the accuracy of rural revitalization strategy policies.

Two farmer villages and two herder villages were investigated in this paper, and the sample size was small to represent the whole agro-pastoral ecotone. Additionally, in order to make a comparison between 2012 and 2016, the quantity of livestock, the area of cultivated land and the price of agricultural products in these two years are also assumed to be the same (take 2016 as the standard), which results in the deficiency of the results. The sample size should be expanded by solid investigation and data analysis to improve the accuracy of the study.

5 CONCLUSION

We took two farmer villages, Pingandi and Fenghuangling, and two herder villages, Wuriduhubu and Haolibao, located in Ar Horqin Banner of north-western China, to analyze the responses of land-use changes to drought and its disparate impact on the livelihoods of farmers and herders. Results showed that, rain-fed land was abandoned by farmers, while grassland was abandoned by herders under drought conditions. Farmers would abandon rain-fed farming, and herders only retained cattle rearing. The losses in livelihood incomes of herders were greater than those of farmers. The results of our analysis clearly demonstrate that the livelihoods of farmers are more stable than those of herders under drought, with livelihood diversification is the key influencing factor.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, BZ; methodology, YL and YQ; software, RM; investigation, JZ; writing—original draft preparation, BZ; writing—review and editing, RM and GJ. All authors have read and agreed to the published version of the manuscript.

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Coupling Coordination Analysis of Natural Resource Utilization Benefits in Beijing From 1978 to 2018

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With the acceleration of economic and social development, the demand for natural resources has increased. To realize the sustainable utilization of natural resources (SUNRs), it is necessary to seek ways to improve natural resource utilization benefits (NRUBs) and promote the coordinated development of economic, social, and ecological benefits. This study explores the coupling coordination relationships of NRUBs in Beijing from 1978 to 2018 and analyzes the influencing factors. We first establish a comprehensive evaluation index system covering economic, social, and ecological benefits to quantify NRUBs. Then, a coupling coordination degree (CCD) model is applied to reveal the evolution characteristics of the coupling coordination relationships among the NRUB system. Finally, the main factors affecting the coordinated development of NRUBs are identified through gray relational analysis (GRA). Three main results are found: 1) from 1978 to 2018, the economic, social, ecological, and comprehensive benefits all have been significantly improved, although with some fluctuations. 2) The coupling coordination relationships of NRUBs show upward trends during the study period, and their coordination types transform from imbalance to coordination. 3) Urbanization, industrial structure, technology innovation, economic development, and environmental awareness all have significant impacts on the coupling coordination relationships of NRUBs. Measures such as transformation of the economic development mode, improvement of public facilities, construction of spiritual culture, ecological protection, and technological innovation need to be recognized to achieve coordinated development. This study can provide a reference for other comprehensive evaluations of natural resources and the formulation of natural resource utilization policies.

Keywords: natural resource utilization benefits, coupling coordination relationship, influencing factors, evolution characteristics, Beijing

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1 INTRODUCTION

Natural resources refer to the material and energy that can be used by human beings in nature, which cover both aboveground and underground, including land, mineral, water, forest, grassland, wetland, and marine resources (Zhang et al., 2021), which are closely related to human survival and development. However, the rapid population and economic growth has put tremendous pressure on resources and the environment (Wolman, 2011; Chen et al., 2020). In the last 50 years, the global population has increased from 3.7 billion in 1970 to 7.8 billion in 2021 (UNFPA, 2021), whereas natural resources continue to be consumed and wasted, leading to the over-exploitation and utilization of natural resources (Liu et al., 2020). The irrational use of resources not only destroys the environment but also threatens the sustainable development of human society (Shafiei and Salim, 2014; Merino-Saum et al., 2018). To save resources and protect the environment, it is necessary to realize the sustainable utilization of natural resources (SUNRs) and improve natural resource utilization benefits (NRUBs) (Roozbahani et al., 2015; Su and Jiang, 2021). In 2015, the United Nations (UN) devised the 2030 Agenda for Sustainable Development, which includes 17 sustainable development goals (SDGs) (Colglazier, 2015). Among them, 12 goals are relevant to SUNRs, and 10 goals can only be achieved by substantially increasing NRUBs (Huang, 2020). Thus, the utilization benefits of natural resources are an important issue related to human development.

Since the reform and opening-up in China, the processes of industrialization and urbanization have accelerated (Xu et al., 2019). The development for 40 years has made China the world's no.2 economy, with the largest population. Although the total amount of natural resources is abundant, a big gap still exists between the per capita resources and the world average. The key to achieving high-quality development is to optimize the way of resource utilization and improve efficiency (Miao et al., 2017). The strategy of ecological civilization construction, put forward at the 18th National Congress of the Communist Party of China (CPC) in 2012, was proposed to save resources, protect the environment, and realize the unity of economic, social, and ecological benefits (Du et al., 2021). In 2020, the Proposal on Formulating the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Goals of 2035 further emphasized improving NRUBs. Due to the inevitable pressure on resources and the environment and the realistic demand for sustainable development, the coordinated development of economic, social, and ecological benefits of natural resources has been regarded as an effective method to save resources (Hansmann et al., 2012; Li et al., 2020). Therefore, exploring the coupling coordination relationships between economic, social, and ecological benefits is helpful to formulate resource utilization policies and achieve the goal of sustainability.

A more efficient way of resource utility is deemed an important step to conserve resources, reduce climate change, and preserve ecological assets (Huysman et al., 2015). In this context, there is a rich body of literature assessing the NRUBs and seeking measures to improve the benefits. The evaluation framework usually takes into account the link between resource utilization and other relevant aspects, including the socioeconomic system, environmental impact, self-supply, and nature conservation (Huysman et al., 2015; Eisenmenger et al., 2016; Noda et al., 2019). In addition to the impacts on regional socioeconomy and environment, many recent studies have shown that natural resource utilization is related to key issues such as economic globalization, ecological footprint, and carbon neutrality (Adebayo et al., 2022; Awosusi et al., 2022; Miao et al., 2022). In terms of measures to improve NRUBs, natural resource balance sheet compilation (Chen et al., 2022), green technology innovation (Miao et al., 2017), and clean energy input (Han et al., 2020) are effective methods. Most of the studies regard NRUBs as a whole and explore the connection with other systems. Some scholars also pay attention to the relationships of the internal economic, social, and ecological subsystems, and the importance of their coordinated development. For instance, Ma and Wen (2021) developed a fuzzy multi-objective linear programming (FMLP) to determine an optimal land use structure considering the relationships of social, economic, and ecological benefits of land. Schratzberger et al. (2019) identified the interactions between and within ecological and socioeconomic benefits of highly protected marine areas (HPMAs) to help marine planners and managers make informed decisions. Laing and Moonsammy (2021) argued that the economic benefit of small-scale mining in Guyana should be weighed against social and ecological benefits to achieve sustainable development. Consequently, the relationships and interactions among economic, social, and ecological benefits need to be studied to explore the optimal resource utilization mode. Recently, researchers have carried out much work on the coordination evaluation (Ye and Qiu, 2021), spatiotemporal variation (Huang et al., 2016; Yuan et al., 2019; Chen et al., 2021), and influencing factors (Yu et al., 2019) among the utilization benefits of different resources. Ji et al. (2020) revealed that the coupling degree of Xiamen City's land use was relatively low while showing a positive trend of development. Tian et al. (2019) proved that the lag of economic benefit was the main reason that restricted the improvement of coupling coordination of land use benefit. However, previous studies mainly focused on the benefits of individual resources, which were insufficient in the comprehensive utilization of natural resources, with a few research studies on water and land resources (Wang and Shi, 2013). In addition, the existing works of literature only studied the coupling relationships between economic, social, and ecological benefits or pair-wise benefits, and the analysis of the shortcomings and factors that affect the coordinated development of the overall benefits is limited. Therefore, this study attempts to explore the coupling coordination relationships between economic–social, economic–ecological, social–ecological, and economic–social–ecological benefits of natural resources through a coupling coordination degree (CCD) model and analyze the influencing factors.

In 2018, China's Ministry of Natural Resources was established to exercise unified functions in the utilization and management of natural resources. In the context of unified management of natural resources, it is necessary to explore NRUBs and their coupling coordination relationships to improve the sustainability of natural resources. Selecting Beijing as the research area, the objectives of this study include the following three parts: 1) constructing an evaluation index system and model of NRUBs from the aspects of economy, society, and ecology; 2) developing a CCD model and analyzing the evolution rules of coupling coordination relationships between economic, social, and ecological benefits from 1978 to 2018; and 3) determining the main influencing factors of the

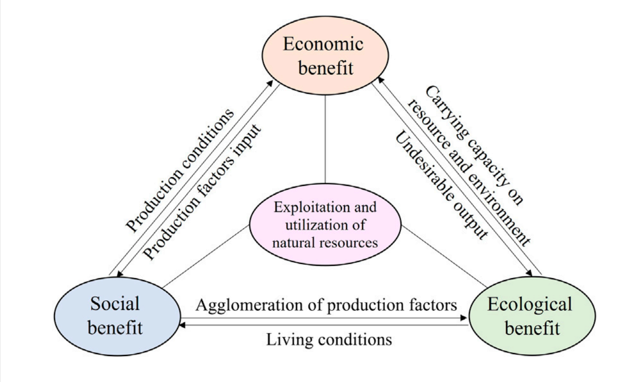

FIGURE 1 | Interaction among economic, social, and ecological benefits.

coordination state of economic, social, and ecological benefits by applying gray relational analysis (GRA) and putting forward corresponding suggestions. This study can provide a reference for the evaluation of NRUBs to promote the sustainable utilization and management of natural resources.

The rest of this study is organized as follows. **Section 2** explains the connotation and interaction of NRUBs. **Section 3** introduces the research framework, study area, and materials and methods. **Section 4** shows the results, including evolution patterns of NRUBs, the CCD of NRUBs and coordination types, and the relational coefficients of the main influencing factors. **Section 5** presents the analyses and discussions based on the results. The main conclusions are summarized in **Section 6**.

2 THEORETICAL BASIS

2.1 Connotation of Natural Resource Utilization Benefits

NRUBs are formed by the interaction between humans and natural resources. As the subjects of natural resource utility, humans have different needs in basic life, economic development, spiritual culture, and environmental protection. As the objects, natural resources have natural, economic, social, and ecological attributes, and rational exploitation and utilization can satisfy the diverse needs of human beings. As a result, humans purposefully invest capital, technology, and labor to use resources to obtain products and services. Therefore, NRUBs can be defined as the general terms of various useful achievements to nature or human development produced in the process of natural resource utilization in a certain region.

NRUBs have significant temporal variation characteristics, which are manifested in two aspects. The process of natural resources from exploitation and utilization to providing products and services to humans will go through a period of time, and the form and size of its benefits will change constantly. Moreover, there are differences in human needs at different stages of social development, leading to changes in the goals of resource exploitation, and changes in NRUBs. Hence, the dynamic monitoring and evaluation of NRUBs is to some extent a reflection of the changes in the social and economic development of the region.

2.2 Interaction Within Natural Resource Utilization Benefits

The economic, social, and ecological benefits are three subsystems of the NRUB system (de Groot et al., 2002; Duguma and Hager, 2011), and they have mutual influences (Liang et al., 2008), as shown in **Figure 1**. Humans exploit and use natural resources based on their own needs to acquire economic benefits and put the economic benefits into public services and infrastructure construction to obtain social benefits (Tian et al., 2019). In this process, if the resource utilization mode is reasonable and within the carrying capacity of resources and the environment, significant economic and social benefits can be achieved continuously. If undesirable outputs such as environmental pollution and ecological damage are caused by the restriction of capital or technology, the ecological benefits will be affected. Improvement of social benefits promotes the agglomeration of production factors to improve the environmental quality and production conditions (Hu et al., 2020). The increase in ecological benefits has a positive effect on the social benefits by improving living conditions and also creates favorable resource and environmental conditions for economic development.

3 METHODS AND MATERIALS

3.1 Research Framework

Based on the dynamic characteristics of NRUBs and the interrelationship between economic, social, and ecological benefits, this study examines the coordination relationships in the NRUB system in Beijing from 1978 to 2018 and analyzes the influencing factors. First, we establish an evaluation index system, including economic, social, and ecological benefits. Second, we analyze the evolution characteristics of the NRUBs. Third, we use a CCD model to examine the changing features of the coordinated development within the NRUB system. Finally, we identify the main influencing factors of the coordination relationships in the NRUB system and put forward policy implications for sustainable utilization of natural resources. The research framework is shown in **Figure 2**.

3.2 Study Area

This study is conducted in Beijing, which is a megacity and the capital of China (**Figure 3**). Beijing lies in the central hinterland of North China and extends from 115.7°E to 117.4°E and 39.4°N to 41.6°N. The total area is 16,410.54 km^2, with mountainous areas and plains accounting for 62 and 38%, respectively. As the political and cultural center of China and the economic center of Northern China, Beijing has experienced rapid urbanization and industrialization since the reform and opening-up (Sun et al., 2014; Hao et al., 2020). According to the statistical yearbook of Beijing, the gross domestic product (GDP) increased from 10.9 billion CNY in 1978 to 3,310.6 billion CNY in 2018, and the

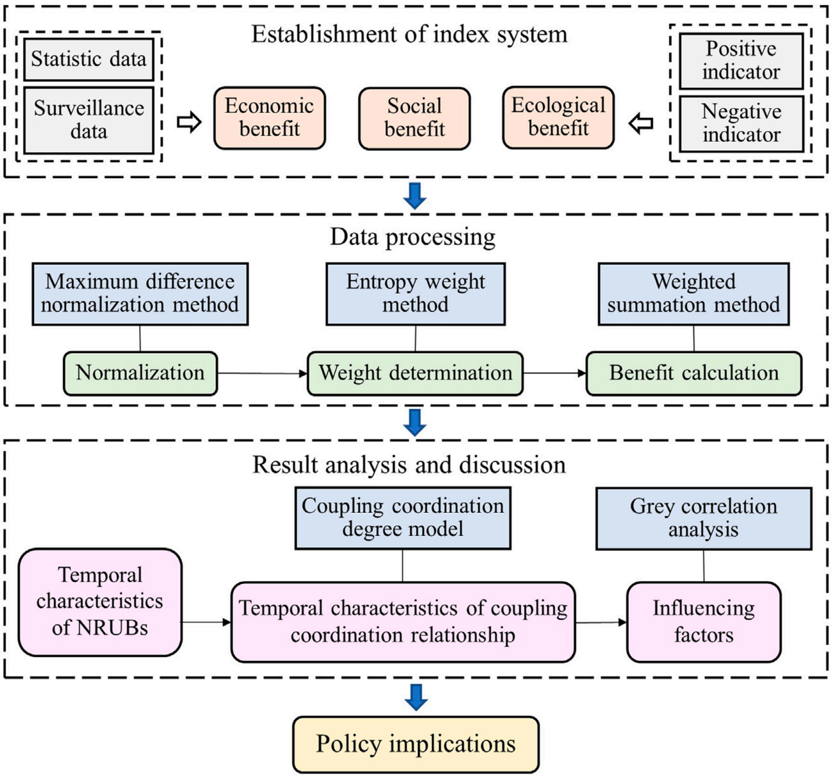

FIGURE 2 | Research framework.

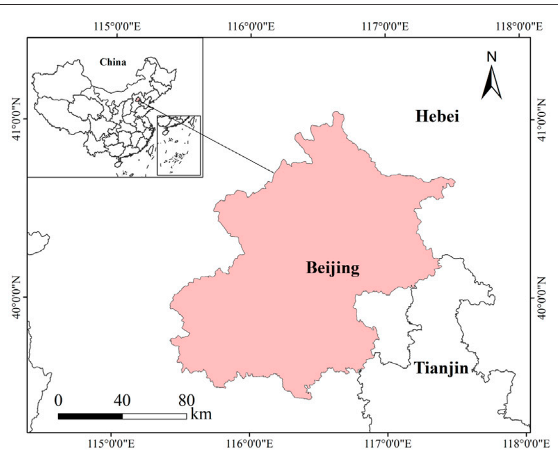

FIGURE 3 | Study area.

population increased from 8.7 million in 1978 to 21.5 million in 2018. In 2018, it achieved about 3.60% of China's GDP and supported 1.54% of the country's population, with only 0.17% of land resources and 0.13% of water resources. Economic development and population growth have put significant pressure on resources and the environment. In turn, resource shortage, inefficient resource utilization, and environmental pollution will restrict the sustainable development of economy and society. Consequently, it is vital to increase NRUBs and seek ways to promote the coordinated development of economic, social, and ecological benefits in Beijing.

3.3 Data Source and Pre-Processing

This study takes Beijing as the evaluation unit and studies the evolution characteristics of NRUBs and their coupling coordination relationships from 1978 to 2018 yearly. The data are mostly obtained from the Beijing Statistical Yearbook (1980–2020) and China Population and Employment Statistics Yearbook (1988–2019). We refer to the latest version of economic data, which has been revised officially so that the data from different years are comparable. In addition, some indicators were not counted in 1978; for instance, energy consumption per 10,000 CNY of GDP and forest virescence ratio were first counted in 1980, and indicators related to water resources started in 1988. Therefore, trend line fitting is used to supplement the lacking data. The coefficients of determination (R^2) are all greater than 0.9, indicating that the fitting is accurate. The data on natural reserves are from the official website of the Beijing Municipal Ecology and Environment Bureau (https://sthjj.beijing.gov.cn/).

The index system contains both positive and negative indicators. To eliminate the influence of magnitude and measurement, the maximum difference normalization method is adopted, whose formula is as follows:

TABLE 1 | Index system for assessing NRUBs.

Criteria layer	Indicator layer	Unit	Property	Weight
Economic benefit	I_1 GDP per unit area	10^4 CNY/km^2	+	0.303
	I_2 Financial revenue per unit area	10^4 CNY/km^2	+	0.360
	I_3 Gross output value of agriculture per unit area	10^4 CNY/ha	+	0.205
	I_4 Energy consumption per unit of GDP	ton of SCE/10^4 CNY	–	0.076
	I_5 Water consumption per unit of GDP	m^3/10^4 CNY	–	0.056
Social benefit	I_6 Population density	person/km^2	+	0.314
	I_7 Road network density	km/km^2	+	0.271
	I_8 Per capita daily domestic water consumption	m^3	–	0.172
	I_9 Per capita housing area	m^2	+	0.243
Ecological benefit	I_{10} Forest virescence ratio	%	+	0.259
	I_{11} Consumption of chemical fertilizer per unit area	ton/ha	–	0.214
	I_{12} Sewage treatment rate	%	+	0.263
	I_{13} Proportion of natural reserve area	%	+	0.264

Note: "+" and "–" represent the positive and negative indicators, respectively.

$$\text{Positive indicators}: x'_{ij} = \frac{x_{ij} - x_{\min j}}{x_{\max j} - x_{\min j}},$$

$$\text{Negative indicators}: x'_{ij} = \frac{x_{\max j} - x_{ij}}{x_{\max j} - x_{\min j}},$$

where x_{ij} refers to the original value of indicator *j* in year *i*; $x'_{ij}$is the normalized value; and $x_{\min j}$ and $x_{\max j}$ represent the minimum and maximum values of indicator *j*, respectively.

3.4 Methods

3.4.1 Index System

The key to analyzing the benefit is to select appropriate indicators and construct a comprehensive evaluation index system. The indicators are almost acquired from previous studies (Liang et al., 2008; Huang et al., 2016; Xia et al., 2018). A total of 13 indicators (I_1–I_{13}) are selected to construct the index system (**Table 1**). The selection follows the principles of availability, typicality, and scientificity, combined with the actual situation in Beijing.

Economic benefit refers to the ratio of the product or service obtained to the costs such as labor, capital, and the amount of resources. Five indicators are selected to represent the economic benefit, namely, GDP per unit area, financial revenue per unit area, gross output value of agriculture per unit area, energy consumption per unit of GDP, and water consumption per unit of GDP. GDP per unit area (I_1) and gross output value of agriculture per unit area (I_3) directly measure the output value of unit natural resources, while financial revenue per unit area (I_2) represents the indirect earnings brought by resource utilization. Energy consumption per unit of GDP (I_4) and water consumption per unit of GDP (I_5) reflect the economic output capacity and intensive utilization of natural resources.

Social benefit is the satisfaction of social needs after utilizing natural resources, which is related to people's livelihood and social sustainable development. Population density, road network density, per capita daily domestic water consumption, and per capita housing area are chosen to quantify the social benefit. Here, population density (I_6) is regarded as a positive indicator from the perspective of resource utilization efficiency, indicating that land is capable of carrying more people. Road network density (I_7) and per capita housing area (I_9) reflect the living convenience and comfort of residents. Per capita daily domestic water consumption (I_8) is a negative indicator, representing the ability to save natural resources in daily life.

Ecological benefit refers to the impacts on the eco-environment, which is represented by the forest virescence ratio, consumption of chemical fertilizer per unit area, sewage treatment rate, and proportion of natural reserve area. The forest virescence ratio (I_{10}) is similar to the forest coverage rate, reflecting the greening situation of the region. The utilization of natural resources will lead to some adverse environmental consequences, which are measured by the consumption of chemical fertilizer per unit area (I_{11}) and sewage treatment rate (I_{12}). The proportion of natural reserve area (I_{13}) is chosen to represent the conservation of the environment and ecology.

3.4.2 Entropy Weight Method

This study applies the entropy weight method (EWM) to determine the weight of each indicator. The EWM determines the weight according to the degree of dispersion of data and avoids the subjective influence of the evaluator (Liu et al., 2018). Three equations are used and the formulas are shown as follows:

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}},$$

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij},$$

$$w_j = \frac{1 - e_j}{m - \sum_{j=1}^{m} e_j},$$

where x'_{ij}refers to the normalized value of indicator *j* in year *i*; p_{ij} is the proportion of x'_{ij}in the sum of the normalized values of the indicator; e_j is the information entropy of indicator *j*; and w_j refers to the weight of indicator *j*.

The economic, social, and ecological benefits are regarded as equally important subsystems. Therefore, the sum of weights of each subsystem is 1, and the values of each benefit range from 0 to 1. Then, the weighted summation method (Xu et al., 2020) is used to calculate the values of economic, social, ecological, and comprehensive benefits.

TABLE 2 | Coordination types.

Coupling coordination degree D	Type
D∊[0,0.2]	Serious imbalance
D∊(0.2,0.4]	Moderate imbalance
D∊(0.4,0.6]	Basic coordination
D∊(0.6,0.8]	Moderate coordination
D∊(0.8,1]	Good coordination

3.4.3 Coupling Coordination Degree Model

Originating from physical science, coupling refers to the relationships between different systems that affect each other through various interactions (Huang and Fang, 2003), and has been applied in environmental studies (Guo et al., 2015). Based on the coupling theory, a CCD model is developed to analyze the relationships between economy, society, and environment (Cheng et al., 2019; Li and Yi, 2020); economy, resources, and environment (Xing et al., 2019; Han et al., 2021); urbanization and eco-environment (Ma et al., 2021; Yang C. et al., 2020); urbanization and natural resource benefits (Tong et al., 2020; Wang et al., 2020); etc. Given that there is a coupling relationship among the economic, social, and ecological benefits of natural resource utilization, the CCD model is suitable to explore the coupling coordination relationships among NRUBs.

We analyze the coupling coordination relationships among both two pairs of the three subsystems (Yang Y. et al., 2020) and the three subsystems (Han et al., 2021). The formulas for calculating the coupling coordination degrees of the pair-wise benefits are as follows:

$$C_{12} = 2 \times \left[\frac{B_1 \times B_2}{(B_1 + B_2)^2} \right]^{\frac{1}{2}},$$

$$C_{13} = 2 \times \left[\frac{B_1 \times B_3}{(B_1 + B_3)^2} \right]^{\frac{1}{2}},$$

$$C_{23} = 2 \times \left[\frac{B_2 \times B_3}{(B_2 + B_3)^2} \right]^{\frac{1}{2}},$$

$$T_{12} = \alpha B_1 + \beta B_2,$$

$$T_{13} = \alpha B_1 + \gamma B_3,$$

$$T_{23} = \beta B_2 + \gamma B_3,$$

$$D = \sqrt{C \times T},$$

where B_1, B_2, and B_3 represent the values of economic, social, and ecological benefits, respectively; C_{12}, C_{13}, and C_{23} are the coupling degrees of economic–social, economic–ecological, and social–ecological benefits, respectively; T_{12}, T_{13}, and T_{23} refer to the development index of economic–social, economic–ecological, and social–ecological benefits, respectively; α, β, γ are the contribution coefficients of each benefit; and $\alpha + \beta = 1, \alpha + \gamma = 1, \beta + \gamma = 1$. This study assumes that the economic, social, and ecological benefits are of equal importance; therefore, $\alpha = \beta = \gamma = 1/2$. D is the coupling coordination degree.

For the coupling coordination degree in three subsystems, the calculation methods of C and T have slight differences, as follows:

$$C = 3 \times \left[\frac{B_1 \times B_2 \times B_3}{(B_1 + B_2 + B_3)} \right]^{\frac{1}{3}},$$

$$T = \delta B_1 + \varepsilon B_2 + \mu B_3,$$

where C and T represent the coupling degree and development index of economic–social–ecological benefits, respectively; δ, ε, μ are the contribution coefficients; and $\delta = \varepsilon = \mu = 1/3$.

After the calculation of the coupling coordination degree, it is usually divided into several coordination types subjectively, as shown in **Table 2**. The higher the D value, the better the coupling coordination relationship (Yang Y. et al., 2020).

3.4.4 Gray Relational Analysis

GRA is a method to measure the correlation degree between two factors according to the similarity of their developing trends and is widely applied in the quantitative analysis of dynamic systems (Guo, 2021). To ensure the dependence of indicators, factors affecting the coupling coordination relationships of NRUBs are selected based on previous literature (Yu et al., 2019; Zhu and Sun, 2019), including economic development (F_1), industrial structure (F_2), urbanization (F_3), environmental awareness (F_4), and technological innovation (F_5). Per capita GDP, proportion of the tertiary industry, proportion of urban population, education level, and number of granted patents are calculated to characterize these factors, as shown in **Table 3**.

Then, the relational coefficients between the CCD and the factors are calculated through the GRA. The larger coefficient reflects the greater influence. The formulas are as follows:

$$\xi_{kl}(t) = \frac{\min_k \min_l |Z_k(t) - F_l(t)| + \rho \max_k \max_l |Z_k(t) - F_l(t)|}{|Z_k(t) - F_l(t)| + \rho \max_k \max_l |Z_k(t) - F_l(t)|},$$

$$\xi_{kl} = \frac{1}{n} \sum_{t=1}^{n} \xi_{kl}(t),$$

where $\xi_{kl}(t)$ is the relational coefficient between the CCD and a factor in year t; $Z_k(t)$ and $F_l(t)$ represent the normalized values of the CCD and influencing factors, respectively; ρ is the identification coefficient, which is normally set to 0.5; and ξ_{kl} is the overall relational coefficient.

4 RESULTS

4.1 Evolution Patterns of Natural Resource Utilization Benefits

Based on the evaluation index system, the values of economic, social, ecological, and comprehensive benefits of natural resource utilization

TABLE 3 | Factors affecting the coupling coordination relationships of NRUBs and indicators.

Factor	Indicator
F_1 Economic development	Per capital GDP
F_2 Industrial structure	Proportion of tertiary industry
F_3 Urbanization	Proportion of urban population
F_4 Environmental awareness	Education level
F_5 Technological innovation	Number of granted patents

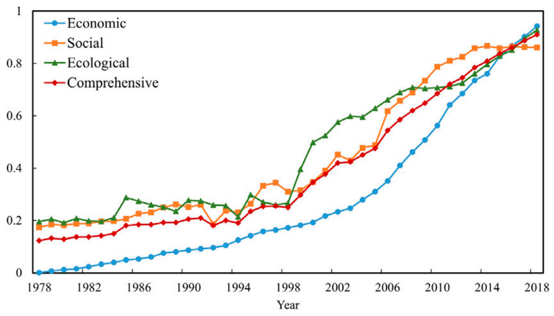

FIGURE 4 | Changing curves for the values of NRUBs.

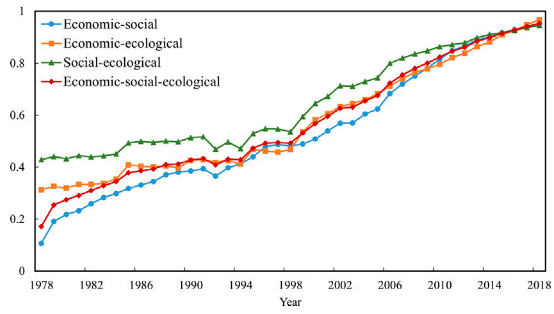

FIGURE 5 | Evolution curves of coupling coordination degrees of NRUBs.

and their evolution trends are shown in **Figure 4**. From 1978 to 2018, all the benefits significantly improved, with some fluctuations. The economic benefit shows a trend of steady growth, although it is the lowest for most of the study period. From 1978 to 2000, the economic value is low and grew slowly, with its value rising from 0.001 in 1978 to 0.193 in 2000. Since the 21st century, it increased rapidly and surpassed social and ecological benefits in 2016. The changing trend of the social benefit increases slightly at the beginning of the study period. During the 1991–2006 period, the social benefit increases with fluctuations, which decreases in 1992, 1998, and 2003 and increases in 2006 noticeably. Since 2006, it displays a steady upward trend and tended to be stable, maintaining at about 0.86 after 2013. The overall trend of the ecological benefit can be described as fluctuating growth. In the first 30 years of the study period, the value of the ecological benefit was almost the highest. Except for notable increases in 1985, 1995, 1999, 2000, and the last 6 years, the changes in the ecological benefit in other years are relatively insignificant. The comprehensive benefit, comprising the economic, social, and ecological benefits, showed an evolution trend of rising from 1978 to 2018, and the growth rate gradually accelerates. There are also several slight fluctuations in the curve, due to the changes in the social and ecological benefits; however, the upward trend is steady on the whole.

4.2 Coupling Coordination Degree of Natural Resource Utilization Benefits and Coordination Types

The coupling coordination relationships among the economic, social, and ecological benefits of natural resource utilization are analyzed according to the CCD model. The evolution characteristics of the coupling coordination degrees and the coordination types are shown in **Figures 5**, **6**, respectively. It can be noted that the coupling coordination degrees of the ecological–social, economic–ecological, social–ecological, and economic–social–ecological benefits all have upward trends during the study period, although with some fluctuations.

Specifically, the coupling coordination relationship of the economic–social benefits displays an upward trend overall, while the degree is relatively low at the beginning of the study period. From 1978 to 1993, the coordination relationship stays at the stage of imbalance, and the degree reaches 0.6 in 1994. After reaching the basic coordination, the coordination relationship of economic–social benefits improves steadily and achieves good coordination in 2010. The overall evolution trend of the coupling coordination relationship between the economic and ecological benefits can be described as steady growth. During the first half of the study period, the coupling coordination degree rises slowly in the fluctuations, with the coordination type changing from moderate imbalance to basic coordination, except for a slight degradation in 1989. Afterward, the coordination degree rises continuously and reaches the stage of moderate-good coordination. For the social–ecological benefits, the coupling coordination relationship reaches the stage of basic coordination at the beginning of the study period, but it improves slowly over a long time. The degree rises from 0.429 in 1978 to 0.536 in 1998 with fluctuations. In the second half of the study period, the evolution curve shows a steady upward trend, with the coordination type reaching the best level in 2007. The changing trend of the coupling coordination relationship among economic–social–ecological benefits combines the evolution characteristics of the relationships of the pair-wise benefits. At the beginning stage, the coordination degree is relatively low, and the coordination type remains at a serious–moderate imbalance for 10 years. During the 1992–2003 period, the degree rises with slight fluctuations. After 2003, the coordination degree is significantly enhanced, and the coordination type reaches a state of good coordination in 2009.

4.3 Relational Coefficients of Influencing Factors

From **Table 4**, we can note that the relational coefficients of the five influencing factors are all more than 0.8, indicating that they have significant impacts on the coordinated development of NRUBs. Among them, the coefficients of F_3, F_2, and F_5 exceed 0.9, and the values are 0.996, 0.982, and 0.977, respectively. The coefficients of F_1 and F_4 are 0.854 and 0.845, respectively, which are slightly less correlated than F_3, F_2, and F_5.

5 DISCUSSION

5.1 Reasons for the Changes in Economic, Social, and Ecological Benefits

As can be seen from **Figure 2**, the economic benefit of natural resource utilization is the lowest for most of the study period,

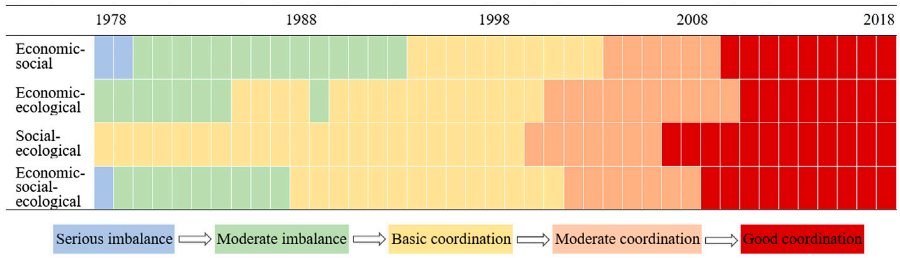

FIGURE 6 | Coupling coordination types of NRUBs from 1978 to 2018.

TABLE 4 | Correlation coefficients of influencing factors.

Factor	Coefficient	Rank
F_3 Urbanization	0.996	1
F_2 Industrial structure	0.982	2
F_5 Technological innovation	0.977	3
F_1 Economic development	0.854	4
F_4 Environmental awareness	0.845	5

indicating that economic factors are the key to the overall improvement of the benefit. The evolution trend of the economic benefit displays an "exponential" curve, with the value rising slowly at the beginning of the study period and then rapidly. This is because China's economy was in its infancy at the early stage of the reform and opening-up, and the resource utilization efficiency was low. For example, GDP per unit area (I_1) in 1978, 1998, and 2018 was 64.73, 1,451.17, and 20,173.62 10^4 CNY/km^2, respectively. The average annual increase in the first and second 20 years was 69.32 and 936.12 10^4 CNY/km^2, respectively, showing that the growing speed of the economy has accelerated. In addition, with the innovation of technology, the amount of resources consumed in production has also been reduced; thus, the degree of intensive resource utilization is significantly improved (Miao et al., 2017; Ding et al., 2019).

In terms of social benefit, the evolution curve displays an upward trend with fluctuations and tends to be stable after 2013. Economic development is regarded as the core of China's reform and development, which has been of significant importance for a long time, with the needs and interests of people being ignored. Therefore, the social benefit of natural resource utilization grows slowly for the first 20 years. It even bottoms out in 1992. Since the 21st century, with the proposal of the Scientific Outlook on Development, increasing attention has been paid to people's needs (Li, 2007). A large number of houses and roads have been constructed to meet the needs of the growing population, leading to the rapid rise of social benefits. Entering the new era of socialism after 2012, the demand for a better life has gradually replaced the demand for materials (Li, 2018). Therefore, the social benefit has changed little in recent years, and further improvement can only be achieved by meeting people's spiritual needs.

For the changing curve of ecological benefit, the fluctuating duration is long and the degree is relatively great. At the beginning of the study period, the value of the ecological benefit is higher than that of economic and social benefits, mainly due to the backward development level, with a low degree of resource exploitation and environmental damage. As the economy and society develop, the exploitation and utilization of natural resources have expanded, whereas the ecological benefit has not achieved enough attention. Therefore, the ecological benefit fluctuates heavily, with its value in 1998 only rising by 0.055 compared with 1978. There is an evident increase in the ecological benefit from 1998 to 2000, mainly due to the fact that 12 natural reserves were set up in the 2 years, leading to the rise in the proportion of natural reserve areas (I_{13}). Since the beginning of the construction of ecological civilization strategy in 2012, the local government has paid more attention to environmental protection; hence, the ecological benefit starts to increase again after 4 years of leveling off.

5.2 Coordinated Development Stage Division of Natural Resource Utilization Benefits

The coupling coordination relationships among economic, social, and ecological benefits of natural resource utilization can be divided into three stages: slow increase (1978–1991), fluctuating growth (1992–2003), and steady improvement (2004–2018).

1) 1978–1991: Initially, the coupling coordination relationship of economic–social–ecological benefits is low, but it improves in the following years, especially in 1979. In this stage, the changing characteristics of the coordination relationship among the three benefits are similar to those of economic–social benefits, while the variations of the coupling coordination relationships of economic–ecological and social–ecological benefits are slight. This is due to the fact that the ecological benefit is maintained at a high level, and the development level of the economy and society is low. With the slow growth of economic and social benefits, the coupling coordination degree has gradually increased.
2) 1992–2003: In this stage, the coupling coordination relationships of economic, social, and ecological benefits and pair-wise benefits all present the characteristics of

volatility. The changing trend of the coupling coordination relationship of economic–social–ecological benefits is most similar to that of social–ecological benefits. This is because the social and ecological benefits fluctuate heavily, while the economic benefit grows steadily. During this period, the economic development significantly influences the society and ecology, indicating that efforts are made to develop the economy and insufficient attention is paid to social development and ecological protection, which is consistent with the hypothesis of the environmental Kuznets curve (Grossman and Krueger, 1995).

3) 2004–2018: The coupling coordination relationships in the NRUB system increase steadily and all reach the level of moderate–good coordination in this period. China has gradually achieved sound and rapid economic development since the 21st century. Additionally, under the guidance of policies such as the Scientific Outlook on Development and Construction of Ecological Civilization, economic development can improve the society and environment through the adjustment of industrial structures and technology upgrading (Xue et al., 2014; Xing et al., 2019), and social and ecological benefits have simultaneously been improved. Subsequently, the coupling coordination relationships of economic–social–ecological benefits and pair-wise benefits enhance rapidly.

5.3 Influencing Factors and Policy Implications

Through the deep analysis of the changes in NRUBs and the coordination relationships, it can be noted that NRUBs are closely related to national policy and region development strategy. Therefore, it is necessary to objectively identify the problems existing in the current benefits and adjust the resource utilization policies to realize the sustainable utilization of natural resources.

Urbanization, industrial structure, technology innovation, economic development, and environmental awareness have noticeable influences on the coupling coordination relationships of NRUBs, as shown in **Table 3**. Urbanization refers to the process of transformation from rural population to urban population, and from agricultural production to non-agricultural production. This transformation aggregates the production factors but also increases the pressure on resources and the environment. The adjustment of industrial structure and economic development increase the demand for natural resources and provide financial guarantee for the exploitation and utilization of resources. Technology innovation is another notable factor. With the improvement of technology, the efficiency of resource utilization will be constantly increased, thus saving natural resources and reducing pollution. Finally, public awareness of environmental protection is also an important factor that affects the coupling coordination development of NRUBs. Only when the public is aware of the importance and scarcity of natural resources can the utilization benefits of natural resources be improved and coordinated development be promoted fundamentally.

The policy suggestions for the coordinated development of NRUBs are listed as follows. First, Beijing's economy has reached a relatively high stage, which needs to be transformed from high-speed development to high-quality development, with less resource consumption and carbon emission. Second, with the continuous growth of the urban population, on one hand, we should perfect public facilities to ensure the resource supply for every resident and strengthen spiritual culture construction; on the other hand, new-type urbanization needs to be promoted to realize urban–rural integration and common prosperity. Third, it is suggested to further consolidate the achievements of Beijing's environmental governance and the redistribution of non-capital functions, and give full play to the role of ecological protection areas as ecological barriers. The government should also strengthen the publicity and education on environmental protection and the construction of the ecological civilization. Last, it is necessary to increase investment in scientific research and cultivate more talented people to improve production technology and increase the efficiency of resource utilization.

5.4 Contributions and Limitations

First, in this study, various natural resources such as land, water, forest, grassland, and wetland are considered as a whole, and a comprehensive evaluation index system covering economic, social, and ecological benefits is established to quantify NRUBs. Different kinds of natural resources have interactions with each other; therefore, this study will provide a theoretical reference for the comprehensive assessment of natural resources and the unified utilization and management of natural resources. Second, the time series are longer than most studies and the interval is 1 year, which can better reflect the changing characteristics of the coupling coordination relationships over a long time. Last, both the coupling coordination degrees of economic–social–ecological benefits and the pair-wise benefits are calculated, which helps better understand the leading reasons affecting the overall coupling coordination relationships in each stage.

Nevertheless, there is still room for further progress of this research. Due to the limitation of data, some important indicators such as forest coverage rate and soil and water conservation rate are difficult to acquire, and the accuracy of indicator values needs to be further improved. In the future, with diversified evaluation dimensions, multi-source data integration and intelligent mode, the evaluation methods of NRUBs will be more scientific. Moreover, the influencing factors can be identified dynamically by stages, so that we can better distinguish the influencing mechanism and the variation trends. The spatial differentiation of coupling coordination relationships will also be studied in future research to understand the differences within the region and make more targeted policies.

6 CONCLUSION

This study establishes an evaluation index system and examines the coupling coordination relationships of NRUBs in Beijing from 1978 to 2018, with the methods of EWM, CCD model, and GRA. We have revealed the evolution characteristics of NRUBs and their coupling coordination relationships and analyzed the causes according to the development policies of Beijing. Finally, the influencing factors are identified and relevant policy implications are put forward. The main conclusions are summarized as follows. 1) From 1978 to 2018, the economic, social, ecological, and comprehensive benefits have significantly improved. The economic benefit shows a trend of steady growth, while the social and ecological benefits rise with fluctuations. The overall evolution trend of the comprehensive benefit is in steady growth with slight fluctuations. 2) The coupling coordination relationships of economic–social, economic–ecological, social–ecological, and economic–social–ecological benefits all exhibit upward trends during the study period, and their coordination types transform from a serious-moderate imbalance to a moderate-good coordination. 3) The relational coefficients between the coupling coordination degree and urbanization, industrial structure, technology innovation, economic development, and environmental awareness are 0.996, 0.982, 0.977, 0.854, and 0.845, respectively, and they all have significant impacts on the coupling coordination relationships of NRUBs. Measures such as transformation of the economic development mode, improvement of public facilities, construction of spiritual culture, ecological protection, and technological innovation need to be recognized to achieve coordinated development.

In the context of the unified management of natural resources, the evaluation of NRUBs and the coupling coordination relationships are of great significance to improve the utilization benefits and realize the sustainable development of natural resources. The findings of this study can provide a decision-making reference for the coordinated development of the economic, social, and ecological benefits and the formulation of natural resource utilization policies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ZY: conceptualization, methodology, formal analysis, and writing—original draft. CZ: conceptualization and formal analysis. YL: data curation and funding acquisition. YP: supervision and writing—review and editing. WZ: writing—review and editing.

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The Spatial-Temporal Evolution Characteristics and Driving Factors of the Green Utilization Efficiency of Urban Land in China

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With the acceleration of urbanization, the urban land area of different spatial scales in China continues to increase, the urban land use efficiency is relatively low, and there are great regional differences. Land is an important material carrier for human production, life, and socio-economic activities. Reasonable measurement of the green utilization efficiency of urban land (Glande) has important theoretical and practical significance for the realization of urban land green use and the formulation of related policies. In this context, based on the publicly available data of 282 China's cities at prefecture-level and above from 2009 to 2019, this study measures Glande with the Super-SBM data envelopment analysis model. After analyzing the spatio-temporal evolution characteristics of Glande, we employ the spatial dynamic Durbin model to analyze the spatial spillover effects. The results showed that: 1) Glande in China shows a fluctuating and rising trend, but it has not reached the effective state; 2) the agglomeration characteristics of urban land green use efficiency are significant, and from a regional point of view, it shows the pattern of western > eastern > central; 3) Glande is the result of the interaction of many factors. In the future, measures should be taken according to urban policies and local conditions, and differential measures should be taken to improve Glande.

Keywords: green utilization efficiency1, urban land2, spatial-temporal evolution3, Super-SBM model4, driving factors5

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INTRODUCTION

China is vigorously promoting the new strategy of changing the mode of economic development, and has put forward five development visions of "innovative, coordinated, green, open and inclusive". The goal of green development is to combine economic, social, and ecological development to create a society that is "resource-conserving" and "environment friendly". Land is an important material carrier for human production, life and social and economic activities. The green development concept of harmonious coexistence and sustainable development between man and nature should run through in the process of land use. To achieve the unity of economic, social and ecological benefits of land use, this process can be defined as green utilization of urban land. Glande is the key to properly solve various production structural contradictions, to achieve the goal of carbon peak and carbon neutralization vision, and to promote sustainable economic and social development. Therefore, the research on Glande has important practical significance to reduce the eco-environmental risk in the development and utilization of urban land and realize the unity of economic, social and ecological benefits.

Since the reform and opening-up, China's urbanization level has increased significantly. In 1987, the urbanization rate was only 17.90%, but reached 58.52% in 2017, with an average annual growth rate of 1.04% far exceeding the world average in the same period (Wang et al., 2019). By 2020, China's urbanization rate has reached 63.89%, and the area of urban built-up area has increased to 61,000 km^2.[1] However, in the face of the high concentration of population and the limited supply of land, the gradual extension of urban boundaries shows the crux of the mismatch between land utilization efficiency and the speed of urbanization, and the improvement of the ecological environment lags behind urban development. Improving the Glande is one of the primary tasks of developing countries. In this context, improving the utilization efficiency of urban land has become the internal requirement to promote sustainable regional construction and the development of national environmental civilization (Wang et al., 2019).

The utilization efficiency of urban land is to maximize the degree of land use focusing on achieving the optimization of economic output, while Glande emphasizes the coupling of "economic-social-ecological" systems, that is, under the given conditions of productive technology, through the minimum unit of input to obtain higher economic benefits, social well-being and reduce the "non-expected" output at the same time. Glande is the land utilization efficiency considering pollution factors (Aiping Wang et al., 2021). Glande is different from the economic utilization efficiency of urban land and the environmental utilization efficiency of urban land, which is mainly reflected in the goal of urban land use. Under the given production technical conditions and the level of input factors, the economic efficiency of urban land use mainly focuses on economic output and takes income maximization as the goal of land use. The environmental utilization efficiency of urban land considers both "desirable" output (such as economic income) and "undesirable" output (such as environmental pollution and ecological destruction). Its goal is to maximize economic benefits and minimize environmental pollution. On the other hand, Glande takes economic income and social dimension output as "desirable" output, and environmental pollution as "undesirable" output. Its goal is to maximize economic benefits and social dimensional output (such as social services) and minimize environmental pollution. Meanwhile, there is also a certain relationship between the three. The environmental utilization efficiency of urban land adds the restriction of "environmental factors" on the basis of the economic efficiency of urban land use, which is the result of the progress and development of the ecological environment. The green efficiency of urban land use is the addition of the "social output factor" on the basis of the environmental efficiency of urban land use, which is the result of progress in social development. The relationship among the three is mainly reflected in the continuous expansion and enrichment of the research content, from the economic field to the ecological environment field and then to the social development field[1].

At present, Glande has been widely concerned in the academic circles. The existing researches mainly focus on the measure of Glande, spatio-temporal characteristics, and driving factors. The first is the measurement and evaluation of land utilization efficiency (Hanif, 2018; Peng et al., 2018; Zhu et al., 2019a). Scholars have carried out a series of optimization on the measurement of urban land use efficiency (Du et al., 2016; Martinho, 2017; Xie et al., 2018). First, the evaluation has evolved from single- to multi-index methods that consider economic, social, environmental, and political factors (Guastella et al., 2017; Ferreira and Feres, 2020; Jin et al., 2018; Jing et al., 2017; Zhou and Tan, 2017). Conventional land utilization efficiency only considers a single indicator, such as land-use density or yield per unit of land (Hui et al., 2015; Desiere and Jolliffe, 2018; Wang et al., 2018; Chen et al., 2019), which does not fully reflect the relationship between multiple inputs and outputs in the process of urban land utilization in terms of efficiency. Second, data envelopment analysis (DEA) is gradually becoming a mainstream method for measuring urban land utilization efficiency. It can apply an optimized method to determine the weights of various inputs, avoid human subjectivity, and effectively evaluate efficiency values more objectively. For example, Xin et al. (2020) and Yang et al. (2010) used conventional DEA methods that did not consider undesirable outputs to measure urban land efficiency from different scales. Third, apart from the economic output, add environmental output such as SO_2 emissions, wastewater emissions, and solid waste as the undesirable output of land use into the efficiency calculation (Hanif, 2018; Peng et al., 2018; Zhu et al., 2019b). The slacks-based measure (SBM) undesirable model has improved on the conventional DEA model to account for the undesirable output of land use, thus becoming the mainstream measurement method for land utilization efficiency. For example, Yang et al. (2015), Tao et al. (2016), and Yu et al. (2019) each applied this research approach to measure and study Glande at different scales. Henceforth, the Super-SBM model based on undesirable outputs is applied to resolve the issue that the efficiency value of the effective decision-making unit cannot be broken down, resulting in the loss of effective decision-making information in practical application (Zhu et al., 2019a; Lu et al., 2020; Peng Wang et al., 2021). What's more, Huang et al. (2014) proposed an SBM model considering global reference and solved the problem that the efficiency could not be compared across time.

In terms of driving factors, scholars believe that there are great differences in the influence of economic development level (Chen et al., 2019), the degree of market openness (Chen et al., 2017; Huang et al., 2017), the level of R&D (Xie et al., 2019; Yan et al., 2020), and the level of public infrastructure (Osman et al., 2016; Sun et al., 2020) on land use efficiency in different cities (Fan et al., 2018). However, most of the existing studies focus on the driving factors of land use efficiency, there are few studies focused on the impacts on Glande (Aiping Wang et al., 2021). Researchers generally hold that the development of green land utilization efficiency also has spatial features. A large number of studies are based on the geographical effect of regional green total factor productivity. There is spatial autocorrelation in the distribution of Glande, and there is a spatial agglomeration effect between ecological efficiency and provincial financial development (Sun and Sun, 2019). Ren et al. have faith in that overall Glande in

[1]Data source: https://www.yicai.com/news/101158825.html.

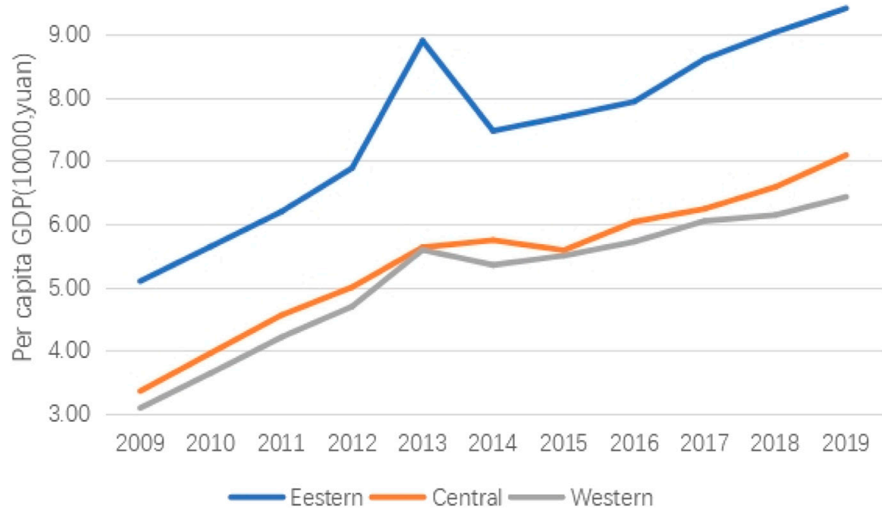

FIGURE 1 | Trend of economic development by regions.

TABLE 1 | Input-output index table.

	Variable type	Index
Input	Capital	Investment in fixed assets
	Land	The area of urban construction land
	Labor	The number of employees in the secondary and tertiary industries
Desired output	Economic	GDP of secondary and tertiary industries in municipal districts
	Social	Average wage of employees on the job
	Ecological	The green area coverage rate of the urban construction land
Undesired output	Soot	Industrial soot discharge
	Wastewater	Industrial wastewater discharge
	SO_2	Industrial sulfur dioxide discharge

China is still not at a high level, with great variance among different areas (Ren et al., 2020). The spatial econometric model is used to analyze the impact of globalization, marketization, and decentralization on Glande, and it is found that there is a certain degree of convergence of "spatial club" in Glande.

Since the 1990s, Chinese local governments have made use of the unique arrangements of the land system to dominate economic development. However, with the transformation of the stage of China's economic development and the continuous accumulation of many potential problems in the model of "Land Driving Development", the effectiveness of land to promote development is declining and unsustainable. China urgently needs to shift from extensive economic growth to intensive economic growth. The mode of intensive economic growth depends on the optimal combination of production factors, through improving the quality and efficiency of production factors, technological progress, improving the quality of workers, and improving the utilization rate of funds, equipment, and raw materials. China is the largest developing country in the world. China's practice of improving the Glande can provide a rich experience for developing countries and provide reference to improve ecological benefits while economic development.

Based on the review of the existing literature, we find that there may be the following research gaps: first, to focus on Glande, rather than utilization efficiency of urban land or ecological utilization efficiency of urban land, or economic utilization efficiency of urban land; Second, taking China as the research object and cities as the observation, to study the current situation and development direction of Glande in developing countries; Third, to select the most cutting-edge methods to measure the Glande more accurately. Accordingly, this paper uses panel data of 282 cities in China from 2009 to 2019 to construct a land-use efficiency evaluation system from the perspective of urban development with land, capital, and labor as input factors, economic and social output as desired output factors, and environmental pollutants as undesired output factors. This paper uses the Super-SBM model to measure the Glande scores and analyzes the spatio-temporal evolution characteristics. Then, the global reference Malmquist index and decomposition index are calculated. After analyzing the spatio-temporal evolution characteristics of the green land utilization efficiency, we employ the spatial dynamic Durbin

TABLE 2 | Driving factors.

Driving factors	Index
Economic development level (Economy)	Per capita GDP
Upgrading of industrial structu re (UpIS)	Proportion of tertiary industry/Proportion of secondary industry
Ecological resource endowment (Esource)	Per capita park green space area
Infrastructure level (Facility)	Per capita road area
Level of investment in science and education (SEInv)	Expenditure on Science and Technology and Education/Local General Fiscal Expenditure
Financial deepening (FD)	Year-end loan balance of financial institutions/GDP
Financial gap (FG)	(budgetary expenditure-budgeted revenue)/budgeted revenue

TABLE 3 | Descriptive statistics of input-output index (N = 3102).

	Index	Mean	Sd	min	Max
Input	Economic	1.306 × 109	2.541 × 109	4.495 × 107	1.688 × 1010
	Social	50,286	18,289	20,132	103,400
	Ecological	39.28	6.619	12.41	57.34
Desired output	Land	143.1	196.7	18	1,263
	Capital	1.554 × 107	1.551 × 107	1.038 × 106	7.941 × 107
	Labor	53.75	69.34	6.921	486.5
Undesired output	Soot	26,070	30,061	296	195,790
	Wastewater	6,202	6,850	113	39,186
	SO_2	42,373	42,337	219	217,663

model to analyze the spatial spillover effects. The potential contributions of this article are shown as follows: 1) this paper uses the Super-SBM model to accurately measure Glande of 282 cities in China, and reveals the regional characteristics and time-varying characteristics; 2) this paper explores the driving factors affecting Glande; 3) this paper takes the largest developing countries as the research object, and the conclusions provide a reference for developing countries to improve Glande.

DATA AND METHODOLOGY

Research Area

China has a land area of about 9.6 million square kilometers, a continental coastline of more than 18,000 km in the east and south, and a water area of more than 4.7 million square kilometers in the inland and border seas. There are more than 7600 large and small islands in the sea area. China is bordered by 14 countries and eight countries at sea. Provincial administrative divisions are divided into 23 provinces, five autonomous regions, four municipalities directly under the Central Government and two special administrative regions. China is the most populous developing country in the world, the third largest in land area, the second largest economy in the world, and continues to be the largest contributor to world economic growth, with a total economic output exceeding 100 trillion yuan in 2020. Specifically, the research object of this paper is 282 prefecture-level cities in China. It is divided according to the standard of economic geographical location, including 100 cities in the eastern region, 99 cities in the central region and 83 cities in the western region. As shown in **Figure 1**, in terms of the level of economic development, the economic development of Chinese cities shows an upward trend, and the eastern region > the central region > the western region.

Super-SBM

In this paper, with reference to the more mainstream method, the environmental pollution index is included in the output item as undesired output. As Glande of the research unit may be optimal at the same time, in order to solve the problem of efficiency comparison between effective units under resource constraints and undesired output, this paper further uses the Super-SBM model. The Super-SBM model considering undesired output is as follows:

$$min\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x_i}}{x_{ik}}}{\frac{1}{r_1 + r_2}\left[\sum_{s=1}^{r_1}\frac{\bar{y}_s^d}{y_{sk}^d} + \sum_{q=1}^{r_2}\frac{\bar{y}_q^u}{y_{qk}^u}\right]}$$

$$s.t.\begin{cases} \bar{x} \geq \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j \\ \bar{y}^d \geq \sum_{j=1, j\neq k}^{n} y_{sj}^d\lambda_j \\ \bar{y}^u \geq \sum_{j=1, j\neq k}^{n} y_{qj}^u\lambda_j \\ \bar{x} \geq x_k, \bar{y}^d \leq y_k^d, \bar{y}^u \geq y_k^u, \lambda_j \geq 0 \end{cases} \quad (1)$$

In the above equation, it is assumed that there are n decision-making units; every decision-making unit is composed of input m, desired output r_1, and undesirable output r_2, x, y^d, y^u, which are the factors in the corresponding input matrix, desired output matrix, and undesirable output matrix; ρ represents the value of Glande.

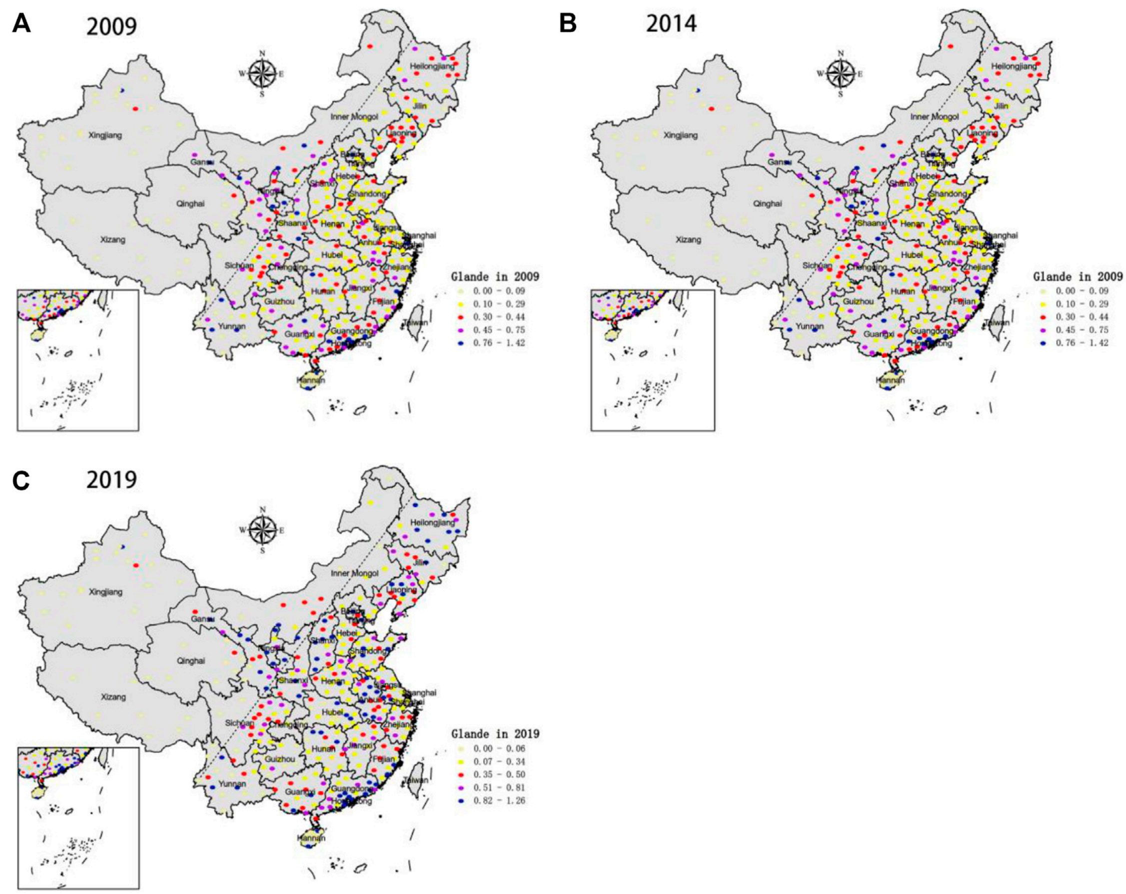

FIGURE 2 | Distribution of Glande in China. **(A)** Distribution of Glande in China in 2009. **(B)** Distribution of Glande in China in 2014. **(C)** Distribution of Glande in China in 2019.

TABLE 4 | The geometric mean of Glande over the years.

		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Glande	Mean	0.381	0.377	0.400	0.432	0.457	0.430	0.442	0.468	0.488	0.503	0.559	0.449
	SD	0.251	0.257	0.267	0.290	0.279	0.280	0.283	0.283	0.296	0.311	0.322	0.289
	Min	0.091	0.087	0.078	0.099	0.112	0.108	0.082	0.128	0.135	0.130	0.147	0.078
	Max	1.425	1.493	1.632	1.658	1.656	1.631	1.663	1.465	1.490	1.370	1.257	1.663
Sglande	Mean	0.462	0.464	0.462	0.484	0.519	0.483	0.483	0.608	0.564	0.569	0.648	0.522
	SD	0.469	0.543	0.308	0.331	0.313	0.307	0.321	1.439	0.359	0.391	0.414	0.570
	Min	0.119	0.120	0.107	0.112	0.142	0.129	0.083	0.132	0.143	0.144	0.162	0.083
	Max	6.542	8.164	1.467	1.775	1.575	1.437	1.853	24.053	2.482	3.219	3.894	24.053
Tglande	Mean	0.894	0.883	0.900	0.923	0.904	0.907	0.938	0.910	0.892	0.918	0.896	0.906
	SD	0.149	0.156	0.153	0.136	0.149	0.142	0.115	0.135	0.141	0.139	0.156	0.144
	Min	0.218	0.173	0.278	0.279	0.280	0.207	0.228	0.061	0.257	0.252	0.147	0.061
	Max	1.000	1.000	1.632	1.658	1.656	1.631	1.663	1.000	1.000	1.000	1.000	1.663

Referring to Aiping Wang et al. (2021), the input includes capital, labor, and land in this paper. The capital input is measured by the city's fixed assets investment (10,000 yuan, RMB), and the land input is measured by the city's urban construction land area (square kilometers). Labor input is measured by the number of employees in the secondary and tertiary industries (10,000). Expected output includes economic, social, and ecological output, in which economic output is measured by the GDP of secondary and tertiary industries (10,000 yuan, RMB), the social output is measured by the average wage of on-duty workers (RMB, yuan), and ecological output is measured by the green coverage rate (%) in the built-up area. Undesired output is environmental pollution, including industrial wastewater emissions (10,000 tons), sulfur dioxide

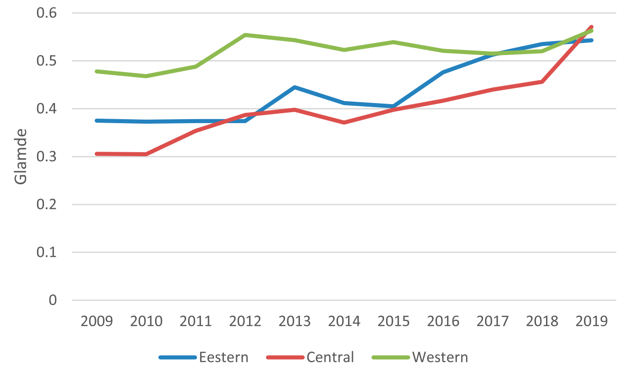

FIGURE 3 | The geometric mean of Glande by regions.

emissions (tons), and industrial soot emissions (tons). Details of the input-output index are shown in **Table 1**.

Global Malmquist- Luenberger Index

In order to study the panel data of observations at multiple time points in order to analyze the effects of technical efficiency and technological progress on productivity changes respectively, the total factor productivity (TFP) index is usually used for further analysis. In order to avoid the rough front surface constructed because of less DMU and the problem that the VRS model may have no feasible solution, the global reference Malmquist model (Global Malmquist) is selected for analysis in this paper, which can effectively avoid the defect of linear programming without solution and the phenomenon of "technology regression" and which also has transitivity proposed by Pastor and Lovell (Oh, 2010).

First, we construct the common reference set of each period, as shown in the following equation.

$$S_g = S^1 \cup S^2 \cup \cdots \cup S^P = \{(x^1, y^1) \cup \cdots \cup (x^P, y^P)\} \quad (2)$$

where S is the reference set, S_g is the common reference set, x is the input variable, y is the output variable, and P is the number of sets of the reference set at different times. Since each period refers to the same front, a single Malmquist index can be calculated, as shown in the following equation.

$$M_g(x^{t+1}, y^{t+1}, x^t, y^t) = \frac{E^g(x^{t+1}, y^{t+1})}{E^g(x^t, y^t)} == EC \times TC \quad (3)$$

E is the distance function, t is the time variable, and M is the Malmquist index under the common reference set. Based on **Eq. 3**, the Malmquist index can be decomposed into efficiency change (EC) and technical change (TC) (Färe et al., 1994). TC represents technological change, greater than one represents technological progress, and less than one represents technological retreat.

Moran's I

The Moran's I test is a spatial autocorrelation measure developed by Patrick Alfred Pierce Moran (Moran, 1950; Li et al., 2007), as shown in the following equation.

Global Moran's I:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{ij}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (4)$$

Local Moran's I:

$$I_i = \frac{(x_i - \bar{x})}{S^2}\sum_{j\neq i}\omega_{ij}(x_j - \bar{x}) \quad (5)$$

Spatial Dynamic Durbin Model

In this paper, referring to the practice of LeSage and Pace (2009), the spatial lag terms of driving factors and dependent variables are included in the static Durbin model. Compared with the static Durbin model, the dynamic Durbin model not only considers the dynamic effect and spatial spillover effect, but also alleviates the endogenous problem of "reciprocal causation" (Elhorst, 2014). Therefore, the first-order lag term of *lnGlande* is introduced into the equation to construct the following dynamic Durbin model.

$$\begin{aligned} lnGlande_{it} &= \alpha + \beta_0 lnGlande_{it-1} + \rho_1\sum_{i=1}^{n}W_{it}lnGlande_{it} \\ &+ \rho_2\sum_{i=1}^{n}W_{it}lnGlande_{it-1} + \theta\sum X_{it} \\ &+ \rho_3\sum_{i=1}^{n}W_{it}X_{it} + u_i + v_t + \varepsilon_{it} \end{aligned} \quad (6)$$

i and t represent city and time respectively; $lnGlande_{it}$ is Glande; X represents the driving factors set; W is the 282 × 282 order spatial weight matrix; ρ_1, ρ_2, ρ_3 are spatial lag coefficient for each variable; u_i and v_t represent individual and time dummy variables respectively; ε_{it} is random distribution item.

Following prior studies with Glande as the dependent variable (Aiping Wang et al., 2021; Yan et al., 2020; Xie et al., 2019), we select the level of economic development, the upgrading of industrial structure, the endowment of ecological resources, the level of infrastructure, the investment in science and education, financial deepening and financial gap as the possible driving factors of Glande. The reasons are as follows. Cities with a higher level of economic development will have more power to improve social and environmental benefits, so the level of economic development may have a positive impact. The process of industrial structure transformation and upgrading is usually accompanied by the reduction of agricultural land and the increase of secondary and tertiary industrial land represented by the industry and service industry. Therefore, land prices continue to rise. For enterprises, the high cost of land will raise the entry threshold, guide the entry of high-efficiency enterprises, and exit inefficient enterprises, to improve the efficiency of land. Since the high value-added industry has both talent and technological advantages and has high output efficiency. The upgrading of the industrial structure guides the government's financial investment in the education, medical, and other public service departments, reduces repeated construction, and improves the value of land output, which is conducive to the improvement of land-use efficiency. As Glande is based on environmental benefits, urban ecological resource endowment, as its ecological basis, may have an impact. Infrastructure involves a wide range of areas, in which convenient traffic conditions not only make the relationship between cities closer but also make the characteristics of industrial agglomeration, factor flow,

TABLE 5 | Glande of different types of cities.

	Not innovative city	Innovative city	Not low-carbon city	Low-carbon city	Not resource-based city	Resource-based city
2010	0.383	0.322	0.379	0.33	0.364	0.397
2011	0.414	0.293	0.402	0.335	0.391	0.415
2012	0.445	0.334	0.438	0.389	0.415	0.456
2013	0.474	0.367	0.461	0.432	0.447	0.473
2014	0.443	0.357	0.431	0.426	0.423	0.44
2015	0.452	0.387	0.44	0.459	0.426	0.466
2016	0.474	0.44	0.468	0.469	0.46	0.482
2017	0.486	0.495	0.478	0.52	0.479	0.501
2018	0.496	0.529	0.496	0.527	0.486	0.528
2019	0.561	0.552	0.545	0.603	0.557	0.561

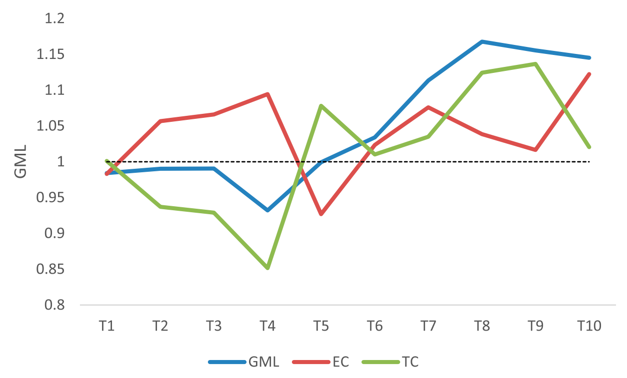

FIGURE 4 | The geometric mean of GML in China.

technology spillover, and information resource sharing more obvious. The increasing innovation ability is an important driving force to support the improvement of Glande, in which education is an important source of human capital accumulation and an important means to improve the ability of independent innovation. Therefore, investment in science and education may also be one of the important driving factors. Financial deepening means that the government reduces excessive intervention in the financial market and allocates financial resources by adjusting interest rates, exchange rates, and other market means. The development of the financial market will affect the quality of urban investment projects, thus affecting Glande. In the choice of financial strategy, land finance as extra-budgetary revenue is the best choice to make up for the financial gap, adopting the "Land Driving Development" mode of selling commercial and residential land at a high price and industrial land at a low price. Therefore, the larger the financial gap is, the more local governments attach importance to the land-use model, and the greater the expectation of good management and use of land, the higher the efficiency of urban land use. Details are shown in and **Table 2**

The cities with many missing data, such as Sansha City and Danzhou City, are removed, some of the missing values are supplemented by looking up the local statistical yearbooks, and the remaining missing values are processed by linear interpolation. In order to avoid the influence of extreme outliers, the continuous variables involved in the study were shrank-tailed by 1%. The data are from Chinese Research Data Services Platforms (CNRDS).

RESULTS

Details of the input-output index variables are shown in **Table 3**.

Glande

The DEA model includes two types: variable scale return (VRS) and constant scale return (CRS). The pure technical efficiency is measured when the scale return is variable, and the comprehensive efficiency is measured when the scale return is constant. The comprehensive efficiency can be decomposed into the product of pure technical efficiency and scale efficiency (Liang et al., 2013). For this reason, after measuring the land utilization efficiency under CRS and VRS respectively, this paper divides it into land scale efficiency (Sglande) and land technical efficiency (Tglande). Land scale efficiency refers to the best output obtained by changing the input-output ratio under the fixed technical level. Its economic meaning is the effect of increasing output caused by economies of scale. If land factors flow to low-productivity enterprises, the long-term average total cost will rise with the expansion of land area, resulting in diseconomies of scale and restraining land scale efficiency. Land technical efficiency refers to the best output of a given input under the maximum technical conditions. Its economic meaning is the effect of increasing output caused by technological innovation, excessive deviation from the technological demand-oriented land-use model will crowd out innovative resources, and then restrain the land technical efficiency (Guo and Zhou, 2020). **Figure 2** shows the distribution of Glande in China, taking 2009, 2014, and 2019 as examples.

Table 4 shows the geometric mean of Glande over the years. As can be seen from **Table 4**, Glande in China shows a fluctuating upward trend from 2009 to 2019, from 0.381 to 0.559, but it has not yet reached the effective state. The national geometric mean is 0.449, indicating that if the existing output remains unchanged, there is theoretical potential for Glande to be improved by 55.1 percent. Land scale efficiency fluctuates from 2009 to 2019, with

TABLE 6 | Results of the global moran's I test.

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Moran's I	−0.009	−0.008	−0.006	−0.006	−0.005	−0.005	−0.003	−0.006	−0.006	−0.006	−0.004
Z-value	−2.429	−1.928	−1.251	−1.086	−0.83	−0.466	0.183	−1.29	−1.031	−1.187	−0.249
p-value	0.008	0.027	0.106	0.139	0.203	0.321	0.428	0.098	0.151	0.118	0.402

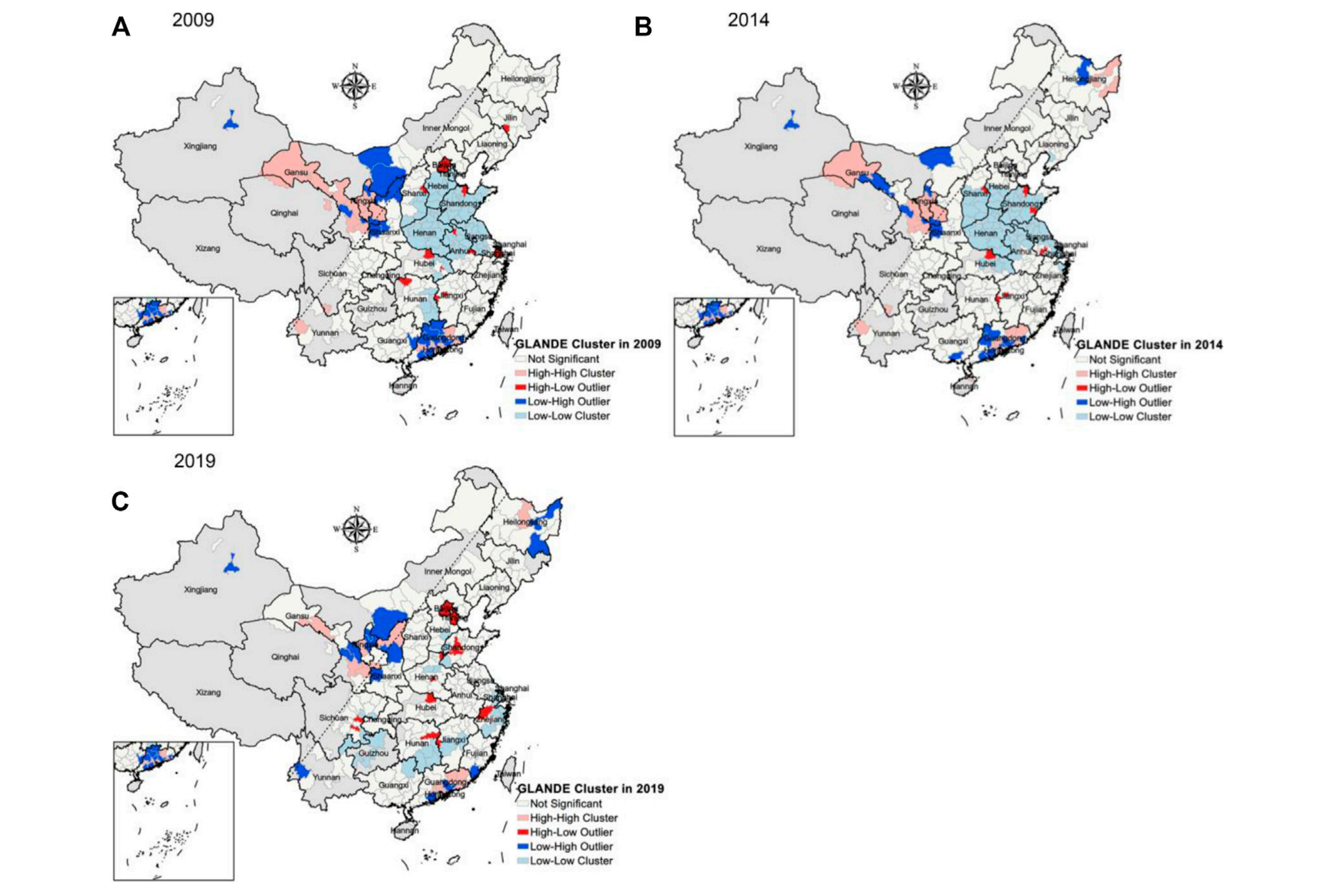

FIGURE 5 | The Moran scatter plot of Glande. **(A)** The Moran scatter plot of Glande in China in 2009. **(B)** The Moran scatter plot of Glande in China in 2014. **(C)** The Moran scatter plot of Glande in China in 2019.

an average of 0.522. From 2009 to 2019, the geometric mean of land technical efficiency was 0.906.

As can be seen from **Figure 3**, Glande shows the pattern of western > eastern > central. The geometric mean of Glande in eastern, central, and western regions all reached the maximum in 2019, which were 0.543, 0.571, and 0.563 respectively. The growth rate of Glande in the eastern and central regions is higher than that in the western regions. The above shows that there is spatial heterogeneity in Glande in China. The reason for the higher Glande in cities in western China may be that Glande takes into account the undesired output, that is, environmental pollution. This also suggests that we should change from the absolute level of economic development to the efficiency, from only the efficiency of land utilization efficiency to Glande.

We further divide cities according to whether they are innovative cities, low-carbon cities and resource-based cities, and analyze the differences of Glande of different types of cities. Innovative city refers to a city that takes scientific and technological innovation as the core driving force of economic and social development, with rich innovation resources, dynamic innovation subjects, efficient innovation services and government governance, and a good environment for innovation and entrepreneurship. Innovative cities agglomerate and allocate innovative resources, establish an innovation-driven intensive urban economic growth model, and the ultimate goal is to achieve urban economic growth and sustainable development. As can be seen from **Table 5**, compared with non-innovative cities, the Glande of innovative cities increased significantly, from 0.322 in 2010 to

TABLE 7 | Spatial econometrics results of driving factors on Glande.

	Main	Wx
l_lnGlande	0.503***	2.000**
	−0.017	−0.978
UpIS	0.029	−0.836
	−0.018	−1.079
FD	−0.036**	1.227*
	−0.016	−0.686
FG	0.005	0.149
	−0.007	−0.253
Esource	0.001*	−0.013
	−0.001	−0.051
SEInv	0.150	−6.942
	−0.163	−6.607
Economy	0.017***	0.156
	−0.004	−0.132
Facility	0.006	−2.406
	−0.050	−2.551
R^2		0.595
N		2,820

*, **, *** indicate significance at the 10%, 5%, and 1% significance levels, respectively.

0.522 in 2019. Low-carbon city refers to the city that keeps energy consumption and carbon dioxide emissions at a low level under the premise of rapid economic development. China announced three batches of national low-carbon pilot lists in 2010, 2012 and 2017, respectively. As can be seen from **Table 5**, from 2010 to 2014, the average Glande of low-carbon cities was slightly lower than that of non-low-carbon cities, but showed an upward trend, and exceeded that of non-low-carbon cities in 2015. Resource-based city is a type of city (natural land) whose leading industry is the exploitation and processing of minerals, forests and other natural resources in this region. As can be seen from **Table 5**, from 2010 to 2019, the average Glande of resource-based cities is higher than that of non-resource-based cities.

Global Malmquist- Luenberger Index

In order to analyze Glande more specifically, analyze the change of the relative position between each city and the production frontier and the change of the production frontier, then calculate the GML of each city from 2009 to 2019. If the GML index is greater than 1, the green total factor productivity shows a growth trend; if the GML is less than 1, the green total factor productivity shows a downward trend; the GML equals one means that the green total factor productivity remains unchanged. At the same time, GML can be decomposed into technology efficiency index (EC) and technology progress index (TC). EC greater than (less than) one represents green technology efficiency rising (decreasing), and TC greater (less than) one represents green technology progress (retrogression). **Figure 4** shows the geometric mean of GML for each year in China.

As can be seen in **Figure 4**, from 2009 to 2010, the geometric mean of GML in China was close to 1, indicating that Glande decreased slightly. From 2012 to 2013, the geometric mean of GML in China was 0.93, and Glande decreased. From 2013 to 2014, Glande remained basically unchanged. From 2014 to 2019, the geometric mean of GML in China is greater than 1, indicating that Glande is on the rise.

Then, the GML index is decomposed into technological progress (TC) and technical efficiency change (EC). TC can be regarded as the displacement of the front surface constructed by the decision-making unit during the inspection period, and EC can be expressed as the position change relative to the front surface. By comparing the values of TC and EC, it can be found that from 2009 to 2014, the contribution to the GML index mainly comes from the improvement of technical efficiency, but from 2014 to 2019, the contribution to the GML index mainly comes from the improvement of technological progress. The inconsistency between EC and TC shows that Chinese cities pay attention to the utilization of technology under the existing resources in the early stage of development and the progress of technology in the later stage.

Driving Factor Analysis

Table 6 shows the results of Global Moran index of Glande in China. It can be seen from **Table 5** that in the 7 years from 2009 to 2012 and from 2016 to 2018, the Moran index of Glande passed the 15% significance test. The Moran index is negative, which indicates that Glande has negative spatial autocorrelation. It is necessary to measure the specific effects of various driving factors on Glande through spatial panels.

Since the Global Moran's I can not reasonably obtain the spatial correlation of each region, this paper analyzes the spatial characteristics of the local area with a Moran scatter plot. In terms of quadrants, Moran's I scatter maps generally contain four quadrants: "Low-Low," "Low-High," "High-Low," and "High-High". L-L indicates that Glande in a certain area and its adjacent areas are relatively low. It shows the characteristics of low concentration and distribution in the region. L-H indicates that Glande in a certain area is low, while the surrounding areas are generally higher, showing the spatial distribution law that the low index area is surrounded by the high index area. H-L corresponds to L-H, indicating the distribution characteristics of the high index area surrounded by the low index area. H-H indicates that Glande in a certain area and its surrounding areas are relatively high, showing a high index of regional agglomeration. **Figure 4** is the Moran scatter plot, taking 2009, 2014, and 2019 as examples. According to **Figure 5**, most cities in Henan, Hebei, Shandong and Jiangsu provinces in China show an L-L layout.

We use the spatial dynamic Durbin model and control the individual fixed effect and time fixed effect to analyze the driving factors, and the results are shown in **Table 7**. The R-square is 0.595 and the log-likelihood is 136.7585, indicating that the model has a high degree of fit and high reliability.

According to the first column of data in **Table 7**, financial deepening, ecological resource endowment, and economic development level pass the significance test at 5%, 10%, and 1% levels respectively, and the coefficients are −0.036, 0.001, and 0.017 respectively, indicating that financial deepening has a negative impact on Glande, while ecological resource endowment and economic development level have a positive impact. In addition, the upgrading of industrial structure

TABLE 8 | Estima ted results of SLM and SEM.

	(1)	(2)	(3)	(4)	(5)	(6)
	SEM	SEM	SEM	SLM	SLM	SLM
	(Time-fixed)	(Spatial-fixed)	(Time-Spatial fixed)	(Time-fixed)	(Spatial-fixed)	(Time-Spatial fixed)
l_lnGlande	0.813***	0.504***	0.501***	0.809***	0.490***	0.499***
	–0.011	–0.017	–0.017	–0.011	–0.017	–0.017
UpIS	0.041***	0.044**	0.031*	0.040***	0.033*	0.032*
	–0.009	–0.018	–0.018	–0.009	–0.017	–0.018
FD	–0.026***	–0.036**	–0.039**	–0.025***	–0.045***	–0.039**
	–0.009	–0.016	–0.016	–0.009	–0.016	–0.016
FG	0.018***	0.005	0.004	0.018***	0.008	0.005
	–0.004	–0.007	–0.007	–0.004	–0.007	–0.007
Esource	0	0.001**	0.001*	0	0.001	0.001*
	0	–0.001	–0.001	0	–0.001	–0.001
SEInv	–0.024	0.2	0.169	–0.024	0.243	0.165
	–0.103	–0.162	–0.162	–0.103	–0.16	–0.162
Economy	0.006***	0.020***	0.017***	0.007***	0.017***	0.017***
	–0.002	–0.004	–0.004	–0.002	–0.003	–0.004
Facility	–0.071***	0.039	0.008	–0.072***	–0.017	0.008
	–0.01	–0.049	–0.049	–0.01	–0.047	–0.049
Spatial	–0.820***	0.721***	–0.774**	–0.784***	0.467***	–0.678**
lambda	–0.314	–0.072	–0.318	–0.289	–0.066	–0.331
Variance	0.066***	0.054***	0.053***	0.066***	0.054***	0.053***
sigma2_e	–0.002	–0.001	–0.001	–0.002	–0.001	–0.001
R^2	0.781	0.727	0.748	0.774	0.736	0.743
N	2,820	2,820	2,820	2,820	2,820	2,820

, **, * indicate significance at the 10%, 5%, and 1% significance levels, respectively.*

passed the significance test at a 15% level (p = 0.105), and the coefficient was 0.029, indicating that the upgrading of industrial structure has a positive impact on the green use efficiency of urban land. According to the second column data, W× financial deepening is significant at a 10% level, and the coefficient is 1.227, which shows that financial deepening has a positive spatial spillover effect, and the surrounding areas have a positive transmission effect on the local green utilization efficiency.

In addition, we carry out an LM test to test whether the model has a spatial effect. LM (error test) and Robust LM (error test) passed the significance test at 1% level (p = 0.000, p = 0.000), LM (lag) test passed the significance test at 5% level (p = 0.043) but did not pass the Robust LM (lag) test (p = 0.322), indicating that using a spatial econometric model is better than using an ordinary regression model. In addition to using the spatial Durbin model, we also test the driving factors with the spatial lag model and the spatial error model, as shown in **Table 8**. We carry out the joint significance test, and the Spatio-temporal fixed spatial lag model and Spatio-temporal fixed spatial error model passed the test. The results of columns 3) and 6) in **Table 8** are basically consistent with the results of the spatial Durbin model in **Table 7**, that is, financial deepening, ecological resource endowment, and economic development are important influencing factors of Glande, and the upgrading of industrial structure has also passed the significance test of 10% level. In addition, the Hausman test significantly rejected the original hypothesis at a 1% level, indicating that the fixed effect model is more suitable than the random effect model.

DISCUSSION

This paper uses the Super-SBM model to measure Glande of 282 cities in China from 2009 to 2019, further calculates the GML index, and uses the Moran index to analyze the spatial autocorrelation of Glande. Finally, we empirically analyze the spatial heterogeneity of the driving factors of Glande based on the spatial dynamic Durbin model. The conclusion are as follows: 1) Glande in China shows a fluctuating upward trend, but has not reached the effective state; 2) Glande in China has spatial heterogeneity, showing a pattern of western > estern > central; 3) from 2009 to 2019, the GML index of Chinese cities changed from slightly less than one to more than 1, and the growth of GML index depended more on technical efficiency in the early stage and technological progress in the later stage; 4) According to the results of Moran index, there is spatial autocorrelation in Glande in China; 5) Financial deepening has a negative impact on Glande, while ecological resource endowment, the level of economic development and the upgrading of the industrial structure have a positive impact. In addition, financial deepening has a positive spatial spillover effect, and the surrounding areas have a positive transmission effect on the local green utilization efficiency of urban land.

Specifically, the endowment of ecological resources plays a significant role in promoting Glande of 282 cities in China, which verifies that urban ecological resources play an important role in improving the local environment of the city, absorbing and purifying the pollutants produced in the process of urban land use, alleviating the urban heat island effect and improving the livable level. The level of economic development can promote the Glande of the city. The higher the level of economic development, the stronger the comprehensive strength of the city, and the greater the input intensity of resource factors per unit area of urban land, which can attract a large number of high-quality investment projects under the survival of the fittest, which is conducive to the improvement of Glande. Glande with advanced industrial structure can be promoted. The secondary industry, which is dominated by the resource processing industry, supports the urban development, while the tertiary industry with new energy and new technology develops relatively slowly, while the cities dominated by the secondary industry tend to emit more pollutants per unit of land. Therefore, it has a negative impact on Glande. Under the action of the market mechanism, low-quality foreign enterprises can gradually phase out and withdraw, increase productivity through the transfer and spillover of environmentally friendly technologies, enter the post-industrial development stage, and gradually reduce the input of new urban construction land. Alleviate the problem of urban sprawl and reduce industrial pollutant emissions. Financial deepening means that the government reduces excessive intervention in the financial market and allocates financial resources by adjusting interest rates, exchange rates, and other market means. With the continuous improvement of the degree of marketization, urban investment is inefficient, the investment project is not a high-quality project, emphasis on economic benefits rather than environmental benefits, Glande is reduced.

The following are implications for improving Glande in China: 1) promoting the green transformation of the economy and speeding up the development of labor-intensive industries to knowledge-and technology-intensive industries; increase support for enterprise green land development, product production, technology research and development, and tighten enterprise pollution standards and environmental protection access threshold; 2) advocating eco-environmental friendliness, further strengthening the concept that "Clear waters and green mountains are as valuable as mountains of gold and silver", improving the ability of urban land pollution control and green GDP assessment, and building a national land carbon emissions trading market; 3) different regions should adopt differential management measures according to local conditions, and the eastern coastal areas should speed up the development of emerging scientific and technological industries and tertiary industries, speed up the construction of a modern industrial system with advanced technology, high added value and high efficiency of resource utilization, vigorously develop cleaner production, and develop diversified innovation space and highly efficient accessible and networked public space. Create an institutional environment and a livable living environment to stimulate the vitality of innovation. The central and western regions should strengthen the construction of urban infrastructure and public service facilities to meet the needs of urban residents, actively introduce advanced production technology and high-end talents, promote industrial optimization and upgrading, and increase the effect of urban industrial clusters.

The possible future research directions are as follows: 1) deepen the research on the interaction mechanism of the driving factors of Glande. In this paper, the discussion of the driving factors focuses on the independent effect of each factor on Glande, and there is a lack of discussion on the mechanism involving the interaction of two or multi-agent systems; 2) this paper focuses on the linear effect of driving factors, but in fact, there may be non-linear relations such as U-shaped relationship or inverted U-shaped relationship, which can be paid attention to in the future; 3) the driving factors studied in this paper are limited, and there may be other important factors that affect Glande (Färe et al., 1994; Huang et al., 2014).

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://www.cnrds.com/Home/Index#/.

AUTHOR CONTRIBUTIONS

LZ conceived and designed the frame work, YY completed data analysis and result collation, and are equal first authors. YC wrote the paper and collected data.

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Urban Comprehensive Carrying Capacity and Development Order: A "Pressure-Capacity-Potential" Logical Framework

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Urban comprehensive carrying capacity determines the scale and development direction of a city and is an important factor in the optimization of main function areas, the arrangement of urban development order, and the demarcation of urban development boundaries in China's new national spatial planning system. Using the constructed "pressure-capacity-potential" model as a theoretical basis, this study combines human factors and natural factors and calculates the urban carrying capacity index by means of multi-factor weighted summation, graded assignment, stepwise correction, and subsection variable weight. From the perspective of the integration and coordination of "three forces," urban development rules are established, and an urban development order based on the framework of "three districts and six types" is put forward. The results reveal four key findings. First, the "pressure-capability-potential" conceptual model analyzes the urban carrying capacity from the perspective of the integration of externality and internality, which can effectively support the orderly arrangement and rational layout of urban development. Second, the urban carrying pressure of Shandong province is general, and the urban carrying capacity is high. The results also showed that the urban carrying potential is low and the urban comprehensive carrying capacity is high. Third, in the "3+6" urban development pattern of Shandong province, priority development and key development zones are the main areas. For the most part, these zones are distributed in the Jiaodong Peninsula, the Jinan–Tai'an–Jining development zone, and the surrounding areas of Weifang, Linyi, Liaocheng, and Heze. Moderate development zones are concentrated in Nansi Lake and the Yellow River Delta. Fourth, the urban development in Shandong province is mainly restricted by landform, water resources, environmental capacity, and geological disasters. Under the premise of ensuring resource conservation and environmental friendliness, using policies and engineering measures to revitalize stock space is an effective way to foster urban development in the 14th Five-Year Plan period. This study can provide reference for the evaluation of urban comprehensive carrying capacity and the establishment of development order in Shandong province and other similar areas.

Keywords: urban comprehensive carrying capacity, development order, pressure–capacity–potential model, urban development pattern, Shandong province

INTRODUCTION

With the rapid advancement of industrialization and urbanization, problems such as resource shortages, environmental pollution, and strained relationships between humans and the land have emerged in various regions (Bai et al., 2014; Long and Liu, 2016; Qu et al., 2021a). Especially in urban areas, the tension between limited resources and unlimited development demand is becoming increasingly prominent (Chen et al., 2016; Dong et al., 2021; Jiang et al., 2021). To solve this problem, it is necessary to evaluate urban carrying capacity, which is also an important basis for reasonably delimiting the city grade, development order, and expansion boundary (Liu et al., 2018; Li and Li, 2019; Wang W et al., 2020). In recent years, with the continuous renewal and development of theories related to urban development and construction, the concept of urban carrying capacity has attracted a great deal of attention (Shen et al., 2020; Weng et al., 2020; Ren et al., 2021) and become an important representation of the relationship between man and nature. It has also emerged as a basis for measuring the coordination between urban development and construction and environmental contexts (Shen et al., 2020; Qu et al., 2021a; Qu et al., 2021b). Therefore, the scientific evaluation of urban comprehensive carrying capacity and the construction of effective urban development and construction orders are of great theoretical and practical significance for effective resource allocation and territorial space planning.

Comprehensive carrying capacity is an important concept that originated from ecology. It refers to the maximum limit of the number of individuals under specific environmental conditions (Meng et al., 2020; Shen et al., 2020). Subsequently, the concept of carrying capacity has been expanded and extended in various fields of environmental science, economics, geography, and sociology (Sun et al., 2018; Wang et al., 2019; Peng and Deng, 2020) and is often used to study the extent to which the development of something in a region is limited. At present, research on urban carrying capacity tends to be diversified (Liu et al., 2020; Wang et al., 2020a; Zhao et al., 2021). In terms of research objects, most of the current research involves resources and environment carrying capacity (Wu H et al., 2021; Zhou et al., 2021; Zhang et al., 2022), water and land resources carrying capacity (Zhang and Zhu, 2022), land resources carrying capacity (Sun et al., 2020), infrastructure carrying capacity (Wang et al., 2020b), ecological carrying capacity (Wu M et al., 2021), atmospheric carrying capacity (Shen et al., 2022a), and traffic capacity (Gao et al., 2022). With respect to the research area, scholars have mainly focused on single cities or urban agglomerations (Wang W et al., 2020; Gao et al., 2021; Shen et al., 2022a; Zhang and Zhu, 2022). From the perspective of research, the analysis of carrying capacity of land resources and water resources has developed into a comprehensive evaluation of the carrying capacity of human factors, such as population, environment, and transportation (Tian and Sun, 2018; Wang et al., 2020b; Sun et al., 2020; Zhou, 2021; Shen et al., 2022a; Shen et al., 2022b; Gao et al., 2022). The DPESBR model (Peng and Deng, 2020) and three-dimensional balance model (Zhang et al., 2022) have been introduced to urban carrying capacity evaluation, resulting in richer research methods and more novel research ideas and perspectives (Shen et al., 2020; Wang et al., 2020a; Shen et al., 2022b; Zhang and Zhu, 2022). In terms of regulation mechanism, conversations around the relationships between urbanization and carrying capacity (Tian and Sun, 2018; Shen et al., 2022b), coordinated development of economic development and environmental protection (Wu H et al., 2021), and urban resilience to emergencies (Shao et al., 2020) have outlined measures and countermeasures that can be adopted to improve or enhance urban comprehensive carrying capacity.

These achievements enrich the theory and method system of urban carrying capacity research and serve as useful references for this study. However, existing studies on urban comprehensive carrying capacity tend to focus on carrying capacity evaluation, and the research results mostly reflect the carrying state with the maximum carrying capacity of the region (Liu et al., 2021), for example, whether the city is overloaded, but ignore the comprehensive carrying pressure and potential of the city, which reduces the practical guiding significance of the research results.

The comprehensive evaluation of the urban comprehensive carrying capacity, pressure, and potential is the key to optimizing the spatial pattern of land and formulating the development order reasonably. Building from existing research that focuses on the measurement of urban carrying capacity, this study introduces the two variables of carrying pressure and carrying potential and constructs a comprehensive urban carrying capacity model based on "pressure-capacity-potential." The evaluation system of urban comprehensive carrying capacity is constructed from a perspective that combines human and natural factors. This study analyzes the urban carrying capacity of 137 administrative units in Shandong province by means of multi-factor synthesis, step-by-step correction, and comparative evaluation. From the perspective of the size and coordination of the "three forces," order rules of urban development are constructed, the restrictive factors of urban carrying capacity are identified, and the regulation and control strategies of urban development and construction oriented to "three districts and six categories" are put forward, providing effective support for the new round of main function zone construction and territorial space planning.

THEORETICAL FRAMEWORK AND RESEARCH METHODS

Theoretical Framework

In this study, urban comprehensive carrying capacity is defined as the maximum amount of human social and economic activities that can be carried by urban construction space under the premise of

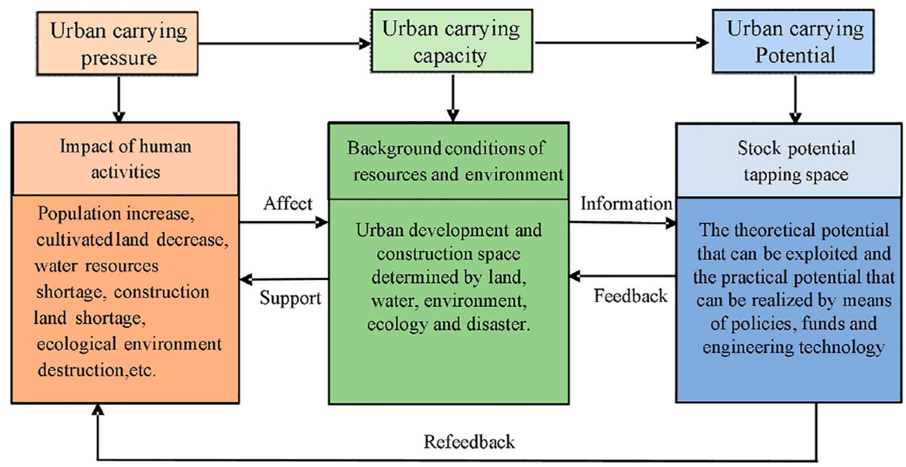

FIGURE 1 | Conceptual model of urban comprehensive carrying capacity.

ensuring ecosystem security and stability within a certain regional scope in the face of the pressure that human activities and social and economic development exert on the demand for urban construction space, make full use of existing resources, and explore the bearing potential through policy or engineering technology adjustment. Therefore, the comprehensive carrying capacity is decomposed into carrying pressure, carrying capacity, and carrying potential. From the perspective of "three forces" coupling and coordination, this study analyzes the carrying level of urban space and systematically answers questions linked to the pressure state faced by urban construction space in a certain period, how much carrying capacity it has, and the extent to which it can carry intense human activities. The conceptual model is shown in **Figure 1**.

First of all, the demand for urban construction land increases with population growth and accelerated urbanization. In order to meet construction needs, urban land presents a "spread out" type of expansion. In addition, pollution caused by industrialization damages the ecological environment and strains the supply of water and land resources. This is the root of "stress." Before the emergence of pressure, various elements of regional resource and environment background together constitute the carrying capacity due to the heterogeneity of the resource environment. The gap between carrying capacity and pressure reflects the state of supply and demand of urban carrying capacity. If the capacity is greater than the pressure, it means that the planned area for urban construction can meet the needs of human production and persist at the present stage. If the capacity is less than the pressure, it means that human demand for construction land cannot be effectively met, which requires the development of new land to fill. In this process, people will employ engineering measures or policies, such as land remediation projects. These measures act on the leading factors of regional development and improve the relationship between the supply and demand of regional land resources or water resources. "Potential" refers to newly added land that is suitable for development as construction land and does not need to occupy ecological land and permanent basic farmland (Liu et al., 2021).

Pressure represents human activities that consume resources and destroy the ecological environment and is the reason for the decline in carrying capacity. Carrying capacity is the comprehensive performance of various environmental elements, and its change provides support for carrying potential. When the carrying capacity decreases, it stimulates the implementation of relevant policies and technology applications and then taps into the potential of stock land to release the potential, which is also the reason for the increase in carrying potential. There are two sources of feedback for carrying potential. One is feedback on resource and environment systems. For example, engineering measures improve the background conditions of regional resources and environments and promote the carrying capacity so that the resource and environment system can better support the pressure brought on by human activities. The other is direct feedback to stress. The increase in carrying potential makes cities and towns more resilient to pressure, and an increase in potentially developable land area can directly meet the needs of human economic activities for construction land. With the continuous advancement of urbanization, in order to meet the needs of social and economic development, the demand for urban construction space and the consumption of resources will increase day by day, bringing new pressure that will be conveyed to the carrying capacity through the feedback process and guide the tapping and release of carrying potential. This kind of "three forces" circulatory feedback action constitutes the urban construction space carrying capacity model. The comprehensive carrying capacity of urban construction is a system composed of pressure, capacity, and potential, which is interrelated and cyclically feedback.

Evaluation Method of Urban Comprehensive Carrying Capacity

Calculation of Urban Carrying Pressure Index

Urban carrying pressure refers to the intensity of human activities carried by the city. The greater the intensity of human activities, the greater the pressure carried by the city. Human activities are usually closely related to land, water resources, and environment,

TABLE 1 | Evaluation index of urban carrying pressure.

Indicator		Computing method	Effect	Weight
Population pressure	Urban population density (Y_1)	Urban population/land area	+	0.26
Land pressure	Urban development intensity (Y_2)	Urban construction land area/urban built-up area	+	0.24
Water resource pressure	Per capita water consumption (Y_3)	Water consumption/population	+	0.24
Environmental pressure	Industrial wastewater discharge per 10,000 yuan of GDP (Y_4)	Discharge of industrial wastewater/GDP	+	0.10
	Industrial SO_2 production of 100-million-yuan GDP (Y_5)	Industrial SO_2 production/GDP	+	0.08
	Production of 10,000 yuan of industrial solid waste (Y_6)	Production of industrial solid waste/GDP	+	0.08

and population is a direct reflection of the intensity of human activities. Therefore, this study comprehensively evaluates the urban carrying pressure from four aspects: population pressure, land pressure, water resource pressure, and environmental pressure (**Table 1**). Population pressure is represented by urban population density. The greater the population density and the greater the construction space required by urban residents for production and living, the greater the pressure. Land pressure is represented by urban development intensity. The larger the construction land area, the greater the land pressure. Water resource pressure is characterized by per capita water consumption. The greater the per capita water consumption, the greater the water resource pressure. The environmental pressure is reflected through the relationship between GDP and waste discharge. The greater the waste discharge per unit of economic output, the greater the environmental pressure.

The urban carrying pressure index is calculated using the multi-factor comprehensive weighting method. Since all the indicators have positive effects on the carrying pressure, the positive range standardization method (Liu et al., 2021) is adopted to normalize the indicators. Then, the entropy weight method is used to calculate the weight of each indicator, and the weighted summation model (**Formula 1**) is used to calculate the pressure index:

$$Y_i = \sum w_{yi} \times y_i \quad (1)$$

where Y_i is the urban carrying pressure index, w_{yi} is the weight value of each pressure indicator, and y_i is the normalized standard value of each pressure indicator.

Urban Carrying Capacity Index Calculation

Urban carrying capacity refers to the maximum carrying capacity that a city can produce by making full and reasonable use of its resources and environment endowment. Urban resources and environment endowment mainly include water resources, land resources, climate, and environment, and geological disasters will have a great impact on urban resources and environment endowment. Therefore, this study selects indicators from land, water, climate, environment, and disaster factors to comprehensively evaluate urban carrying capacity (**Table 2**). The height and slope of land factors are selected to reflect the impact of topographic conditions on urban carrying capacity. The steeper the terrain, the lower the carrying capacity. Water resource elements are represented by total water resources. As the basis of "city size is determined by water quantity," the greater the total amount of water resources, the greater the carrying capacity. Climate factors mainly consider the comfort index, which is used to reflect the temperature and humidity of the city. Appropriate climate conditions can enhance the carrying capacity of the city. Disaster factors mainly consider indicators such as earthquakes and geological disasters. An earthquake is reflected by active fault distance and peak acceleration of ground motion, and geological disaster is reflected by landslide flow, ground subsidence, and ground collapse degree. The greater the degree of disaster, the lower the carrying capacity of the city.

The urban carrying capacity index is calculated using single-factor graded assignment and the integrated correction method (**Formula 2**). First of all, the carrying capacity indicators were divided into five grades and assigned values (5, 4, 3, 2, and 1) (**Table 1**) in descending order based on the methods outlined in "the Guidelines for Evaluating the Carrying Capacity of Resources and Environment and suitability of Territorial Space Development (Trial)." Then, using the principle of short board, based on the grade of land resource elements, the evaluation results of water resources, climate conditions, environmental capacity, and disaster are used to revise them successively. For the lowest value of each individual evaluation, the base grade result is reduced by one level. The carrying capacity of high grade and relative high grade is regarded as high carrying capacity. Those rated as medium and relatively low are classified as medium carrying capacity, and those rated as low are classified as low carrying capacity. Finally, high, medium, and low carrying capacity are assigned the values 3, 2, and 1. The weighted average is carried out according to the proportion of grade area to obtain the urban carrying capacity index of each evaluation unit (**Formula 3**).

$$N_j = min\left(N_{1j}, N_{2j}, N_{3j}, N_{4j}, N_{5j}\right) \quad (2)$$

$$N_{ij} = \sum a_{ij} \times N_j \quad (3)$$

where N_{ij} is the urban carrying capacity index, a_{ij} is the area proportion of different carrying capacity grades, N_j is the single-factor modified grade score, and $N_{1j}, N_{2j}, N_{3j}, N_{4j}, and\ N_{5j}$ are the grade scores of land resources, water resources, climate, environment, and disaster factors, respectively.

Urban Carrying Potential Index Calculation

Urban carrying potential refers to the difference between urban carrying capacity under current utilization state and optimal combined utilization state, including theoretical potential and

TABLE 2 | Evaluation index of urban carrying capacity.

Indicator		Grading assignment				
		1	2	3	4	5
Land resource	Slope (°) (N_1)	>25	15–25	8–15	3–8	≤3
	DEM/m (N_2)	>50	30–50	20–30	10–20	≤10
Water resource	Total water resources/(m^3/km^2) (N_3)	<5	5–10	10–20	20–50	≥50
Climate	Comfort level (N_4)	<32 or >90	32–41 or 82–90	41–51 or 73–82	51–60 or 65–73	60–65
Environment	Atmospheric environmental capacity index (N_5)	≤0.2	0.2–0.4	0.4–0.6	0.6–0.8	>0.8
	Water environmental capacity (t/km^2) (N_6)	<0.04	0.04–0.14	0.14–0.39	0.39–0.96	≥0.96
		<0.8	0.8–2.9	2.9–7.8	7.8–19.2	≥19.6
Disaster	Distance from fault zone (m) (N_7)	<30	30–100	100–200	200–400	>400
	Ground motion peak acceleration (g) (N_8)	≥0.30	0.20	0.15	0.10	≤0.05
	Land subsidence accumulated settlement (mm) (N_9)	>2400	1600–2400	800–1600	200–800	<200

The comfort level was characterized by temperature and humidity index, THI = T-*0.55 × (1-f) × (T-58), where* THI *is temperature and humidity index,* T *is the monthly mean temperature (Fahrenheit), and* F *is the monthly mean relative humidity of the air. The water environmental capacity is controlled by COD and* NH_3*-N.*

TABLE 3 | Evaluation Index of urban carrying potential.

Indicator		Computing method	Effect	Weight
Theoretical potential	Urban idle land revitalization potential (P_1)	The size of unused land within cities and approved land acquisition or conversion of agricultural land, but not supplied	+	0.40
	Industrial and mining abandoned land reclamation potential (P_2)	Scale of industrial and mining land to be restored and reclaimed	+	0.25
	Rural residential land remediation potential (P_3)	Scale of land consolidation for rural residential areas	+	0.35
Correction factors	Per capital GDP (P_4)	GDP/total population	+	0.35
	Local financial revenue (P_5)	The local financial revenue of each county (city, district)	+	0.30
	Urban land price level (P_6)	Average price of urban commercial, residential, and industrial land	+	0.35

practical potential. The urban carrying potential index is selected according to the theoretical potential and the influencing factors of its release (**Table 3**). Among them, theoretical potential includes urban idle land revitalization potential, rural residential land remediation potential, and industrial and mining abandoned land reclamation potential. The correction factors include per capita GDP, local fiscal revenue, and urban land price level, which, respectively, represent the investment capacity and output benefit of national and local governments. The greater the investment capacity, the higher the output and efficiency, and the greater the possibility and enthusiasm for the utilization of urban stock land.

The urban carrying potential index is calculated using the factor correction method (Qu et al., 2012). First, the theoretical potential and socio-economic correction coefficient of urban carrying capacity are calculated using a multi-factor weighted model. Then, the potential index of different administrative units is calculated using the potential correction model (**Formula 4**).

$$P_i = P(T_i) \times f(C_i) \tag{4}$$

where P_i is the urban carrying potential index, $P(T_i)$ is the theoretical potential of urban carrying capacity, and $f(C_i)$ is the correction coefficient of the theoretical potential of urban carrying capacity.

Calculation of Urban Comprehensive Carrying Capacity Index

For urban comprehensive carrying capacity, the greater the pressure, the more the demand for urban construction space. As a result, the city will continue to expand outward, and the supply capacity of resources and the environment will decrease accordingly. The government will take policy and engineering measures to tap into the supply potential of urban construction land and improve the carrying capacity so as to better meet the development needs for construction space. Urban comprehensive carrying capacity is a complex system based on the relationship between development pressure and supply capacity and supplemented by potential exploitation. When the supply capacity is higher than the development pressure, the role of potential exploitation is weak, the cost of urban development is low, and the urban comprehensive carrying capacity mainly depends on the carrying capacity. When the supply capacity is lower than the development pressure, the role of potential exploitation is enhanced. The development cost driven by the revitalization of urban stock land is high, and urban comprehensive carrying capacity depends on the comprehensive effect of carrying capacity and carrying potential. Therefore, the method of subsection and differential weight (**Formula 5**) is adopted to calculate the urban comprehensive carrying capacity index:

TABLE 4 | Urban development order rules based on pressure–capacity–potential model.

Zones	Pressure–capacity–potential	Carrying types	Codes
Priority development zone	N ≥ Y and Q ≥ Y	I	122,123,132,133,233
		II	111,222,223,333
Key development zone	N ≤ Y and Q ≥ Y	III	112,113,213,212,313,323
	N ≥ Y and Q ≤ Y	IV	221,231,232,331,332,121,131
Moderate development zone	N < Y and Q < Y	V	211,322

$$CC_i = \begin{cases} \alpha_1 N_i + \beta_1 P_i\,,\ (N_i \geq Y_i) \\ \alpha_2 N_i + \beta_2 P_i\,,\ (N_i < Y_i) \end{cases} \tag{5}$$

where CC_i is the urban comprehensive carrying capacity index and N_i, P_i, Y_i are urban carrying capacity, potential, and pressure indexes, respectively. $\alpha_1, \alpha_2, \beta_1, \beta_2$ respectively represent the weight values of the "three forces" under different relationships. In order to reflect the difference in carrying capacity and potential under different scenarios, the values of $\alpha_1, \alpha_2, \beta_1, \beta_2$ are 0.75, 0.5, 0.25, and 0.5, respectively.

Construction of Urban Development Order Based on Carrying Capacity Combination

It is necessary to comprehensively consider the grade and coordination degree of the city carrying pressure, capacity, and potential and construct the urban development order pattern according to the priority relationship (**Table 4**) (Gao et al., 2022). Firstly, the "three forces (Y, N, Q)" index score is divided into three grades from small to large using natural breakpoint method and is represented by 1, 2, and 3, forming the relationship combination of pressure, ability, and potential expressed by 3-bit coding. The first digit indicates the pressure level, the second digit indicates the ability level, and the third digit indicates the potential level. Then, the comprehensive goal of urban development is to alleviate carrying pressure, ensure carrying capacity, and enhance carrying potential. Taking Y value as a reference, the size differences of Y, Q, and N are compared, respectively. According to the grade intensity relationship of "three forces," the basic evaluation unit is merged, and the urban priority development zone is divided. Furthermore, considering the coordination among different grade combinations of the "three forces" and the principle of "high-level coordination first, middle-level coordination second, and low-level coordination last," the development types of each evaluation unit are identified in turn to form the urban development and construction system of "three districts and six types."

STUDY AREA AND DATA SOURCES

Study Area

Shandong province is located on the east coast of China in the lower reaches of the Yellow River and has the longitude and latitude range 114°20′ E–122°43′ E (**Figure 2**). It is mountainous at its center with low-lying flat and gentle hills to the east. The provenance also has a warm temperate monsoon climate. With 16 prefecture-level cities and 137 county-level administrative regions under its jurisdiction, the province is the third most populous province in China and one of the country's most developed and rapidly developing provinces. In 2020, the urbanization rate of Shandong province was 62%, and the gross regional product was 7312.9 billion yuan. The tertiary industrial structure was 7.3:39.1:53.6, and the commercial service industry with the city as the carrier was absolutely dominant. According to the main data bulletin of the third land survey in Shandong province, the area of construction land in Shandong province in 2019 was 4,588,239.02 ha. Among them, the land area of towns, villages, industry, and mining is 2,806,478.74 ha, the land area of transportation is 446,405.05 ha, and the land area of water and water conservancy facilities is 1,325,355.23 ha. In 2019, China put forward a strategy for ecological conservation and high-quality development of the Yellow River Basin. Shandong province, as an important urban agglomeration in the Yellow River Basin, plays an important role in the high-quality development of the Yellow River Basin. In addition, Shandong province is also a national comprehensive pilot zone for the transformation of old and new driving forces. In recent years, with the increasing intensity of urban development in the province, the problems of fragile ecological environment, resource background degradation, and insufficient leading role of central cities are prominent. Given this context, it is crucial to comprehensively consider natural and socio-economic factors while evaluating urban comprehensive carrying capacity and exploring reasonable development plans.

Data Sources

The data used in this study consist of social and economic data and resource and environment data. The social and economic data include population and economic development data that were mainly pulled from the 2020 statistical yearbook of Shandong province and prefectural cities. The resource and environment data include information about land resources, water resources, environment, meteorology, disasters, and the ecological environment. The land-use status data were collected from the third Land Resources Survey database of Shandong province (2019). The land-use planning data come from the general land-use plan of Shandong province (2006–2020). The administrative division data are from the National Basic Geographic Information Center (http://www.ngcc.cn/). The digital elevation and MODISNDVI data come from the geospatial data cloud (http://gscloud.cn/) with a resolution of 30 m. The water resources data were obtained from long-term

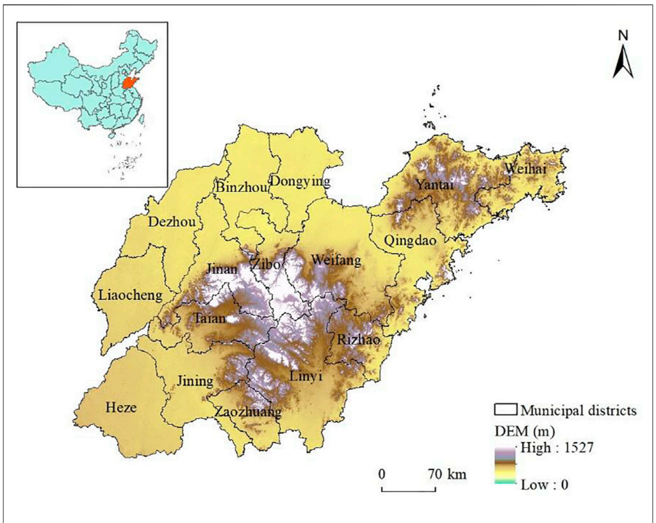

FIGURE 2 | Study area.

precipitation observation data that were gathered by meteorological stations in the study area and adjacent areas in 2019. The soil data were obtained from a detailed investigation of soil pollution status that was conducted in the study area and surrounding areas in 2019, and the soil pollutant content distribution layer was obtained by analyzing the main pollutant content at each point and spatial interpolation. Based on the multi-year average daily temperature and active accumulated temperature ≥ 0°C of meteorological stations in 2019, the Kriging spatial interpolation method was used to obtain active accumulated temperature layers. Geological disaster data, such as active fault and land subsidence, were obtained from the 2019 geographical National Conditions survey data of Shandong province. On this basis, all kinds of maps are transformed into a unified coordinate system to form the basic database of urban comprehensive carrying capacity evaluation.

RESULT AND ANALYSIS

Analysis of Urban Comprehensive Carrying Capacity

Carrying Pressure

The urban carrying pressure index of cities in Shandong province ranges from 0.23 to 0.92, with an average value of 0.45. The carrying pressure is general, and there are obvious differences among counties. The carrying pressure is divided into three grades using the natural breakpoint method (**Figure 3A**). The carrying pressure of Shandong province is mainly at the first level, which includes 61 counties that account for 44.53% of the area and are concentrated in the east, central, and southwest of Shandong province. The secondary region includes 54 counties that account for 39.42% of the area and are concentrated in the northwest, southwest, and southeast coastal areas of Shandong province. The tertiary region includes 22 counties that account for 16.06% of the area and are mainly distributed in the municipal districts of Dongying, Zibo, Yantai, Linyi, and Dezhou. The differential distribution of pressure index in Shandong province is closely related to population and the endowment conditions of water and soil resources. Among them, the first-level regions are rich in land resources, especially in the south of Shandong province, which is abundant in water resources and can meet the needs of an increasing urban population with little pressure. The secondary regions are mainly distributed in densely populated areas, and the population increase intensifies the supply pressure of urban land resources and water resources, especially in the case of the serious water resource shortages in southeast Shandong. Water resource shortages are the main source of pressure in the third-level regions, especially in the northern Shandong province, where the demand for water resources for urban industrial and living development is not fully met, which increases the pressure on urban development and construction.

Carrying Capacity

The urban carrying capacity index of Shandong province is between 0 and 1 with an average value of 0.63, indicating that the overall carrying capacity is high and the spatial agglomeration characteristics are significant. The urban carrying capacity is divided into three grades using natural breakpoint method (**Figure 3B**). The first-level region consists of 38 counties that account for 27.74% of the area and are mainly distributed in southwest Shandong, southeast Shandong, east Shandong, and north Shandong. This region is mainly affected by mountain and hill landforms and geological disasters, and its urban carrying capacity is low. The second grade includes 34 counties that account for 24.82% of the area and are relatively concentrated in the coastal areas of western Shandong and northern Shandong. The main restricting factors are the low environmental volume in western Shandong and the relative shortage of water resources in the northern Shandong coastal area. The third level consists of 65 counties that account for 47.45% of the area and are mainly distributed in the central and northwestern and eastern coastal areas of Shandong province. These counties have developed river systems, flat terrain, no obvious geological disasters, and good resources and environment, which are factors suitable for urban development and construction.

Carrying Potential

Shandong province's urban carrying potential index is between 0.08 and 0.78 with an average of 0.28. The overall potential level is low, and the spatial distribution is relatively scattered. The urban carrying potential index is divided into three grades using the natural breakpoint method (**Figure 3C**). The first-level region includes 49 counties, accounting for 35.77% of the area. It is slightly similar to the first-grade bearing capacity region and has relatively high theoretical potential. At the same time, the low level of social and economic development affects the release of theoretical potential to a certain extent. The second-level region is the largest, covering 60 counties that account for 43.80% of the area and are mainly distributed in central Shandong, western Shandong, and part of the Peninsula. These regions have average theoretical potential, relatively high levels of social and economic

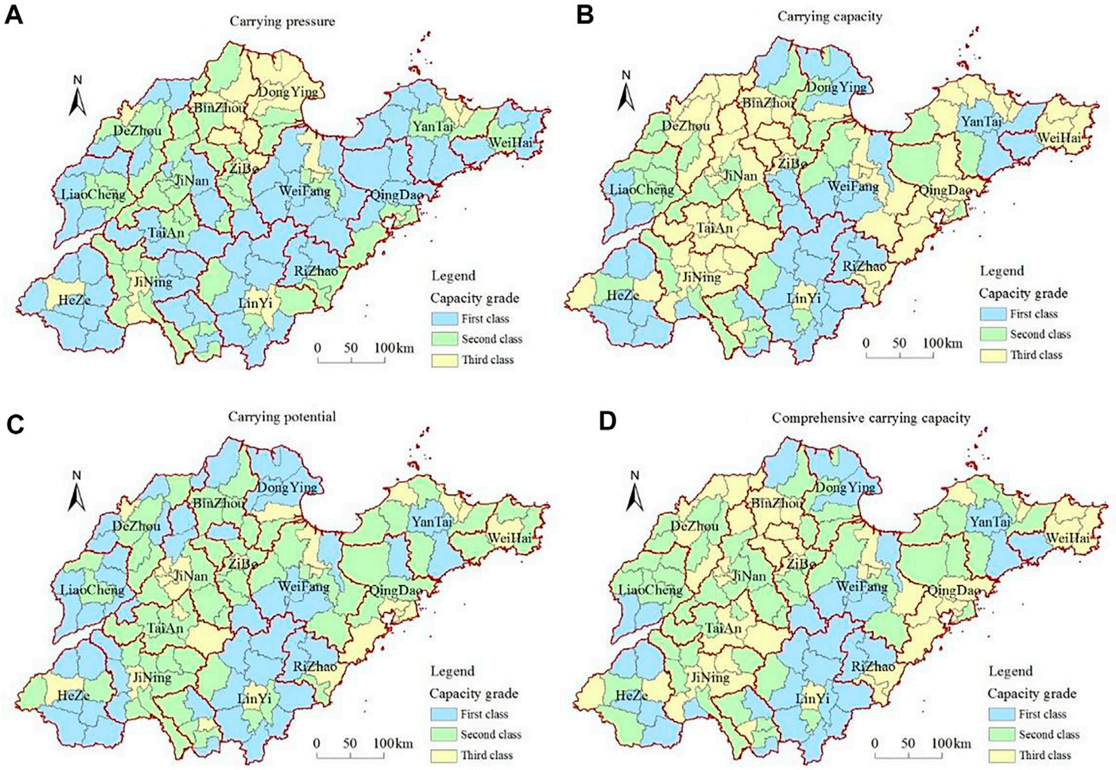

FIGURE 3 | Grades of urban comprehensive carrying capacity in Shandong province. **(A)** Carrying pressure, **(B)** carrying capacity, **(C)** carrying potential, and **(D)** comprehensive carrying capacity.

development, and medium levels of comprehensive potential. The third level includes 28 counties that account for 20.44% of the area and are mainly distributed in the vicinity of municipal districts. The potential of existing cities and industrial and mining land is large, and the social and economic development level is relatively high, which is conducive to the release of potential.

Comprehensive Carrying Capacity

The index of comprehensive urban carrying capacity in Shandong province is between 0.04 and 0.93 with an average of 0.54, indicating a high level of comprehensive carrying capacity on the whole (**Figure 3D**). There are 41 counties whose urban carrying capacity index is lower than the urban carrying pressure index, accounting for 29.93% of the area. The comprehensive carrying capacity index is low, ranging from 0.04 to 0.7 with an average of 0.21, which is also the main area of first-level carrying capacity. Among these counties, the urban carrying pressure of northern Shandong is large, and the urban carrying capacity and potential are low. Other regions are relatively low in urban carrying pressure, capacity, and potential.

There were 96 counties whose urban carrying capacity index was higher than the stress index, accounting for 70.07% of the total. The comprehensive carrying capacity index was relatively large, ranging from 0.28 to 0.93 with an average of 0.69, and the spatial distribution was relatively balanced. Among these counties, the secondary carrying capacity region includes 46 counties that are mainly distributed to the west of central Shandong province. The urban carrying capacity is mainly middle–low level, and the urban carrying capacity and potential are mainly middle–high level. The region with the largest comprehensive carrying capacity includes 50 counties, mainly cities, counties, and the surrounding areas of each city. The urban carrying capacity is mainly medium–low level, while the carrying capacity and potential are high.

Type and Pattern of Urban Development

The spatial agglomeration characteristics of the six types of urban development and construction and the three regions constituted by them are obvious in Shandong province (**Figure 4A**). In terms of the priority of development order, the number of counties from class I to class VI was normally distributed, and there were slightly more counties in class III and only two in class VI. The corresponding development areas are mainly key development zones, including 62 counties. The number of priority development zones and moderate development zones is 56 and 19, respectively. The details are shown in **Figure 4B**.

Priority Development Zone

Under the conditions of the potential released by the existing resources and environment, funds, engineering measures, and

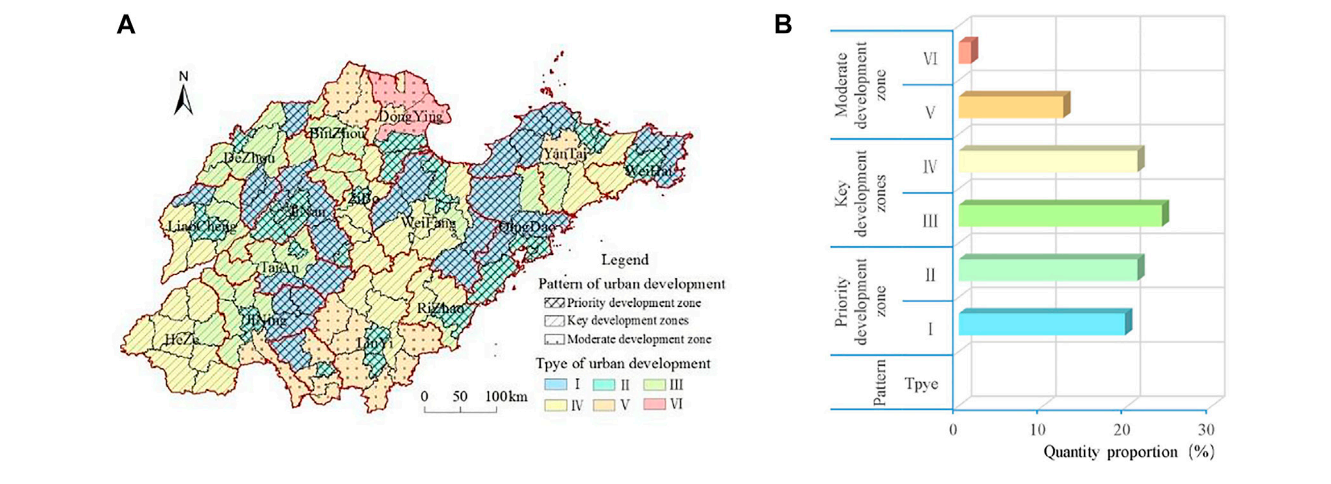

FIGURE 4 | (A) Pattern of urban development order and **(B)** quantity proportion in Shandong province.

policies, the urban carrying capacity and potential can cope with the pressure of urban development and construction brought on by social and economic development. These areas can give priority to urban construction and development at the beginning of the 14th Five-Year Plan. There are 27 counties in the category I region, accounting for 19.71% of the total, and mainly distributed in the belt area of Jiaodong Peninsula and Jinan, Tai'an, and Jining. This type of region has low urban bearing pressure, high capacity and potential, strong comprehensive urban carrying capacity, and few restricted factors and is the core of the three development areas of Shandong province (the Jiaodong City cluster, the provincial capital city cluster, and the southern Shandong City cluster). During planning, the construction land index should be given priority over urban development and construction in this region. Class II includes 29 counties, accounting for 21.17% of the total, mainly distributed in the periphery of class I and the municipal districts of Linyi, Jining, Liaocheng, and Dezhou. The urban carrying pressure, capacity, and potential of this type are relatively coordinated and all at a high level. Favorable social and economic conditions provide an important guarantee for unleashing potential, while abundant potential provides sustained support for social and economic development.

Key Development Zones

Only one aspect of the existing resources and environment and stock space potential can cope with the pressure of urban development. Among them, class III includes 33 counties, accounting for 24.09% of the total and are concentrated in Dezhou, Liaocheng, Jining, and Binzhou and scattered in Weifang and Yantai. The relationship between the urban carrying capacity of this type is relatively moderate, and the background condition of resources and environment is relatively superior, but it can release less potential. With the increasing pressure of economic development on urban development and construction, it is difficult to continuously meet the demand for construction land. In the future, intensive utilization of land supply should be strictly implemented, and the potential of stock space should be fully explored at the same time. Category IV includes 29 counties that account for 21.17% of the total and are mainly located in Heze, Linyi, Weifang, and Rizhao. The coordination of urban comprehensive carrying capacity of this type is also at a medium level. The existing resources and environment cannot cope with the demand pressure of urban development and construction. However, the potential scale is relatively large, and the potential should be fully released in the future to eliminate the potential risk of increased pressure.

Moderate Development Zone

The carrying system of urban construction is in an unbalanced state, and the long-term carrying pressure destroys the resources and environment. Even though increasing support for engineering measures and policies can help, it is difficult to effectively alleviate the pressure of urban development and construction. Category V includes 17 counties, accounting for 12.41% of the total and are mainly distributed in the vicinity of Nansihu Lake in southern Shandong and the Yellow River Delta in northern Shandong. The urban carrying capacity and potential of this type are less than the pressure, and the combined force of the two can basically support the needs of urban development. In the future, we should control the scale of urban development and construction, pay attention to the full combination of the utilization of current resources and the utilization of stock space, and take measures to ensure urban development. Category VI includes two counties, which are distributed in the estuary of the Yellow River in Dongying. The urban carrying capacity and potential of this type are far less than the pressure, and the coordination is seriously unbalanced. Although it is located in a plain area, this region's resources and environment are obviously limited, and the ecological importance is more prominent. Large-scale urban development and construction activities should be banned in the future, and human activities can be carried out appropriately on the premise of ensuring the stability of the ecosystem.

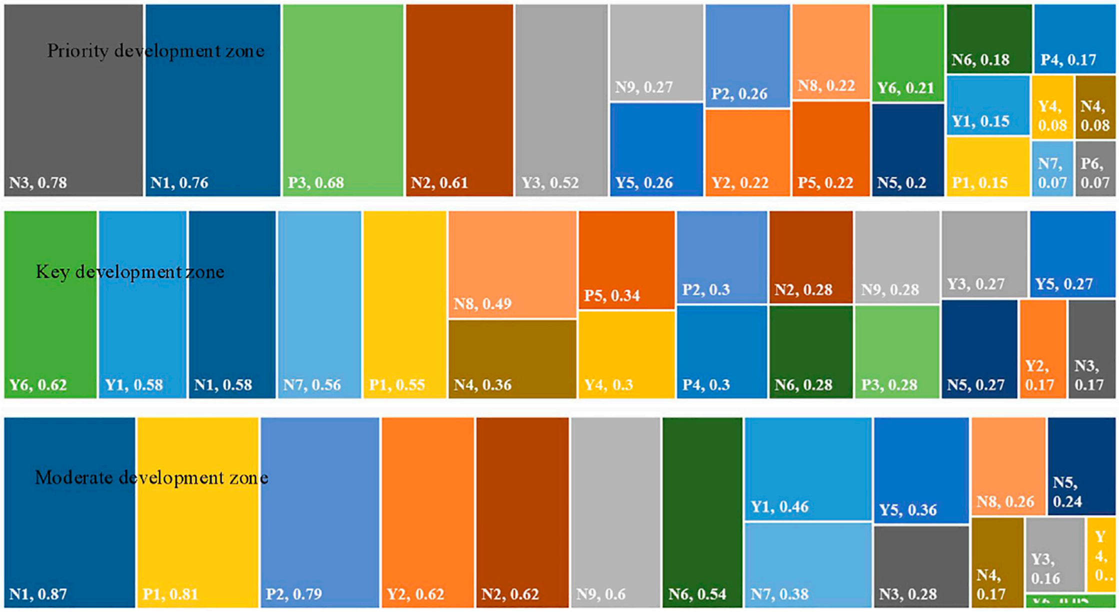

FIGURE 5 | Obstacle factors of urban comprehensive carrying capacity in Shandong province.

The Limiting Factors and Control Strategies of Urban Development in Different Types of Regions

The diagnostic model of obstacle factor was used for reference, and the evaluation value and optimal value of each index of carrying pressure, capacity, and potential were compared. The weight of each indicator was taken as the contribution degree. The equivalence of "three forces" was taken as the basis for distinguishing significant obstacle factors. The restrictive factors of urban development and construction in different types of regions are obtained (**Figure 5**), and differentiated control strategies are put forward.

(1) The obstacle factors of urban comprehensive carrying capacity in development zones are less and include Y3, N1, N2, N3, and P3. These zones are mainly limited by water resource shortages, terrain conditions, and low potential for urban industrial and mining utilization. Therefore, this region should improve quality and efficiency, give full play to its own economic advantages, increase the construction of water resource guarantee projects, and guarantee the water resource supply for urban development through water diversion, storage, and water-saving measures. In addition, with the formulation of a new round of territorial space planning comes reasonable demarcation of urban development boundaries. Ecological protection should be strengthened in mountainous and hilly areas located outside of the city. Low hills within the city should be laid out as urban parks. The coordination between urban construction and ecological protection according to local conditions should also be promoted. At the same time, on the premise of ensuring the intensive use of urban land resources, we should implement certain policies, such as comprehensive land improvement, across the whole region and link the increase and decrease in urban and rural construction land. By tapping into the potential of rural construction land and replacing urban and rural land, we will solve the problem of insufficient land supply in order to pave the way for future urban development and constantly improve the competitiveness of cities.

(2) There are many limiting factors of urban comprehensive bearing capacity in key development zones, including nine factors: Y1, Y2, N1, N2, N5, N8, N9, P2, and P6. The main problem lies in the large pressure of population and land and factors such as topographic conditions, environmental capacity, geological disaster sensitivity, urban and rural construction land potential, and urban land price restrict urban development. Therefore, the region should stick to the path of new-type urbanization and green development. We should give priority to the control of urban water and air environment and the reduction and prevention of disasters, strengthen the construction of pollution reduction and disaster-fighting infrastructure, encourage enterprises to develop energy conservation and emission reduction technologies, reduce the discharge of pollutants, and gradually change the urban living environment. At the same time, we should intensify the improvement of existing construction land, focusing on the reconstruction of villages in cities, and the improvement of abandoned industrial and mining land. We should also promote the renewal of old urban areas, increase space for flexible urban

development, guide the directional expansion of cities, promote the stability and improvement of urban land prices by improving the quality of cities, and promote the high-quality development of the regional economy.

(3) The moderate development zone has the most limiting factors, including Y1, Y2, Y4, Y5, Y6, N3, N5, N6, P1, P2, P4, P5, and P6. The main problem is that the development and construction of cities are restricted by factors such as poor terrain conditions, insufficient water resources, low environmental capacity, low stock potential, and weak economic capacity under the conditions of large pressure on population, land, and environment. Therefore, the region should fully implement the strategy of ecological protection and high-quality development. First of all, the system of carrying capacity control, regional access, and permission for conversion of ecological space should be implemented to ensure that the area of ecological space is not reduced, the ecological function is not reduced, and the ability to guarantee ecological services is gradually improved. At the same time, we should implement water-saving and emission reduction policies, strengthen the production technology improvement of enterprises that use large amounts of water resources and discharge serious pollution, gradually improve the quality of regional air and water environment, and improve the purification effect of the environment. Secondly, scientific planning of urban development space, rational optimization of industrial structure, strict control of urban development scale, increase per unit of land input, and improve the efficiency of urban land use. Moreover, we should properly tap into the potential of construction land in urban and rural areas in the region. On the premise of giving priority to rural development, surplus targets should be used to supplement the needs of urban development and promote integrated urban–rural development in the region.

CONCLUSION AND DISCUSSION

Based on the concept of urban carrying capacity, this study synthesizes external and internal urban factors and constructs the concept model of "pressure-capacity-potential" urban comprehensive carrying capacity and the corresponding evaluation index system.

By using the methods of multi-factor weighed summation, graded assignment, and graded modification, we were able to calculate subsection variable weight, the carrying pressure index, the capacity index, the potential index, and the comprehensive carrying capacity index. We then set urban development order rules using the two aspects of comprehensives and coordination and formed the urban development pattern of "three districts and six types." Finally, the study puts forward differential suggestions for the restrictive factors of urban development of different carrying types. The research results of this study have strong practicability and can provide guidance for the optimization of regional main function areas and the orderly arrangement of urban development. The main conclusions of this study are as follows:

Firstly, comprehensive evaluation of urban comprehensive carrying capacity from three aspects of urban carrying capacity, carrying pressure, and carrying potential is helpful for decision-makers to accurately and comprehensively understand the characteristics of urban carrying capacity, and then formulate development strategies in line with reality.

Second, the urban carrying pressure in Shandong province is closely related to population and water and soil resource endowment conditions. The carrying pressure in Shandong is mainly medium and low, but there are a few areas with high pressure. These areas account for 16.06% of the province and are mainly distributed in the municipal districts of Dongying, Zibo, Yantai, Linyi, and Dezhou. The overall urban carrying capacity of Shandong province is high, and the high- and middle-grade capacity areas account for 72.26% of the total and are mainly distributed in the central, western, and northeastern coastal areas of Shandong. The low-grade capacity areas are mainly affected by mountain and hill landforms and geological disasters. The overall urban carrying potential of Shandong province is low, and the potential areas of middle and low grades account for 79.56% of the total, which is mainly restricted by low theoretical potential and unbalanced social and economic development. The overall level of urban comprehensive carrying capacity in Shandong province is high, and regions where the urban carrying capacity is higher than the carrying pressure are dominant. The unbalanced and low level of "three forces" in some regions restricts its comprehensive carrying capacity.

Third, the urban development pattern of "three districts and six categories" proposed by the study has obvious spatial agglomeration characteristics. The number of counties (cities and districts) in the three main areas of priority development, key development, and moderate development decreased successively, accounting for 45.26, 40.88, and 13.87% of the total, respectively. On the whole, it is suitable for urban development and construction. The number of counties (cities, districts) of urban development types from class I to class VI was normally distributed. The high-grade types are mainly distributed in Jiaodong Peninsula, the Jinan–Tai'an–Jining development belt, and the municipal districts of Weifang, Linyi, Liaocheng, and Heze. Moderate development zones are concentrated in Nansihu Lake and the Yellow River Delta.

Four, the urban development of Shandong province is mainly restricted by landform, water resources, environmental capacity, and geological disasters. The degree of constraint varies in different development areas and types. Priority development zones should focus on improving quality and efficiency and give full play to their economic advantages to solve the problem of insufficient water and land resources. Key development zones should follow the path of new-type urbanization and green development and address problems such as low urban quality and inadequate supporting facilities.

Moderate development zones should fully implement the strategy of ecological protection and high-quality development and coordinate ecological protection and restoration with urban and rural integrated development.

It should be noted that due to the limitation of difficult data acquisition, this study only analyzed the urban comprehensive carrying capacity in Shandong province in 2019. It will provide more effective information to analyze the spatio-temporal variation characteristics of urban comprehensive carrying capacity based on big data.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

Conceptualization, BL; methodology, BL and MG; formal analysis, BL and MG; data curation, BL; writing—original draft preparation, LZ and CQ; writing—review and editing, LZ and CQ; visualization, BL and HJ; supervision, ZZ and GD. All authors have read and agreed to the published version of the manuscript.

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Risk Assessment and Regulation Strategy of Farmland Marginalization: A Case Study of Mengjin County, Henan Province

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The marginalization of farmland is the progression of farmland utilization from high to low net profit, and the abandonment of farmland is its extreme form, and cultivated land marginalization is an important problem that needs to be properly controlled in the process of economic and social development. In this paper, cultivated land was extracted from the land database and evaluated from the aspects of natural suitability, farming convenience and farming opportunity cost, etc. By setting the combined weight of the three evaluation results and stacking them with the forest land extracted from remote sensing images, the potential risk range of cultivated land marginalization was identified, and an empirical study was carried out in Mengjin County, Henan Province. Results showed that: 1) the natural factors of cultivated land were stable and not easy to change, and the natural suitability was the basic condition that affected the marginalization of cultivated land. There was a spatial correlation between the natural suitability of cultivated land and the cultivation convenience, and the risk of marginalization of cultivated land with poor natural suitability and inconvenient cultivation conditions was higher. 2) The high-opportunity cost areas are mainly distributed in the inner suburbs of cities, and the cultivated land in this area is highly likely to be adjusted to high-benefit agriculture such as flowers, vegetables and sightseeing agriculture. Therefore, the risk of abandonment of cultivated land is less. 3) Adjusting cultivated land with poor natural suitability and inconvenient tillage conditions to forest land is conducive to the restoration of regional fragile ecology. Comprehensive improvement of cultivated land with high natural suitability but inconvenient tillage is an important way to delay the marginalization of cultivated land. This study provides a new idea for the formulation of farmland marginalization prevention and control policies at county level.

Keywords: farmland, marginalization, natural suitability, farming conditions, opportunity cost

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1 INTRODUCTION

The marginalization of farmland is the progression from high to low net profit of farmland utilization, and the abandonment of farmland is its extreme expression (Aide and Grau, 2004). Since the reform and opening up of China and with rapid urbanization, job opportunities for farmers have increased substantially, and non-farm incomes have increased rapidly, these increases have led to increased migration of the workforce from rural to urban areas and non-farming sectors (Xin et al., 2011). From 2002 to 2013, the average reduction in the agriculture workforce in China was 11.33 million persons (Li et al., 2017). Due to the influences of both a continuous increase in non-farm incomes and a gradually declining proportion of farm income to the total income of rural families, the opportunity cost of farming has increased extensively. This phenomenon is especially pronounced in remote mountainous regions that have been experiencing significant migration of young workers from farming villages to non-agriculture sectors. Because the agricultural sector is labor intensive, the decline and aging of the workforce and the continuous marginalization of low-quality farmland exemplified by hillside farmland have led to the abandonment of farmland with poor production quality and yield (Rudel et al., 2005; Edward et al., 2010; Baumann et al., 2011; Strijker, 2005; Li and Zhao, 2011).

The marginalization and abandonment of farmland is a common phenomenon in developed countries in Europe and North America. This trend has attracted the attention of many scholars and governments. In the early 1990s, Mather (1992) coined the term "forest transition," which refers to situations in which the forested area of a country or a region transitions from net reductions to net increases in a U-shape trend. This phenomenon was first observed in developed countries in Europe and North America and was subsequently observed in Latin America and Southeast Asia (Sklenicka et al., 2014; Ruskulea et al., 2013; Romero-Calcerrada and Perry, 2004; Sayadi et al., 2009; Terres et al., 2015). Alcantara et al. (2012) Using MODIS time series data, Alcatraz et al. Studied the abandonment of farmland in Central and Eastern Europe and found that in 2005, approximately 1/5 of local farmland was abandoned. Studies in Europe, America and new industrial countries have proved that economic growth creates a large number of non-agricultural employment opportunities, which is an important reason for the transformation of inferior farmland into forest land (Li et al., 2017).

China has a large mountainous area and a large proportion of sloping farmland. Restricted by terrain in mountainous areas, mechanization development is blocked. With the massive transfer of labor force in mountainous areas, farmland abandonment in mountainous areas is becoming more and more serious. Shao et al. (2015) made a systematic analysis on the characteristics of farmland marginalization in mountainous areas of China on a large scale based on sampling survey data, and believed that the rise of agricultural labor price increases the cost of farming. In the case of relatively stable agricultural product prices, agricultural production profits are compressed, leading to the marginalization of farmland. Many scholars chose different research regions to conduct empirical analysis (Yan et al., 2016; Li et al., 2017; Li and Li, 2017). The above studies have provided an in-depth understanding of farmland abandonment and forest transformation in mountainous areas of China (Li and Li, 2019). From the microcosmic layer, to give up farming is each family decisions, Zhang et al. (2014) used Wulong county peasant household survey data to prove that the unit land area of agricultural labor less farmers, the higher probability of abandoned. Based on the case of Chongqing, Shi et al. (2016) proved that farmers' abandonment rate of farmland increased with the increase of cultivation distance, plot elevation and plot slope. In recent years, in the process of agricultural industrial structure adjustment, induced some areas of cultivated land "non-grain" tendency. In some places, the adjustment of agricultural structure is simply understood as reducing grain production, some operators illegally plant trees and dig ponds on basic farmland, and some industrial and commercial capital transfer farmland to non-food crops. Represented by functional decline, the use of cultivated land in many places presents adverse trends such as "marginalization" and "abandonment of farmland" (Li and Li, 2016; Wu et al., 2019; Xue and Zhang, 2017; Zhang, 2016).

Through the above analysis it can be seen that the current research on factors affecting farmland marginalized identification mainly concentrated in two aspects: First, on a macro scale, the development trend of farmland abandonment and forest transformation in mountainous areas was confirmed by using the change rate of mountainous area NDVI and farmland, and it was considered that the limitation of mountainous terrain conditions was the main factor leading to farmland marginalization. This kind of research can effectively reflect the overall situation of farmland marginalization in mountainous areas, but it cannot accurately identify the parcel level and explain the causes of farmland marginalization in plain areas. The second is to examine the impact of parcel and families on farmland abandonment by using household survey data at the micro scale, and to conclude that lack of household labor and lack of farmland transfer are the main factors leading to farmland marginalization. Based on the survey data, this kind of research concludes that if there are too few samples, it is suspected of overgeneralization. If there are too many samples, it is time-consuming, laborious, and not economically feasible. Moreover, it cannot effectively predict the potential risk range of farmland marginalization, and it is easy to form unenforceable "air policy" in specific prevention and control operations.

China has attached great importance to the protection of cultivated land, and established a relatively perfect cultivated land protection system (Liu et al., 2020; Lu et al., 2021; Zhou et al., 2021). However, due to the gradual, complex, and unstable characteristics of cultivated land marginalization, Furthermore, many factors influence this process, such as environmental conditions, workforce characteristics, the development level of the agricultural sector, geographic conditions, the level of economic development, and agricultural policies. Therefore, the extent of farmland marginalization is expected to vary among villages, types of farmers, and farmland parcels within the same landform unit, resulting in the increasingly serious trend of cultivated land non-grain conversion (Su et al., 2020; Yang and Zhang, 2021; Wang and Hou, 2021). The General Office of the State Council has made it clear that the limited cultivated land resources must be given priority to grain production, and the conversion of cultivated land to forest land, garden land and other types of agricultural land should be strictly controlled. At present, with the upgrading of consumption and the tightening of resources and environment, China's grain production and demand will maintain a tight balance for a long time. The marginalization of cultivated land is an important symbol of the degradation of cultivated land resources. The disorderly development of cultivated land marginalization is bound to impact on food security. Under the influence of the COVID-19 pandemic and the conflict between Russia and Ukraine, international food prices have been rising. With the alarm of the food crisis sounding, issues related to farmland protection and food security have been escalating again. Therefore, it is of positive and practical significance to identify the potential risk range of future marginalization of cultivated land and formulate targeted prevention and control policies for maintaining food security.

Farmland protection is among the top priorities for the Chinese government (Li, 2019). The "Dynamic Balance of Total Farmland Area Policy" (DBTFA) in the land management system was created to ensure the stability of farmland area in china. Under the enormous pressure to conserve farmland, as one of their performance evaluation criteria, local governments often disregard the actual utilization of farmland in their data on farmland statistics, although some farmland has been abandoned or adjusted to forest land, it is still counted as farmland in the farmland database. Therefore, this study extracted farmland data from the land database, and evaluated the natural suitability of farmland, cultivation convenience and opportunity cost of farmland in a multi-dimensional manner. The weights of different evaluation dimensions were set, and different combination schemes were simulated, which were superimposed with the forest land extracted from remote sensing images to identify the main controlling factors affecting the marginalization of farmland, so as to provide a reference for the formulation of reasonable and effective policies of farmland protection and utilization.

2 THEORETICAL FRAMEWORK

2.1 Identification of Farmland Marginalization Factors

Using a stepwise algorithm and taking into account natural suitability, farming conditions, and opportunity cost, we perform a multidimensional analysis of the spatial distribution of farmland marginalization. First, the level of natural suitability is the foundation for the identification of farmland marginalization. Historically, people have selected for use as farmland land that has natural conditions conducive to cultivation. Farmland with poor natural conditions is only cultivated to sustain food supply, and the level of natural suitability even in modern society remains the key consideration in determining whether farmland will be marginalized. Second, as the labor cost of farming continuously grows, adopting large-scale farming and intensified cultivation and replacing manual labor with mechanization are crucial ways to maintain the profitability of the agricultural sector. However, limitations, such as basic infrastructure and farmland parcel size, may render impossible the use of large-scale operations to improve labor productivity. As labor cost increases, areas with small parcels and farmland with inferior farming conditions are likely to be marginalized. Third, in the market economy, the utilization of farmland is also influenced by the level of regional economic development and the efficiency of farmland utilization. The opportunity cost of farming increases as non-farm income and job opportunities increase. When the profitability of the farm equals zero or is negative, a rational farmer will lose the motivation to continue farming. Therefore, farmland in regions with a higher opportunity cost is likely to be marginalized and abandoned. Next, combining the previously described evaluation system and using the integrated weighted model to calculate the total value of single evaluation units, the total value of each evaluation unit is calculated using the frequency histogram of the total score of the evaluation units. Using a natural breakpoint method, we divide the interval for the level of farmland marginalization under the perspective of each dimension.

Last, by assigning different weights to various evaluation dimensions, we simulate the potential risk of marginalization under different scenarios. Using remote sensing images, we analyze the spatial distribution of the reforestation of farmland. Subsequently, using an overlay analysis of remote sensing images, we systematically identify the main factors that contribute to farmland marginalization (**Figure 1**).

2.2 Evaluation of the Natural Suitability of Farmland

High-quality farmland is capable of fulfilling the basic elements required for crops to grow, such as sunlight, water, and nutrients, and its soil quality is stable and static and can reveal its basic land conditions. In a traditional agricultural society, the pressure from continuous population growth has led to the cultivation of land with lower natural suitability. As society transforms and labor productivity increases, farmland with lower natural suitability is likely to be marginalized. Classification of agricultural land diagnostic index is to select factors that have a significant impact on the quality of agricultural land. The diagnostic index is divided into different grades or levels to evaluate the natural suitability of cultivated land, which has been included in the national standards. Referring to the agricultural land grading standards where the research area is located, we consider the terrain slope, surface soil quality, soil thickness, organic matter content, and soil structure of the selected area as the evaluation criteria to assess the natural suitability of farmland.

2.2.1 Evaluation Indicators of Natural Suitability

Terrain slope—an important basis for determining farmland quality. Terrain slope is a crucial factor that influences the degree of natural suitability. A higher likelihood of soil degradation exists in an area with a steeper slope. At the same time, fertility and the moisture retention rate will be poorer.

Surface soil quality—has a significant impact on various composite crop growth reactions. Mengjin County is in the transitional zone of the second and third steps. There is also a substantial difference in soil quality within this region,

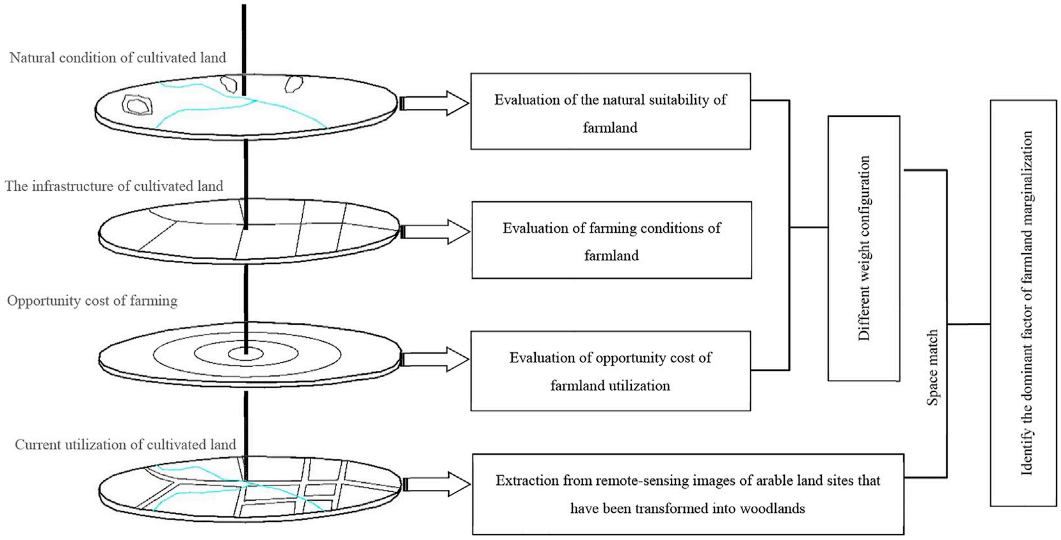

FIGURE 1 | Conceptual framework for the identification of marginal factors of farmland.

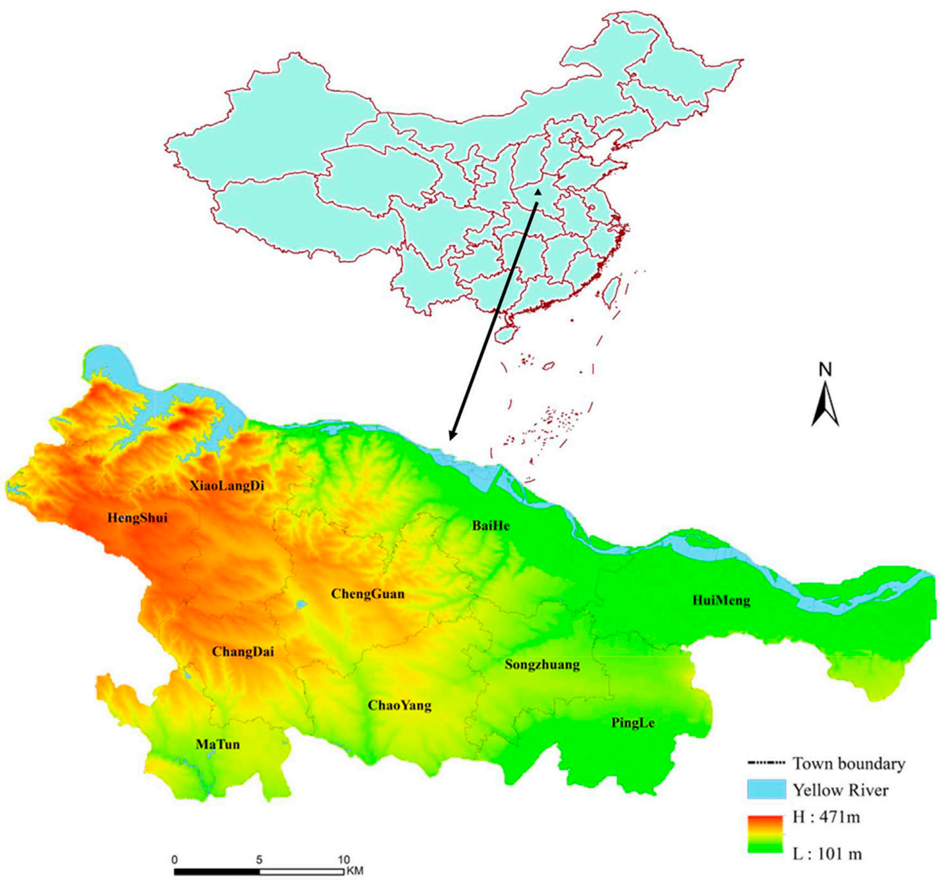

FIGURE 2 | Map of mengjin county.

TABLE 1 | Evaluation indicators of natural suitability of farmland.

Category	Grades and values of factors					Weight
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	
	5	4	3	2	1	
Terrain slope (°)	<2°	2°–5°	5°–8°	8°–15°	>15°	0.29
Surface soil quality	Medium soil	Light soil	Heavy soil	Sandy soil	Sandy	0.21
Soil thickness (cm)	>150	100–150	60–100	30–60	<30	0.25
Organic matter content (%)	≥4.0	3.0–4.0	2.0–3.0	1.0–2.0	≤1.0	0.10
Soil structure	Entirely soil, soil/clay/soil	Soil/clay/clay, soil/sand/soil	Clay/sand/clay, entirely clay	Sand/clay/sand, soil/sand/sand	Others	0.15

throughout which alluvial soil, cinnamon soil, and red clay are found. Surface quality is one of the most important factors that influences natural suitability.

Soil thickness—thick soil is not only beneficial for crop growth but also provides better moisture retention and fertility.

Organic matter content—for soil, the distribution of nutrients is highly related to its organic matter, and soil with higher organic matter content has better fertility and aggregate structure. Therefore, the level of organic matter content is an important indicator of soil fertility.

Soil structure—an important indicator of soil development. Well-developed soil tends to show a regular and systematic structure, coupled with sufficient thickness and absence of an obstructive layer.

2.2.2 Factor Scoring and Weight Allocation

Using the likelihood of farmland marginalization as the basis of our evaluation, the indicators for the natural suitability of land are categorized into 5 grades, using 5, 4, 3, 2, and 1 to represent the level of natural suitability, where areas with lower natural suitability are more likely to be marginalized. Using agricultural land classifications and grading results as our reference and employing quantitative and qualitative methods, we quantify each factor and determine its weight (**Table 1**).

2.3 Evaluation of Farming Conditions of Farmland

Farming conditions are crucial to the condition and utilization level of the farmland. Improving farming conditions can promote higher and more stable agricultural productivity and serves as an effective and important path that ensures higher production and efficiency. Through a series of engineering measures, people attempt to improve the farming conditions of farmland parcels, which increases agricultural efficiency and lowers the cost of farming. Hence, areas with less ideal farming conditions tend to be marginalized. With the increasing popularity of mechanized farming, the convenience of farming should not only consider the farming distance, but also fully consider the suitability of mechanized farming field. Combining data availability and considering the attributes of the research area, this study selects farming distance, connectivity of the roads throughout the farmland, size of the farmland parcels, level of centralization and contiguity of the farmland parcels, and irrigation condition as the criteria with which to evaluate whether farming conditions are ideal.

2.3.1 Indicators of Farming Conditions

Farming distance—Farming distance is the distance between farmland parcels and a farmer's residential area. Because a certain symbiotic relationship exists in the spatial distribution of the village dwelling and the farmland, there has to be a certain farming radius between the farmland and the farmer's village of residence. Once a reasonable farming radius is exceeded, the convenience of the farmland will decline drastically.

Interconnectivity of the roads among parcels—The roads among parcels serve as the transport paths for agricultural supplies, mechanized farming, and other agricultural activities. A farming unit with a more convenient road network can provide the basis for higher agricultural productivity. Greater numbers of interconnected roads among farmland parcels lower the cost of mechanization. The connectivity of the road network between parcels is calculated using **Formula 1** as follows:

$$K = \frac{m}{M} \tag{1}$$

In **Formula 1**, K is the road connectivity index; m is the number of farmland parcels within the village area with interconnected roads; and M is the total number of farmland parcels within the village area.

Size of the farmland parcels—Farmland parcel size is the unit area of a farmland parcel. Farmland parcels that are small and dispersed have significant negative impacts on the efficiency of mechanized farming, the composite output rate of the farmland, and the efficiency of agricultural production technology. Here, we incorporated the conditions of farmland parcels in Mengjin County to assign values to farmland parcels of different sizes.

Centralization and contiguity level of farmland parcels—The centralized and contiguous nature of the farmland parcels affects the level of agricultural mechanization and its efficiency. This research uses the village as the measurement unit, with the level of farmland centralization as a reflection of contiguity. A higher value means a higher degree of farmland fragmentation or division; in contrast, a lower value shows a lower division and, hence, higher farmland contiguity. The centralization and contiguity of the farmland are calculated using **Formula 2** as follows:

TABLE 2 | Evaluation indicators of farmland marginalization based on farming conditions.

Category	Grades and values of factors					Weight
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	
	5	4	3	2	1	
Farming distance (m)	<200	200–400	400–600	600–800	>800	0.18
Interconnectivity of roads on the farmland	>0.8	0.6–0.8	0.4–0.6	0.2–0.4	<0.2	0.24
Size of farmland parcels (hm^2)	>4	3–4	2–3	1–2	<1	0.20
Parcel contiguity	<0.02	0.02–0.04	0.04–0.06	0.06–0.08	>0.08	0.17
Irrigation condition	Highly satisfactory		Satisfactory		No irrigation	0.21

$$P = \frac{L}{A} \tag{2}$$

In **Formula 2**, P is the level of farmland centralization and contiguity, L is the total perimeter of the farmland within the village area, and A is the sum of the farmland area within the village.

Irrigation condition—Farmland with good irrigation conditions has higher productivity and, thus, higher profit from operations. Taking into consideration the availability of basic farming infrastructure in the research area as well, we have assigned different values to different types of farmland parcels.

2.3.2 Factor Scoring and Weight Allocation

Combining the actual situation in the research area and the objective of our evaluation, as well as consideration of the level of influence of varying farming conditions on farmland marginalization, we assign values 5, 4, 3, 2, and 1 to score the quality of the evaluation factors. In this way, we are quantifying and grading the farming conditions. For factors that have fewer grades, intermediate values, such as 4 and 2, can be eliminated. An analytic hierarchy process is used to verify the weight allocated to the evaluation factors of the farming conditions (**Table 2**).

2.4 Evaluation of Opportunity Cost of Farmland Utilization

In the urbanization process, the shift of the farming workforce to non-farming sectors is an inevitable trend, and job opportunities in the non-farming sector increase continuously. In turn, this increases the opportunity cost of farming, reduces agricultural investment, and causes extensive usage or even abandonment of farmland. In the current stage, due to the lack of a calculation method to accurately estimate the opportunity cost of farming, combined with the research objective and data availability, this research chooses to use per-capita income, distance to the city, labor allocation, farming scale, and other factors as proxy indicators to collectively represent the opportunity cost of farming in the area.

2.4.1 Evaluation Indicators of the Opportunity Cost of Farming

Per-capita income—as the income in a rural household continues to increase, the percentage of the net income generated from the primary industry continues to decline. Therefore, in a high-income region, the capital and labor invested in farming are declining, and the utilization frequency of farmland is falling. In a low-income region, due to the lack of alternatives to increase their income, farmers tend to more highly value farmland utilization.

Distance to the city—as the city expands, the basic infrastructures in the surrounding rural areas continue to improve, villages that are closer to the city have a higher possibility of benefiting from industry and capital transfer, and as non-farming job opportunities increase, there is a higher likelihood that farmers will find a livelihood outside of agriculture. Consequently, the opportunity cost of farming increases, and thus, the likelihood of farmland marginalization increases.

Labor allocation ratio—in an area in which non-farming job opportunities are more abundant, there is usually almost no excess labor in the rural household. Therefore, the ratio of the village population employed in the agricultural sector can reflect the opportunity cost of farming. Lower farming labor to the total population ratio results in a higher opportunity cost of farming in the said village. Consequently, farmland in villages is more likely to be marginalized. Here, using the village as the unit of measurement, we can calculate the labor allocation ratio using **Formula 3** as follows:

$$I = \frac{J}{S} \tag{3}$$

In **Formula 3**, I is the labor allocation ratio; J is the number of people in the village employed in the agricultural sector, referring to individuals who perform agricultural work or businesses; and S is the total population of the village, referring to the total population size of the village.

Dominance index of the farming scale—in large-scale farmland utilization, there will be a scale effect. An area with a higher dominance index of the farming scale has a lower opportunity cost of farming, which lowers the risk of farmland marginalization, and vice versa. The index of the farming scale is calculated using **Formula 4** as follows:

$$Q_i = (G_i/T_i)/(G_z/T_z) \tag{4}$$

In this formula, Q_i is the dominance index of the farming scale in village i; G_i and G_z respectively indicate the total farmland area in village i and throughout the entire county; and T_i and T_z

TABLE 3 | Evaluation factor of farmland marginalization based on the opportunity cost.

Category	Grades and scores of factors					Weight
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	
	5	4	3	2	1	
Per-capita income (yuan)	<8500	8500–9000	9000–9500	9500–10000	>10000	0.31
Distance to the city (km)	>10	8–10	5–8	3–5	<3	0.26
Labor allocation ratio	>0.4	0.3–0.4	0.2–0.3	0.1–0.2	<0.1	0.28
Dominance index of the farming scale	>1.5	1.25–1.5	1.0–1.25	0.5–1.0	<0.5	0.15

TABLE 4 | Weighted verification scheme based on different combinations.

Category	Weight of natural suitability	Weight of farming conditions	Weight of opportunity cost
Natural suitability oriented	0.5	0.2	0.3
Farming conditions oriented	0.3	0.5	0.2
Opportunity cost oriented	0.2	0.3	0.5

respectively indicate the total land area in village *i* and throughout the entire county.

2.4.2 Factor Scoring and Weight Allocation

In consideration of the complexity of the opportunity cost of farming and the diversity of the factors that influence it and given the identification of the likelihood of farmland marginalization as the basis of scoring, we quantify and grade the factors that influence the opportunity cost of farming. The Delphi method is used to determine the weight of each evaluation factor (**Table 3**).

2.5 The Total Value of Individual Evaluation Units

Combining the previously described evaluation system and using the integrated weighted model to calculate the total value of single evaluation units, we obtain **Formula 5** as follows:

$$Z = \sum_{k=1}^{n} W_k . v_k \tag{5}$$

In **Formula 5**, Z is the total score of the evaluation units; n is the number of evaluation factors; W_k is the weight of evaluation factor k; and V_k is the quantified value of evaluation factor k.

The total value of each evaluation unit is calculated individually using the frequency histogram of the total score of the evaluation units. Using a natural breakpoint method, we divide the interval for the level of farmland marginalization under the perspective of each dimension.

2.6 Verification Based on Remote Sensing Images

The marginalization of farmland is the outcome of the interplay among multiple factors, such as natural suitability, farming conditions, and opportunity cost. To identify the main factors that contribute to farmland marginalization, this research formulates three weight allocation schemes based on land capacity-oriented, farming conditions-oriented, and opportunity cost-oriented perspectives. Then, the main factors that influence farmland marginalization are identified (e.g., **Table 4**).

First, using the Image Classification tool in ArcGIS10.2, we utilize the maximum likelihood classification to obtain remote sensing images of forested land in Mengjin County in 2017. Subsequently, we perform spatial superposition of the farmland in the current and forested areas obtained from remote sensing images, thereby obtaining the spatial distribution of the current farmland reforestation. Last, we analyze the evaluation outcomes of schemes with different orientations and their degree of fit with land reforestation.

3 MATERIALS AND METHODS

3.1 Study Area

Mengjin County is located in the west of Henan Province in a transitional area of China's second and third terrain steps on the southeast border of the Loess Plateau. Yanshi City and Gongyi City lie to the county's east, Xin'an County to its west, Luolong District of Luoyang City to its south, and Jili District of Luoyang City, Jiyuan City, and Mengzhou City to its north, on the other side of the Yellow River (**Figure 2**). As a typical county in the middle and lower reaches of the Yellow River, Mengjin County has a unique geographical environment, and the evolution of cultivated land resources in the region is rapid. In the north of the county is Xiaolangdi Reservoir, a reservoir of the Yellow River. Since the dam was intercepted in 1997, the main channel of the Yellow River has been controlled in a fixed channel. In the northwest is the loess gully area, along the edge of Xiaolangdi Reservoir. In the south, the urban area of Luoyang is adjacent to the county. The traditional modes of development neglect the

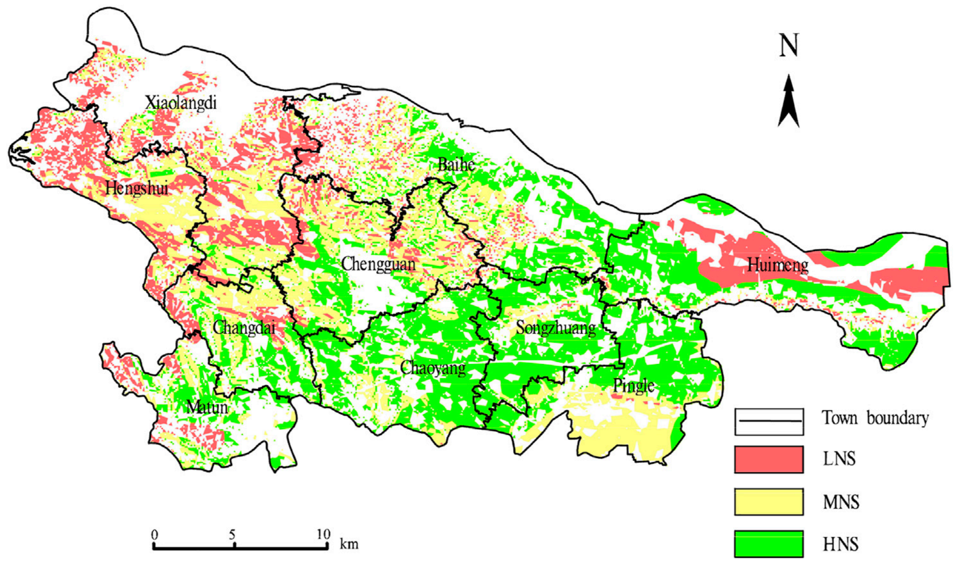

FIGURE 3 | Map of spatial distribution of natural suitability of farmland in Mengjin County.

influence of cultivated land exploitation and utilization on regional ecological security and lead to instability in the area and quality of cultivated land, presenting concerns for food security. In the region, clarification of the main factors contributing to farmland marginalization is of significant importance for assuring local crop safety.

3.2 Data

The main sources of data used in this research are 1) statistical data, such as population and average population income, generally from the Mengjin County Statistical Yearbook (2018); 2) data on land utilization, which are based on the data from the Second National Land Survey of Mengjin County, which was updated in 2018 (1:5000); 3) remote sensing data from Google Earth (0.98*0.98 m); 4) soil data from Henan Province's soil database (1:5000).

4 RESULTS

4.1 The Natural Suitability of Cultivated Land

Based on natural breakpoints, the natural suitability of farmland throughout the county is divided into three intervals: high natural suitability (HNS), medium natural suitability (MNS), and low natural suitability (LNS).

As shown in **Figure 3**, farmland with HNS is distributed across Chaoyang, Songzhuang, the northern part of Pingle, and southwest of Huimeng. These areas have relatively flat terrains, the soil is mainly alluvial and cinnamon soil, and the soil layer is thick. Hence, most of these areas are considered ideal parcels with stable production. The total area of farmland with HNS is 189.00 km^2, representing approximately 45.06% of the total farmland area. From the perspective of natural suitability, the risk of marginalization is low for this type of farmland. Farmland with MNS is mainly distributed along the southern part of Pingle, the northern part of Chengguan, central Hengshui, and southwest of Baihe, whereby the terrains are relatively inclined, and the soil is composed of calcareous cinnamon soil with high viscosity, thus posing certain limitations to farmland utilization. The farmland area with MNS totals 141.64 km^2, representing approximately 33.77% of the total farmland area. From the perspective of natural suitability, the risk of farmland marginalization for this type of farmland is moderate. Farmland with LNS is mainly dispersed around Xiaolangdi, the northern part of Hengshui, and the Yellow River floodplain area in Huimeng. Farmland around Xiaolangdi and Hengshui has soil that is mainly composed of clay, and the topography poses immense limitations on them. Farmland in the northern part of Huimeng has soil that is mainly composed of silty sand, with severe leakage of moisture and fertilizer. The area of farmland with LNS is 88.81 km^2, representing approximately 21.17% of the total farmland area. From the perspective of natural suitability, this type of farmland faces a higher risk of marginalization.

The natural suitability of farmland land is mainly based on soil and topographic elements, which are relatively stable and not easy to change. Based on the natural suitability, the higher risk of marginalization farmland in Mengjin is mostly cultivated land with large topographic relief, shallow soil and poor soil. These cultivated land have poor natural endowment and fragile ecology as a whole. With the acceleration of urbanization and industrialization, more non-agricultural employment opportunities have been created, and a large number of rural households have transferred to other places for employment, which has created social and economic conditions for returning farmland to forest and grass vegetation in LNS areas.

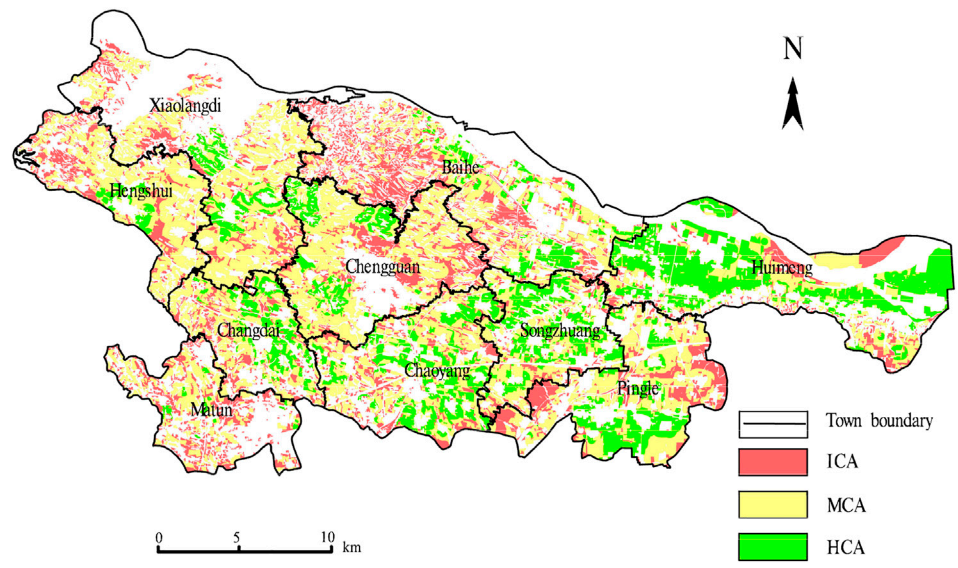

FIGURE 4 | Map of the spatial distribution of farming conditions in Mengjin County.

4.2 The Farming Conditions of Farmland

Using natural breakpoints, the farming conditions in the entire county can be divided into three intervals: highly convenient area (HCA), moderately convenient area (MCA), and inconvenient area (ICA).

As shown in **Figure 4**, the overall farming condition of the entire county is fragmented and spatially distributed in a scattered manner. Farmland with HCA is concentrated in Chaoyang, Songzhuang and Huimeng. These areas are characterized by flat terrain, large farmland parcels, high levels of centralization and contiguity, and the availability of comprehensive basic farming infrastructures. The total farmland area with HCA is 103.69 km^2, representing approximately 24.72% of the entire farmland area. Having high and stable productivity, this type of farmland is less likely to be marginalized than are other types. Farmland with MCA is concentrated in Xiaolangdi, Hengshui, Chengguan, Matun, and the eastern part of Baihe. These areas are limited by the topography and have small farmland parcels and insufficient basic agricultural infrastructure. Consequently, they are not suitable for mechanized agriculture and large-scale farming. The size of the areas with MCA is 214.05 km^2, representing approximately 51.03% of the total farmland area. From the perspective of farming conditions, this type of farmland faces a moderate risk of marginalization. Farmland with ICA is mainly located to the west of Xiaolangdi, to the west of Baihe, in the central and east parts of Chengguan, in the southern part of Matun, and north of Pingle. The topography has limited farmland most severely in Xiaolangdi and Baihe, which have highly fragmented farmland parcels and lack basic agriculture infrastructure. Farmland in Chengguan, Matun, and Pingle has highly fragmented parcels, a high rate of intersection between farmland and building zones, and small farmland parcels with irregular shapes due to urban diffusion. As such, it barely fulfills any requirement for large-scale farming. The total size of the farmland areas with ICA is 101.71 km^2, which accounts for approximately 24.25% of the total farmland area. From the perspective of farming conditions, this type of farmland has a high risk of marginalization.

The distribution of farmland in Mengjin is fragmented and sporadic, which includes not only poor connectivity and inconvenient cultivation caused by natural factors such as topography and landform cutting, but also inconvenient cultivation caused by human factors such as unreasonable layout of roads and drainage and irrigation systems, as well as ownership cutting caused by farmers' contracting. Because the natural conditions of farmland are difficult to change, it is an important way to postpone the marginal utilization of farmland to improve the farmland with high natural suitability but not convenient cultivation.

4.3 The Opportunity Cost of Farmland Utilization

Using natural breakpoints, the opportunity cost of farming in the entire county is divided into three intervals: low opportunity cost (LOC), moderate opportunity cost (MOC), and high opportunity cost (HOC).

As shown in **Figure 5**, regions with HOC of farming are mainly dispersed around the southern part of Matun, the central and southern parts of Chaoyang, the southern part of Pingle, the central part of Chengguan, and the west of Baihe Town. These core regions of Mengjin County's "Double Wing" program have numerous non-farming job opportunities and high per-capita income, but scattered farmland parcels and poor farming

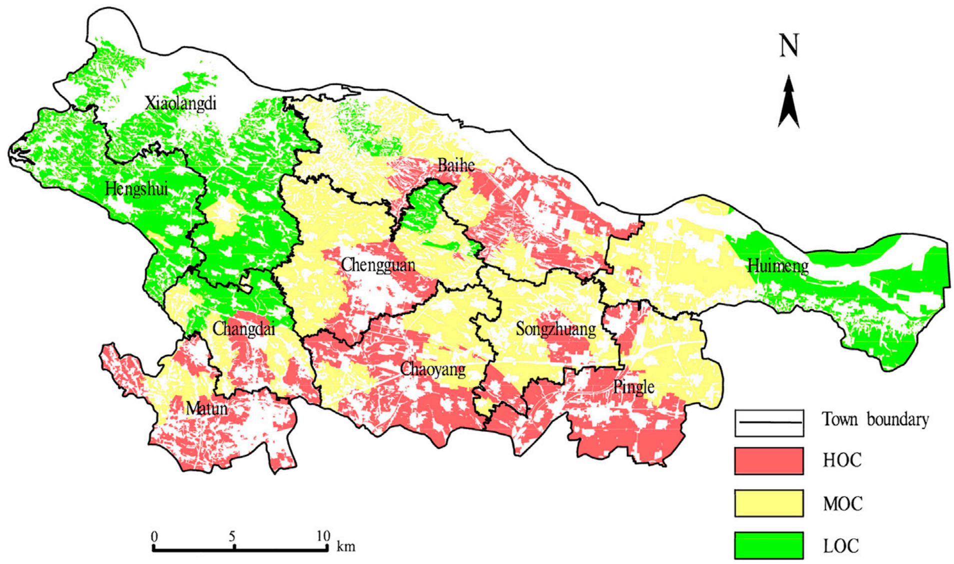

FIGURE 5 | Map of the spatial distribution of opportunity cost of farming in Mengjin County.

conditions. Consequently, farmers need to rely on transferring their farmland management rights to maximize their profitability. The total size of farmland with HOC is 119.32 km^2, accounting for approximately 28.45% of the total farmland. From the perspective of opportunity cost, this type of farmland has a high risk of marginalization. Farmland with MOC is mainly distributed in Songzhuang, the north of Chaoyang, the northwest part of Chengguan, the north of Pingle, and the west of Huimeng. These regions are under the influence of urban radiation, and their farmland is centralized and contiguous and has superior farming conditions, making them well suited for large-scale farming. The total size of farmland with MOC is 164.57 km^2, accounting for approximately 39.23% of the total farmland area. From the perspective of opportunity cost, this type of farmland faces a moderate risk of marginalization. Regions with LOC are mainly dispersed around Hengshui, Xiaolangdi and east of Huimeng. These regions are far from the city, the farmers have few non-farming job opportunities, the ratio of income from the agriculture sector is high, and the cultivation of farmland is highly valued by the farmers. The total size of farmland with LOC is 119.32 km^2, accounting for approximately 28.45% of the total farmland area. From the perspective of opportunity cost, the risk of marginalization of this type of farmland is low.

In suburban areas, farmers can obtain higher economic benefits by adjusting their cultivated land to flowers, fruits and trees, etc. In addition, most of the farmers in this area have the expectation that their cultivated land will be occupied by construction, and arid farmland occupied the compensation price is low, therefore, Mengjin high opportunity costs less farmers give up farming.

The impact of opportunity cost on farmland marginalization varies with context, in contrast to conventional perception. Farmland with high opportunity cost is usually located in suburban areas with high levels of non-agricultural employment opportunities. In these areas, farmland usage tends towards floraculture, vegetable growing, sightseeing agriculture, and other agricultural practices. Furthermore, farmers living in suburban areas typically anticipate crop compensation in case of land expropriation. Both of these conditions induce farmers to fully utilize their farmland or to operate farming-related plantation/industries. Furthermore, farmers living in suburban areas typically anticipate crop compensation in case of land expropriation. Both of these conditions induce farmers to fully utilize their farmland or to operate farming-related plantation/industries.

4.4 Verification of Results

The interpretation of the results of the remote sensing images shows that, of the current 419.45 km^2 of farmland throughout the county, the areas that have been reforested total 36.47 km^2, which accounts for approximately 8.69% of the total farmland area. As shown in **Table 5**, there is a low degree of fit between the size of the reforested part of the farmland evaluated through a high, medium, and low risk of marginalization and an opportunity cost-oriented evaluation, of which farmland reforestation has been more strongly influenced by the natural suitability and farming conditions. In this case, farmers abandon their farmland as a rational choice to maximize their profit; therefore, farmland with poorer natural suitability is more likely to be abandoned. In addition, the increase in agriculture mechanization or capital investment is less likely to reduce the labor cost for farmland with inconvenient farming conditions. As such, when the labor cost continues to increase, this farmland is more likely to be abandoned.

TABLE 5 | Area distribution of reforested farmland under different evaluation dimensions.

Category	High risk/reforested land	Medium risk/reforested land	Low risk/reforested land
Natural suitability km^2	86.56/15.54	201.14/16.75	131.75/4.17
Farming conditions km^2	92.95/17.03	193.14/13.85	133.36/5.59
Opportunity cost km^2	79.10/6.28	187.144/19.02	152.91/11.18

5 DISCUSSION

5.1 Large-Scale Grain Crop Cultivation is an Important Way to Reduce the Marginalization of Cultivated Land

With the advancement of urbanization in China and the increase in wages in non-farming sectors, the balance between labor allocation and farmland utilization has been disrupted. In addition, the disparity between grain price control and the rising costs of agricultural means of production, such as chemical fertilizers, seeds, and equipment, have reduced the average profit potential of farmland with low cultivation suitability. As a result, increasing numbers of rural laborers have transitioned into secondary and tertiary industries to maintain family income. Farmland parcels with poor land capacity and low profitability are the first to be marginalized. Although the abandonment of farmland is decided by farmers' families, large-scale grain crop cultivation can also bring profits. Large-scale farmland transfer is regarded as the prerequisite for the development of modern agriculture or scaled-up agriculture production (Zou et al., 2019). If farmers are guided to conduct land transfer in an orderly manner, not only can their income be increased, but also the marginalization of cultivated land can be reduced. In most cases, it takes much more labor to grow non-food crops than food crops. Moreover, the average patch area of non-food cropland is small and the aggregation degree is low, which cannot produce economies of scale. Therefore, for the cultivated land planting non-food crops, we should improve the industrial layout planning, combined with the types of non-food crops, to guide the agglomeration effect of cash crops planting. Agricultural authorities should speed up the mechanization of farmland in hilly and mountainous areas, support the construction of grain processing facilities, extend the industrial chain, carry out large-scale and brand projects, and improve the efficiency of grain operation. In the future, we should strengthen the improvement of cultivated land with high natural suitability but medium and low cultivation conditions, appropriately merge land plots, cooperate with the popularization of small agricultural machinery, and create conditions for large-scale operation, so as to reduce the risk of marginal utilization of cultivated land.

5.2 There Is Little Difference in Farming Opportunity Cost at the County Level

The opportunity cost of labor force farming is an important factor affecting farmers' land use decision-making. The gradient difference of economic development among the eastern, central and western regions of China is very significant, but the difference of economic development level within a county is not particularly significant. Therefore, the difference in the opportunity cost of farming has a relatively small impact on the abandonment of cultivated land within the county, but the impact of opportunity cost of cultivated land will be particularly large if it is compared on a national scale. The evaluation result of opportunity cost of farming selected in this paper is a relative value, which can only reflect the relative difference within Mengjin, As farmers move in a comprehensive range, more in-depth studies are needed to select the evaluation index of opportunity cost of farmland utilization.

5.3 Withdrawal of Inferior Cultivated Land From Cultivation is Beneficial to Ecological Restoration

The goal of the DBTFA policy is to guarantee national food security. Over the more than 30 years of implementation of this policy, the stability of the cultivated land area has been maintained, but the utilization of cultivated land has lacked effective management. In China, most land suitable for reclamation has been reclaimed. Presently, the land that can be developed into arable land is mainly ecologically fragile land, such as barren mountain or beach areas with poor soil quality and challenging conditions for cultivation. The improper development and utilization of land can easily cause ecological problems. In addition, there is a high risk that cultivated land with poor conditions will be abandoned due to economic considerations.

In the past period, the relevant national authorities lacked a systematic understanding of ecological civilization construction, and took improving forest coverage rate as the policy focus to promote ecological civilization construction. Under the guidance of relevant policies, large-scale land space greening projects have been carried out on both sides of highways, which to some extent promotes the "non-grain" conversion of cultivated land. At present, the work of national spatial planning in various regions should reflect the requirements of national spatial development strategy, coordinate the relationship between food security, ecological civilization and sustainable development, take the same national spatial management and control concept as the work direction, reasonably delimit ecological space, urban construction space and agricultural development space, and optimize the management and control mode of spatial resources.

From the perspective of ecological restoration, the removal of poor-quality farmland from farming will support the recovery of a regionally weakened ecology. At the same time, such a removal can provide the space required to nurture biodiversity. However, from the perspective of food safety, the intensifying marginalization of farmland may threaten the region's food safety. Therefore, further study is required to understand the developmental pattern of farmland marginalization and its influencing factors to formulate more rational and effective regulatory policies.

6 CONCLUSION

1) Soil, slope and other natural factors in the evaluation index of natural suitability of cultivated land are stable and not easy to change. Natural suitability is the basic condition that affects the marginal utilization of cultivated land. Interconnectivity of roads on the farmland, Parcel contiguity, irrigation condition index and the moderating effect of terrain factors, such as natural suitability and cultivation convenience has certain spatial correlation, but, in the spatial distribution of the natural suitability is not entirely agree with farming convenience degree. For example, the farmland soil quality is relatively poor in the yellow river beach, but flat belt land, Road accessibility and cultivated land contiguity are high, so the risk of marginal use of cultivated land in beach area is low.
2) From the verification results of remote sensing images, it can be seen that poor natural suitability and inconvenient farming conditions are the main influencing factors of cultivated land marginalization in Mengjin County, which is also a high-risk area of cultivated land marginalization utilization. Due to the poor natural suitability and inconvenient farming conditions of the region, its food production capacity and ecological environment conditions are relatively poor. As a result, the natural suitability poor tillage and inconvenience of cultivated land adjustment back to forest land, help regional fragile ecological restoration, the impact on the food security is also very limited.
3) The areas with high opportunity cost of cultivation are mostly in the urban suburbs, while the suburban areas are also relatively concentrated areas with high quality cultivated land, and the non-grain utilization of regional cultivated land is relatively common. From the actual situation of Mengjin, the abandoned land utilization in the areas with high opportunity cost cultivation is less. Because through the adjustment of industrial structure also can get high profits, This is also related to the relatively small differences in opportunity costs of farming within counties.
4) The research method in this paper is a basic method to reflect the evolution law of cultivated land marginalization, but it will show inadequate adaptability for areas with special phenomena. For example, when identifying the leading factors of cultivated land marginalization, only conversion of cultivated land to forest land is used as a reference, which also leads to the inability to give a reasonable explanation for typical situations. For example, in some areas, farmers are forced to plant trees in cultivated land in order to improve the landscape effect. If there are a large number of landscape trees in a place, the applicability of such research methods would appear unconvincing (Wang and Hou, 2021).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

In this paper, XG processed the data and wrote the main contents of the paper. XW and WC provided ideas for the paper. All the authors discussed the results and implications and commented on the manuscript at various stages.

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Assessment and Contributing Factors of the Spatial Misallocation of Construction Land: A Case Study of Shandong, China

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Spatial misallocation is an essential reason for the low utilization efficiency of construction land. Optimizing the spatial pattern of construction land allocation can improve the efficiency of economic operations and resilience to food crisis and climate change challenges. This study constructs a quantitative measurement method for the spatial misallocation of construction land (SMCL), proposes a new government market society support (GMSS) analytical framework for the contributing factors with interlocked relationships, and conducts empirical research in Shandong, China, which is a typical area with a rapid development of construction land and significant regional disparity. It is concluded that the SMCL ensues through the interaction and coevolution of the GMSS system, which plays a key role in adjusting the construction land use sequence, structure, and efficiency under the regulation of the upper government. Effectively using the estimation method based on the equal marginal output principle, the SMCL in Shandong is established as a downward trend, with evident temporal and spatial differentiation characteristics and spatial morphological mode changes, although most sub-regions are significantly approaching the adaptation interval with fluctuation. Furthermore, the empirical results of the regression model indicate that there are different effects and intensities on the SMCL among the contributing factors under the GMSS framework, wherein the local government force has an aggravating and the greatest effect, the market forces have a dual and second-ranking effect, the social forces play a positive but still weak role, and the support system has a differentiated improvement effect. However, the impacts of various dimensional factors on the SMCL also have heterogeneity in the development stages and different regions. Generally, in the low-level development stage and underdeveloped areas, the effect of local government intervention is stronger, the market forces' importance is lower, and the social forces and support systems remain insufficiently robust.

Keywords: spatial misallocation of construction land, equal marginal output, GMSS analytical framework, influencing factors, Shandong, China

1 INTRODUCTION

The intensive utilization of land resources is not only an important reflection of a country or a region's economic and social development quality but also a necessary condition for sustainable development (Estoque et al., 2021; Lu et al., 2021; Hjalager et al., 2022). As the spatial carrier of rapid industrialization and urbanization in developing countries, construction land has maintained a rapid growth trend in recent decades, thereby posing increasingly severe challenges to global climate change, food security, and ecological environment protection, thus forcing them to pay more attention to the improvement of construction land utilization efficiency (Kissinger et al., 2019; Mendoza-Ponce et al., 2021; Pal et al., 2021). However, owing to various reasons, such as immature factor markets, excessive administrative intervention, and improper regional competition, there are serious misallocations of construction land among regions, industries, and enterprises in developing countries, hence resulting in a massive reduction of production efficiency and waste of land resources (Huang and Du, 2017; Jian Wang et al., 2020; Luo et al., 2022).

As one of the developing countries in the world with the largest total amount of construction land, fastest growth rate, and most evident human–land contradiction, China's construction land misallocation (CLM) is even more prominent. In particular, the differences among regions in China are particularly obvious: local governments have to launch continuous central–local games and fierce inter-regional competition to obtain more construction land quotas under the institutional logic of the stimulation of economic growth by the central government *via* local decentralization (Song et al., 2020; Fu et al., 2021). However, it is very difficult to allocate construction land quotas that perfectly match the goal of maximizing output efficiency, especially when the central government tries to balance economic efficiency and regional development rights, which makes the spatial misallocation of construction land (SMCL) in China particularly typical and has been a remarkable obstacle to the intensive use of construction land (Chien, 2015; Bo, 2020; Liu et al., 2021; Zhou et al., 2022).

There are multidimensional negative impacts of the SMCL in China, including not only the direct consequences of loss of economic efficiency and waste of land resources but also the indirect consequences, such as industrial convergence among regions, industrial upgrading dilemma, public service insufficiency, ecological environment decline, food crises, social conflicts, and government corruption (Fang and Tian, 2020; Han Wang et al., 2020). While China is in a critical period of transforming its development mode, optimizing its economic structure, and transforming its growth drivers, ensuring the equal development rights of different regions and establishing a more effective governance mechanism to improve the overall utilization efficiency of construction land have become urgent issues. Therefore, the research on quantitatively measuring the SMCL and identifying its contributing factors and effects is fundamental to relative theoretical and practical targets.

By summarizing and sorting the existing literature, this study selects a quantitative measurement method and establishes a new analytical framework for the contributing factors of the SMCL. It takes Shandong province, China, as the study area to conduct the empirical research. The marginal contribution of this study is three-fold. First, based on the principle of equal marginal output, this study estimates the degree of the SMCL in the study area, which clearly reveals the volatile coupling characteristics of the SMCL and the regional development model, effectively identifies the spatial–temporal differentiation pattern and spatial correlation combination pattern of the SMCL, and further deepens the cognition of the evolution law of the SMCL in regions with rapid growth in construction land and significant internal differences. Second, the article establishes a government market society support (GMSS) analytical framework composed of government, market, social, and supporting system forces and discusses the moderating effect of the coevolutionary relationship of mutual influence and cross-connection on the SMCL, which presents a clearer theoretical summary of the system of factors influencing the SMCL. Third, by selecting representative indicators and constructing an econometric regression model, this study conducts a multi-angle empirical test on the role nature, role strength, and spatiotemporal changes of contributing factors in different dimensions. It provides a deeper understanding of the reasons behind the formation of the SMCL and its spatiotemporal changes, which can provide references for a more accurate regional construction land allocation strategy.

The remaining of this article is organized as follows: **Section 2** reviews the existing literature and provides a summary and an evaluation. **Section 3** proposes a new analytical framework of the contributing factors of the SMCL and clarifies the strategies of quantitative measurement and econometric model construction. In **Section 4**, the empirical results are analyzed and evaluated *via* a robustness test. **Section 5** provides an analysis of the spatiotemporal heterogeneity of the contributing factors. The article is concluded and discussed in the final section.

2 LITERATURE REVIEW

2.1 Performances of the Spatial Misallocation of Construction Land

Construction land allocation has a diversity of participating subjects, allocation modes, functional uses, and time sequences of the realization process; therefore, its misallocation characteristics can be presented in different forms and fields (Opp et al., 2014; Wang et al., 2019; Fu et al., 2021). Notably, CLM performances are ultimately manifested as idle, inefficient, or overutilization of construction land. Hsieh and Klenow (2009) pointed out that the unequal marginal benefits of land between sectors or regions are the key identifying features of the regional misallocation of land resources. Other scholars also agreed with this viewpoint and believed that land misallocation typifies the violation of the efficiency principle, and it is manifested as marginal output differences among regions and sectors (Dheera-Aumpon, 2014; Aumpon, 2018). Banerjee and Moll

(2010) further categorized resource misallocation into connotative and extensional misallocation, arguing that the former is characterized by the unequal marginal output of land utilization, while the latter is characterized by the fact that the marginal output is equal but has not yet reached the optimal state. This has also become a theoretical reference for SMCL research.

However, some scholars have indirectly analyzed the characteristics of land misallocation by economic and social consequences occasioned by land resource misallocation. They generally believe that resource misallocation can lead to significant productivity differences and efficiency losses, the degree of which can reflect the level of misallocation (Banerjee and Moll, 2010; Restuccia and Rogerson, 2017; Song et al., 2020). Kimura et al. (2011) analyzed the failure of the land factor market caused by transaction costs and believe that CLM not only leads to differences in the output efficiency but also hinders the free flow of factors and causes evident land externality losses. Chen (2017) established a two-sector general equilibrium model to quantify the loss in production efficiency engendered by land misallocation. Some scholars have conducted empirical analyses of China's land market and found that the government's strategic land supply behavior not only causes CLM among sectors and regions but also wastes a large amount of land resources (Du and Peiser, 2014; Wu et al., 2018; Hui Wang et al., 2020). In addition, scholars who discussed related fields, such as capital, labor, and housing market misallocation, could also provide abundant references vis à vis the characteristics of the SMCL (Midrigan and Xu, 2014; Liu and Wong, 2015; Dai and Cheng, 2019; Wu et al., 2020; Shi, 2022).

2.2 Measurement Methodology of the Spatial Misallocation of Construction Land

The existing literature mainly includes three types of measurement methods for the CLM. The first is the characteristic index method, which mainly selects one or several key indicators to characterize the CLM level. Huang and Du (2017) used the ratio of the average price of commercial land to the average price of industrial land to measure land misallocation. Some scholars use the proportion of land sold to the total land area (Li et al., 2016) or the ratio of the average price of land for a certain industry to the average price of industrial land (Huang and Du, 2017) to measure land misallocation. The data of the characteristic index method are easy to obtain, and the method is simple and direct, but it often only reflects one aspect of land misallocation and cannot fully reveal the overall state (Zhang et al., 2021). The second method is the parametric or non-parametric estimation approach. Guanchun Liu et al. (2018) used stochastic frontier analysis to measure the relative efficiency of construction land, while Song et al. (2022) used data envelopment analysis to measure the efficiency of urban land use output. From an efficiency level perspective, these methods show the overall state of CLM, but they can only reflect the relative degree of misallocation among different regions and cannot obtain the actual gap with the optimal allocation state. The third method is the multivariate linear equation solving technique. Song et al. (2020) studied the input–output relationship of land resources in different regions based on the calculated value and economic output of various land resource assets and reflected the regional misallocation of land resources by the differences in land output efficiency between regions. Other scholars have developed econometric equations to measure differences in the marginal output of land or productivity share covariance (Olley and Pakes, 1996), the relative productivity of factors (Yansui Liu et al., 2018), and the productivity gap caused by resource misallocation (Brandt et al., 2013), which are used to measure the level of land misallocation. However, these measurement methods can only be used to evaluate the allocation efficiency of land resources and cannot determine the specific state and source of land misallocation.

2.3 Contributing Factors and Determining Mechanism of the Spatial Misallocation of Construction Land

The research on the contributing factors and determination mechanisms of the SMCL covers a wide range. 1) Government intervention: through the monopoly of the land market and the inclined land supply policy, the government has sacrificed factor productivity and caused a loss of allocation efficiency while achieving the goal of macro-control (Brandt et al., 2013). However, Breton (1996) finds that local governments have increasingly become the actual controllers of land resources and compete with other regions with superior institutional arrangements and lower land prices, resulting in an SMCL. Meanwhile, the government's differentiated policies in different sectors and regions, including state-owned and non-state–owned sectors, as well as government corruption and other reasons, can exacerbate the misallocation of resources (Shuhong Wang et al., 2020). It also further strengthens CLM (Brandt et al., 2013). 2) Market environment: distorted factor prices or imperfect factor markets have always been a significant reason behind land misallocation in developing countries (Banerjee and Moll, 2010; Aoki, 2012; Shenoy, 2017; Tang et al., 2020). Harrison (1982) and Wen et al. (2022) believed that accelerating the construction of a unified construction land market and promoting the process of land marketization will help alleviate the SMCL and improve land utilization (Baross and Mesa, 1986). Kimura et al. (2011) believed that reducing the transaction costs of market players is an important means to play the role of the land market. In addition, the lack of land property rights is an institutional reason that hinders the free trade of land, thereby causing land misallocation (Chen, 2017; Huang and Du, 2017; Chen et al., 2021; Gao et al., 2021). 3) Regional economic structure and development level: the characteristics of regional economic development and its structural characteristics, such as population agglomeration, economic development level, industrial structure, technology level, and land fiscal policy, have a significant impact on CLM (Huang and Du, 2017). Song et al. (2022) researched on resource-based cities using the Tobit model and found that it is more effective for local governments to improve land use efficiency by investing in road networks and science and technology. Britos et al. (2022) also confirmed that the degree of distortion in the land market in each region is related to road accessibility, ethnicity, and education level. Based on the data of listed manufacturing enterprises in China from 2010 to 2019, Li et al. (2022) also concluded that information and communications technology is positively correlated with the total factor productivity of manufacturing enterprises, which indirectly proves that the supply of regional science and technology has a positive impact on land allocation.

From the literature review, it is apparent that the current research results on the characteristics, measurement methods, and contributing factors of land misallocation have accumulated significantly, and this can provide valuable references for the research on the SMCL. However, the research has two drawbacks. First, most of the existing studies only discuss CLM among sectors, and there are still relatively few discussions on the SMCL issue. This may be more meaningful for areas with the rapid growth of construction land and significant regional development gaps. Second, the contributing factors proposed by the existing research involve a wide range of factors, and the types of factors are relatively complex, albeit they lack a highly concise and systematic analytical framework, which is also necessary to form targeted theories in related fields and guide the policy practices of developing countries.

3 THEORETICAL FRAMEWORK AND EMPIRICAL STRATEGIES

3.1 Theoretical Framework

With the gradual improvement in the level of economic and social development in developing countries, the diversification of governance subjects and participation methods provides conditions for various stakeholders to jointly improve resource misallocation (Lu and Zhang, 2019; Chen and Lin, 2021; Silal and Saha, 2021). Previous studies have often regarded government power as the leading factor in the SMCL in developing countries, but practical cases and theoretical studies have begun to pay increasing attention to the role of market players and social forces in recent years (Calic and Ghasemaghaei, 2021; Yang and Lee, 2021). According to the classic theory of national and regional governance (Kollintzas et al., 2018; Lin et al., 2022), this study proposes a system of factors that influence the SMCL, composed of government, market, and social forces. Nonetheless, considering the basic support conditions for the three types of factors to play their respective roles, a GMSS theoretical framework is constructed wherein the GMSS system jointly affects the SMCL. In China, the upper-level government mainly controls the construction land in the lower-level area by planning approval, issuing the number of available quotas, and specifying the investment and tax intensity density of the construction land. However, under the condition of the same management and control framework and management and regulation robustness, the final SMCL level is determined by the adjustment mechanism within each region, which is also the research strategy and premise of most research institutes (Huang and Du, 2017; Dai and Cheng, 2019; Shuhong Wang et al., 2020; Wu et al., 2020; Fu et al., 2021). Under the GMSS analytical framework, there are: 1) local government forces: they intervene in the allocation of construction land mainly by implementing favorable policies for specific industries, improving the level of infrastructure and public service support, setting the benchmark price of local construction land, ordering and structuring the administrative grant, issuing permits for construction activities, and supervising the construction process. Because of these effective interventions, the government can impose critical external constraints on the overall efficiency of construction land use. 2) Market power refers to micro-market entities, such as enterprises and professional service institutions that provide enterprises with other production factors. They use the existing market system to maximize economic benefits under the condition of government intervention by lobbying the government, flexibly controlling production and investment decisions, conducting mutual transactions between market entities, and adjusting locations. The role of these micro-market players can ultimately be reflected in the macro-level structural features, such as regional industrial structure, factor supply environment, and spatial agglomeration structure, which represent the pattern of market power comparison. 3) Social forces are social subjects, including residents and non-profit organizations. To enjoy high-quality regional public services, they express their interests and sensitize the society on the rationality of government intervention and the compliance of enterprises to play an indirect regulatory role as a third party and affect the final SMCL degree. 4) Support systems, including regional natural conditions, ecological environment carrying capacity, completeness of infrastructure construction, public supply of scientific and technological innovation, and other factors. In a certain period, they can play a supporting or restricting function on the influence and interaction of the three forces and also determine the upper or lower limit of the utilization efficiency of producing factors to some extent, which also constitutes an important force that affects the SMCL. The four forces of the GMSS form a coevolutionary action system through mutual influence and causality to adjust the SMCL implementation, structure, and efficiency status. The interaction between them is easy to understand. Taking market adjustment forces as an example, they not only affect the government decision-making, social welfare level, and investment structure supporting system construction through lobbying, product supply, capital investment, and so on but also are significantly constrained by government regulation, social supervision, and regional investment carrying and return capacity. Thus, there is a pattern of interactive influence is formed between market regulatory forces and other forces. The analytical framework for the contributing factors of the SMCL is illustrated in **Figure 1**.

3.2 Empirical Strategies

3.2.1 The Spatial Misallocation of Construction Land Measurement Method

The quantitative measurement of the SMCL is a challenge that needs to be addressed before the empirical analysis herein. However, most of the existing methods are based on the

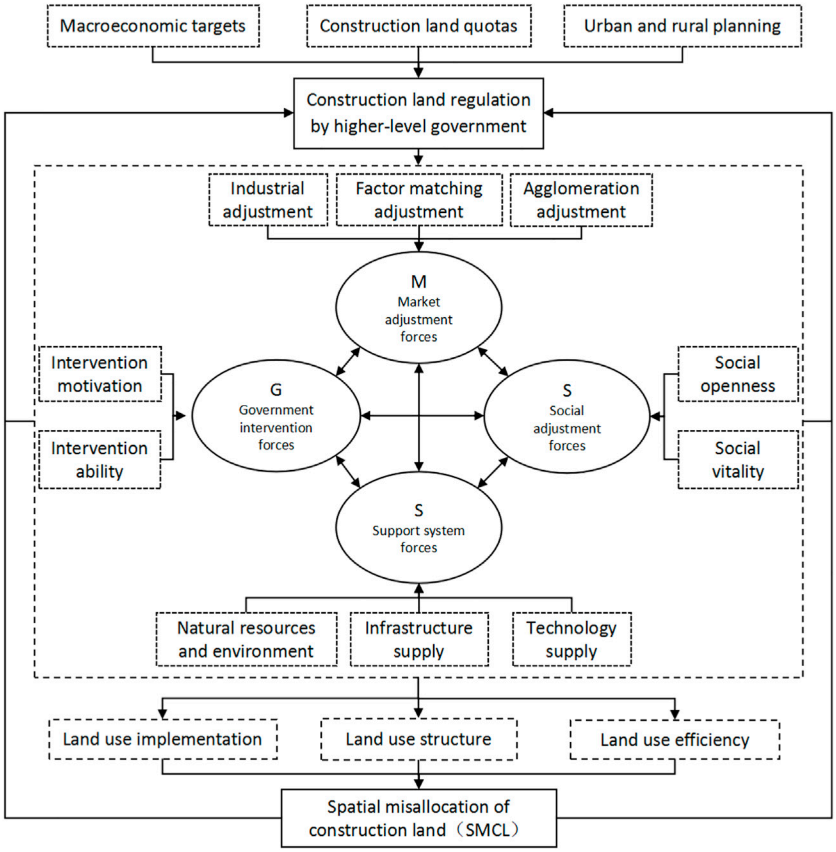

FIGURE 1 | GMSS analytical framework for the influencing factors of the SMCL.

relative evaluation of the allocation efficiency after resource input and can neither determine the nature and actual level of the misallocation nor obtain the optimal allocation size and more specific and clear implications for the regulation strategy. According to the basic economic theory, in a multiregional competition process, the marginal output of construction land input should be equal among regions, which can be an ideal equilibrium state for effective construction land allocation. Based on this logic, we can measure the SMCL in four steps.

First, we construct an estimation equation for the marginal output elasticity of regional construction land. The Cobb–Douglas production function has the attributes of stability, convenience of calculation, and linearizability. This study takes construction land as an independent factor of production and incorporates it into the Cobb–Douglas regional production function together with the input of capital and labor, and we obtain:

$$Y_t = AK_t^{\alpha}L_t^{\beta}S_t^{\gamma}. \tag{1}$$

We take the logarithm on both sides of the equation to obtain the estimated marginal output elasticity of the construction land input as follows:

$$\ln Y_t = \ln A + \alpha lnK_t + \beta lnL_t + \gamma lnS_t, \tag{2}$$

where A represents the regional comprehensive technical level and is defined as a constant to simplify the relevant calculation; Y_t indicates the total regional output; K_t indicates the capital stock; L_t indicates the quantity of labors; S_t indicates the total amount of regional construction land, represented by the urban construction land in the regions of the study area; and α, β, γ are the coefficients to be estimated. Because construction land is mainly used for non-agricultural production, Y_t is expressed as the gross domestic product (GDP) of the secondary and tertiary sectors for the year, and L_t is expressed as the gross number of employees in the secondary and tertiary sectors. Referring to Wu (2016), based on the fixed capital investment amount, the perpetual inventory method is used for calculation, and the formula is

$$K_t = (1 - \delta_t)K_{t-1} + I_t \tag{3}$$

$$K_0 = \frac{I_0}{\delta_0}. \tag{4}$$

Among them, K_t is the capital stock of the year; δ_t is the depreciation rate, referring to Wu et al. (2014), taking 10% uniformly; I_t is the fixed asset investment in the current year; K_0 is the capital stock in the base period; and I_0 is the base period fixed asset investment.

Second, we empirically estimate the parameters by collecting years of actual data in the estimation equation presented earlier

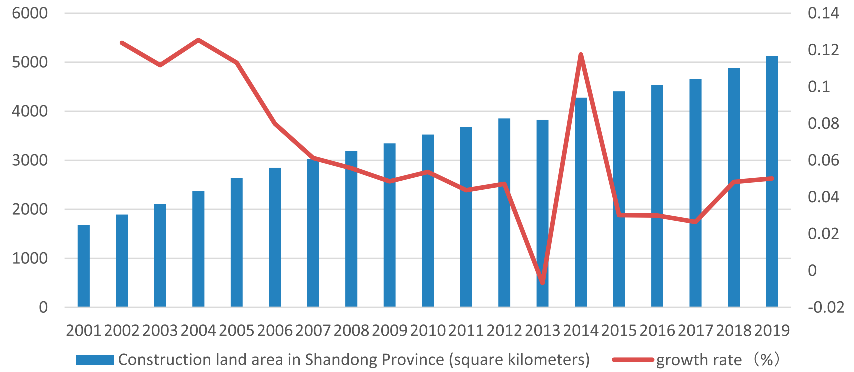

FIGURE 2 | Changes of the construction land area in Shandong province between 2001 and 2019.

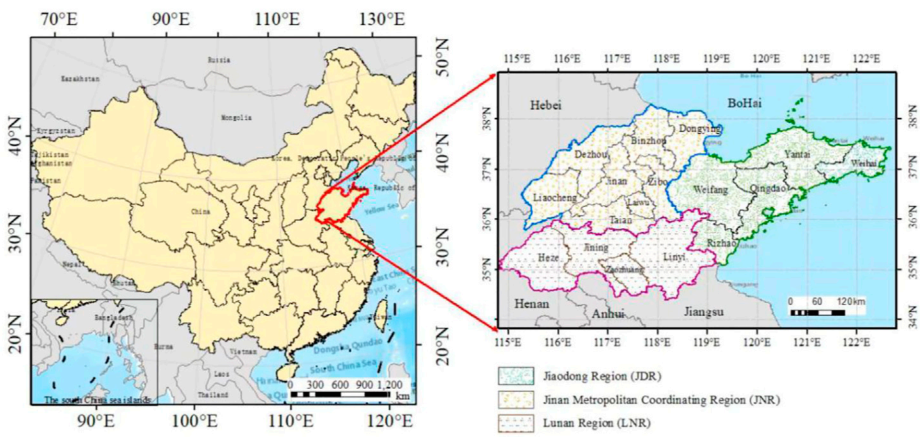

FIGURE 3 | Location and sub-regional divisions of the study area (Shandong province).

and using the panel data regression method to empirically estimate the marginal output elasticity of construction land in the study area.

Third, according to the principle of the equal marginal output of construction land between regions and referring to the calculation methods of Zhang et al. (2021) and Xie et al. (2022), the following simultaneous equations are established:

$$MPS_{1t} = MPS_{2t} = \ldots = MPS_{17t}, \tag{5}$$

$$MPS_{it} = \gamma A K_{it}^{\alpha} L_{it}^{\beta} S_{it}^{*\gamma-1}, \tag{6}$$

$$\sum S_{it}^{*} = \sum S_{it}, \tag{7}$$

where MPS_{it} is the theoretical marginal product elasticity of construction land in sub-region cities in the study area, which should be equal to each area at the theoretical scenario in the study area. S_{it}^{*} is the theoretical construction land area, calculated according to the formula, and S_{it} is the actual construction land area. Using MATLAB to solve the aforementioned equations, the theoretical construction land scale of each area, denoted by S_{it}^{*}, can be obtained.

Finally, by comparing the scale of the actual and theoretical construction land in each region, the SMCL rate expressed by specific numerical values in a certain area can be calculated, denoted by m_{it}:

$$m_{it} = \left(S_{it} - S_{it}^{*}\right)/S_{it}^{*}. \tag{8}$$

If $m_{it} > 0$, the actual construction land area is larger than the theoretical construction land area, which means that too much construction land is allocated, that is, an excessive misallocation. If $m_{it} < 0$, the actual construction land area is smaller than the theoretical construction land area, which indicates a misallocation shortage. The larger the absolute value of m_{it}, the higher the SMCL degree in this area. This estimation method can calculate the specific value of the SMCL level and obtain the ideal allocation scale of construction land, which helps to conceptualize more precise regulation policies.

TABLE 1 | Parameter estimation results of Shandong province's production function.

	Capital (K)	Labor (L)	Land (S)	F-value
Coefficient	0.69***	0.21**	0.12**	2596.47
t-value	27.48	2.20	2.16	

*Note: ***p < 0.01, **p < 0.05, *p < 0.1.*

3.2.2 Model Setting and Variable Selection

Based on the aforementioned information, we take the measurement results of the SMCL rate as the explained variable and use the various contributing factors under the GMSS framework as the explanatory variables. Then, the econometric regression equation for the SMCL in typical regions of China can be constructed further. A quantitative empirical test is conducted on the role nature of different factors and their influence strength. In addition, this study undertakes heterogeneity analysis and robustness tests in different periods and sub-regions to gain a deeper understanding of the impact of different factors on the SMCL and its dynamic changes, thereby enriching existing research.

According to the GMSS analytical framework, each explanatory variable of the econometric model is determined by considering the literature references and data availability. 1) Government power factors: generally, the level of dependence of local governments on construction land leasing can reflect their motivation to intervene in construction land allocation, which can be calculated by the proportion of land leasing income to total fiscal revenue, denoted as $land_{it}$. Public fiscal expenditure is the most important means by which local governments intervene in economic and social development. Therefore, the proportion of local fiscal expenditure to GDP is selected to represent the degree of government intervention, denoted as gov_{it}. 2) Market power factors: the macrostructural characteristics formed by various market players are mainly considered. Presently, China and Shandong province are still in the rapid development stage of industrialization; therefore, the proportion of added value with the secondary industry to GDP is selected to represent the industrial pattern of market players, denoted as ind_{it}. The level of urbanization is the most direct indicator of the regional spatial structure, which can be represented by the proportion of the urban population to the total population, denoted as $urban_{it}$. Capital is one of the key factors influencing land value realization, so the loan balance of financial institutions, which can better reflect the environment of other production factors supplying than proportion indicators or per capita indicators, is used and denoted as $finan_{it}$. 3) Social force factors: the variable selection is made from the perspectives of social vitality and social openness. Among them, the measurement of social vitality is more complicated, but in existing data the level of residents' consumption can more intuitively reflect the actual state and degree of influence of residents' participation in economic operations. Expressing it by the total retail sales of social consumer goods, denoted as $consu_{it}$, the degree of social openness is closely related to the level of its foreign economic ties, calculated by the proportion of the total regional import and export values to GDP, and recorded as $open_{it}$. 4) Supporting system factors: it involves a wide range of factors; however, for developing countries currently in the period of rapid industrialization, innovation system support, and infrastructure system support are the two most important factors affecting the efficiency of construction land use. Therefore, regional science and technology investment is selected to represent the supply level of local technological innovation, expressed as the expenditure of scientific and technological activities of industrial enterprises above a designated size in the region, denoted as $tech_{it}$. The highway density represents the completeness of infrastructure construction, expressed as the highway mileage per 100 square kilometers in the region, denoted as $road_{it}$.

As all the explanatory variables are positive values and the sign of the misallocation rate represents whether the construction land allocation is excessive or short, its absolute value can also measure the degree of misallocation. Therefore, the explained variable is expressed by the absolute value of the SMCL rate in each sub-region calculated earlier, denoted as am_{it}.

Finally, the econometric regression model is constructed as follows:

$$am_{it} = \beta_0 + \beta_1 ind_{it} + \beta_2 open_{it} + \beta_3 urban_{it} + \beta_4 land_{it} + \beta_5 gov_{it} + \beta_6 lntech_{it} + \beta_7 lnconsu_{it} + \beta_8 lnroad_{it} + \beta_9 lnfinan_{it} + \mu_i + \delta_t + \varepsilon_{it}. \quad (9)$$

The subscript i represents different regions in Shandong, and the subscript t represents different times. μ_i, δ_t, and ε_{it} represent the time fixed effect, regional fixed effect, and random error terms, respectively.

3.2.3 Study Area and Data Sources

This study selects Shandong province, China, as the empirical research area and investigates the measurement of the SMCL, the evolution characteristics of the spatiotemporal pattern and its contributing factors. The typical value of the study area is mainly reflected in three aspects.

First, Shandong is a province with a large population and economy along the eastern coast of China. It not only plays an important role in China's regional development pattern but also is highly similar to China's national conditions due to its natural resource endowment, climatic conditions, population, and industrial structure. It is considered to be a classic epitome of the evolution of China's economic and social development (Lu et al., 2011; Chen et al., 2022). In 2020, Shandong achieved a GDP of RMB 8.31 trillion, while the three industrial structures were in the ratio of 7.3:39.9:52.8, the permanent population at the end of the year was 101.70 million, and the urbanization level reached 63.94%. Overall, Shandong is still in a rapid industrialization and urbanization stage. Since 2000, the scale of urban construction land in Shandong has increased from 1,058.92 km^2 to 3,951.85 km^2, with an average annual growth rate of 8.1%, significantly exceeding the growth rate of urban population,

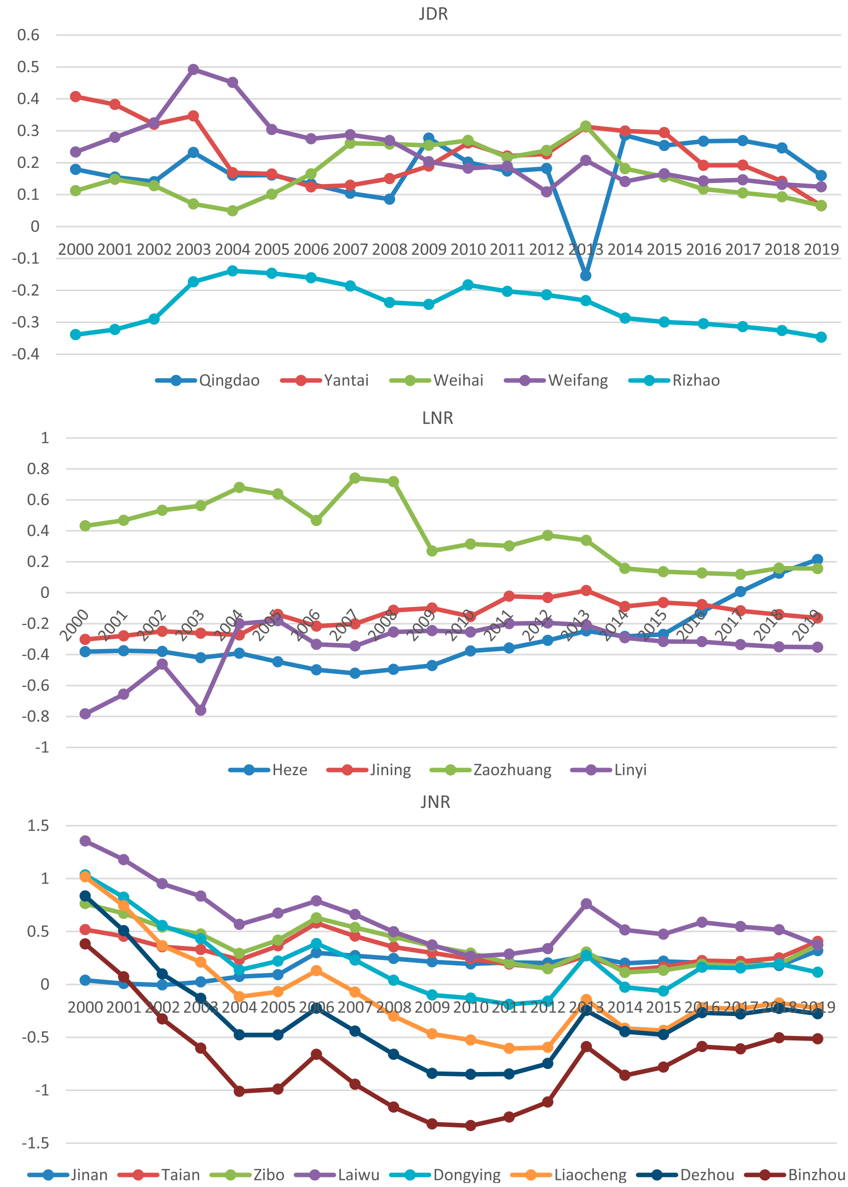

FIGURE 4 | SMCL changes of different regions in Shandong Province between 2000 and 2019.

and the pressure of the low level of construction land utilization and the large contradiction between supply and demand always exists (**Figure 2**). Therefore, taking Shandong as the research area clearly shows the evolution of the SMCL process during the rapid growth period.

Second, Shandong has formed a gradient development pattern of three major regions as the Jiaodong region (JDR), Jinan metropolitan-coordinating region (JNR), and Lunan region (LNR). The differences in the regional economic development levels and industrial structure characteristics are significant, which is helpful in identifying the characteristics of the SMCL and the regional heterogeneity of its contributing factors (**Figure 3**).

Third, as a northern province in China, governments at all levels in Shandong have a profound historical tradition of intervening and regulating the allocation of construction land (Qu et al., 2021). However, in recent years, Shandong has continued to promote a market-oriented process of construction land allocation in accordance with the requirements of the central government for comprehensively deepening reforms. A new type of allocation mechanism, led by the government, with enterprises as the main body and extensive participation of social forces and supported by scientific and technological innovation, is taking shape, which is also a typical value for examining the role of contributing factors and their dynamic

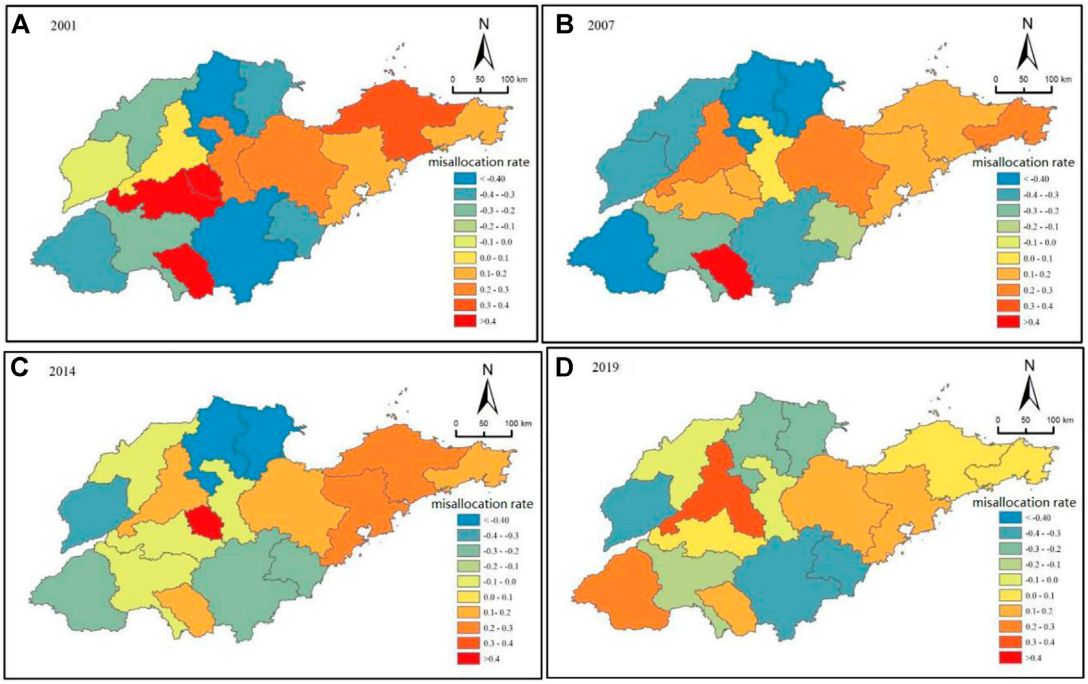

FIGURE 5 | Spatial pattern and evolution of the SMCL in Shandong province between 2001 and 2019. **(A)** 2001; **(B)** 2007; **(C)** 2014; (5) 2019. Note: This figure shows only the results of 4 years, and the others can be obtained by contacting the correspondence author.

changes under the GMSS construction land misallocation analytical framework.

This article takes 2000–2019 as the research period, and the required data are obtained from public statistical databases, such as "Shandong Statistical Yearbook," "China Land and Resources Statistical Yearbook," and "China Urban Construction Statistical Yearbook," which are all available at https://data.cnki.net/ and http://tjj.shandong.gov.cn/. Even though the Laiwu region was merged into the Jinan region in January 2019, this study still considers the Laiwu region as a separate administrative area.

4 RESULTS

4.1 The Measurement Result of the Spatial Misallocation of Construction Land

Before estimating the main parameters of **Eq. 2**, the Hausman test was performed. The test results rejected the null hypothesis, and the fixed effects model was used to estimate **Eq. 2**. The results of the regression using the panel data of 17 cities in Shandong during the study period are shown in **Table 1**.

Among them, the marginal product elasticity coefficient of the capital factor $\alpha = 0.69$, the marginal product elasticity coefficient of the labor factor $\beta = 0.21$, and the marginal output elasticity coefficient of construction land input $\gamma = 0.12$, all passed the 5% significance level test. Therefore, the production function of Shandong is obtained as

$$Y = 0.24K^{0.69}L^{0.21}S^{0.12}. \tag{10}$$

Calculations are performed based on the obtained functions. Owing to the large sample size of cities in the study area, we display the measurement results and their time series changes according to three economic regions of Shandong. As shown in **Figure 4**, from 2000 to 2019, the SMCL degree in Shandong generally showed a declining trend. In 2000, the highest value of the SMCL rate in the province reached 0.59, which meant that the actual construction land usage in Laiwu exceeded approximately 59% of its theoretical construction land usage. The lowest value is −0.78, which means that the actual construction land in Linyi is much lower than its theoretical construction land scale, and the shortage in misallocation is very serious. In 2019, the distribution range of the SMCL is compressed between −0.35 and 0.31, which indicates that the SMCL of Shandong has been significantly reduced.

From the perspective of regions, except for a few areas such as Jinan and Liaocheng, the urban construction land in most areas significantly approaches the adaptation range. This shows that with the gradual improvement of market mechanisms and governance capacity, the SMCL has improved as a whole. Among them, cities with moderate and low levels of economic development, regions with a higher proportion of agriculture or traditional industries, and those with slower rates of industrialization and urbanization have a higher probability of shortage misallocation. However, the SMCL of none of the regions continuously improves or deteriorates without fluctuation. This shows that the regulation level of the provincial government still needs to be further strengthened.

Simultaneously, there were two regions that reversed their nature of misallocation during the study period. Among them, the Zibo region is a traditional industrial region. In 2000, the actual construction land use exceeded 24.57% of its theoretical value, but it dropped to −3.22% in 2019. In the context of governments all over China competing for construction land permit indicators, this also means that its regional competitiveness is significantly declining, while the Heze region is a traditional agricultural region. Industrialization and urbanization have developed rapidly in recent years. During the study period, the level of misallocation increased rapidly from −0.38 to 0.21. This proves that industrialization and urbanization strategies are still an apparent driving force for local governments to compete for construction land resources.

From the perspective of the three major regional plates in Shandong, the utilization of urban construction land within each plate is obviously close to the adaptation range. Although there are regions of excessive misallocation and shortage misallocation within each region, on the whole, the numerical distribution of the SMCL level in JDR is biased toward excessive misallocation, and most cities have obvious characteristics of agglomeration in a suitable range. The numerical distribution of the LNR is relatively discrete, but the overall bias is toward shortage misallocation, and the numerical distribution of the JNR is centered at zero and distributed symmetrically up and down, but the convergence trend is not obvious. It can be seen that it is suitable for the overall economic development level and development stage of the regional economic sector, and there are also certain regional differences in the misallocation pattern of urban construction land, while it provides a basis for the regional heterogeneity test of contributing factors in the following.

Combined with the spatial distribution map of the SMCL in some years, it can be seen more clearly that the SMCL in the province tends to ease, and the number of extremely high and extremely low values progressively decrease. In terms of the spatial pattern, in the base period of the study, Shandong generally presented an excessive misallocation agglomeration area with the east–west central zone as the core and a shortage misallocation agglomeration area on the north and south flanks. By 2019, it had been transformed into a high-value surface agglomeration area in JDR with Qingdao as the center, a high-low combination area in JNR with Jinan as the center, and an LNR with a staggered distribution of high and low values. In the new century, Shandong has implemented the breakthrough Yantai, breakthrough Jinan, and breakthrough Heze strategies. Shandong also has regional development ideas, such as double centers and solid provincial capitals. In these practices, the government plays an important role in the SMCL (**Figure 5**).

4.2 Empirical Analysis Results

This study adopts the stepwise regression method, adds variables in steps, and uses STATA 15 software for regression analysis. The regression results show that the explanatory power of the model significantly improves after adding variables in steps, and all variables pass the 5% significance test except for the insignificant level of land finance dependence in the final regression model, proving the overall rationality of the variable selection. We judged the specific influence of each factor based on three aspects. First, the sign of the regression coefficient represents the influence direction of the corresponding factor; a positive value means that the factor has an aggravating effect on the SMCL, and a negative value means that it has a mitigating effect. Second, the magnitude of the absolute value of the regression coefficient represents the impact strength of this factor on CLM, and the larger the absolute value, the stronger the aggravation or mitigation effect. Third, regardless of whether it is marked with "*" or not indicates whether the influence of the factor has passed the statistical test of the significance level, and the regression coefficient without marked "*" indicates that although the factor has a certain influence on the spatial mismatch of construction land, but the actual probability of having an impact is low.

The final empirical results show that each dimension of the GMSS system has a significant impact on the SMCL. In terms of the role of the government, the degree of land financial dependence is positively correlated with the SMCL rate, but it is not significant. For every 1% increase in the land financial dependence level, the SMCL rate increases by 0.022%. This indicates that the motives of land transfer in various regions of Shandong cannot influence the scale of construction land allocation by higher-level governments in the region, and it shows the policy rigidity of the tightening construction land supply adopted by the Chinese government to

TABLE 2 | Temporal heterogeneity effects of the multidimensional contributing factors of the SMCL.

Variable	2001–2010	2011–2019
	am_{it}	am_{it}
$land_{it}$	−0.019	0.035***
	(0.04)	(0.00)
gov_{it}	2.249***	1.820***
	(0.51)	(0.61)
ind_{it}	0.694***	0.470***
	(0.00)	(0.00)
$urban_{it}$	−0.257***	−0.413***
	(0.06)	(0.11)
$lnfinan_{it}$	0.038*	0.251***
	(0.08)	(0.03)
$open_{it}$	−0.154***	−0.109**
	(0.05)	(0.04)
$lnconsu_{it}$	0.003	−0.293***
	(0.04)	(0.02)
$lntech_{it}$	−0.046*	−0.033*
	(0.02)	(0.03)
$lnroad_{it}$	−0.209***	−0.227***
	(0.03)	(0.04)
Constant	0.752*	1.205**
	(0.39)	(0.55)
Observations	170	144
R-squared	0.341	0.585
Number of groups	17	17
FE	Yes	Yes
F	2,394	2,6609

*Note: Standard errors in brackets, ***p < 0.01, **p < 0.05, *p < 0.1.*

ensure food security and prevent the tendency of urban real estate (Fan et al., 2021; Huang et al., 2022). The degree of government intervention has a significant positive impact on the SMCL rate, and its elasticity coefficient reaches 1.728, indicating that although the government cannot determine the scale of available construction land, local governments can greatly affect the utilization efficiency of urban construction land and exacerbate the misallocation contradiction, such as formulating local industrial policies, adjusting the supply price and supply structure of construction land, and other intervention measures, which is consistent with the conclusions of most studies (Cheng et al., 2022).

In terms of market power, the proportion of the secondary industry has a significant positive correlation with the SMCL rate, with an elasticity coefficient of 0.63. The fundamental reason is China's low-priced industrial land policy to implement the industrialization strategy, which will inevitably lead to the basic fact that the higher the proportion of the secondary industry, the higher the SMCL rate. However, compared with the results in some studies, the proportion of the secondary industry and the SMCL rate have no significant correlation, or even a significant negative correlation, which is obviously more in line with theoretical logic and practical experience (Huang and Du, 2017). Of course, the significant positive correlation between the two also means that more attention should be paid to the balance between the industrialization strategy and the improvement of the comprehensive output efficiency of urban construction land, especially to curb the extensive use of construction land in the secondary industry to achieve sustainable urban development under the constraints of land resources. At the same time, the growth of the regional credit scale has a significant aggravating effect on the SMCL level, indicating that a loose credit environment will lower the market entry threshold to a certain extent, resulting in inefficient land use. The urbanization rate is significantly negatively correlated with the SMCL rate. This indicates that it can help the agglomeration-based economic development model to improve the efficiency and vitality of economic operations by promoting mechanisms such as the sharing of infrastructure and service facilities, accelerating knowledge spillover, and reducing information asymmetry, thereby improving the SMCL.

In terms of social factors, the regional consumption capacity is significantly negatively correlated with the SMCL rate, and the deviation correction effect coefficient reaches −0.135. It is confirmed that social consumption can force enterprises to continuously transform and upgrade from the demand side, which helps to improve the mismatch of construction land and promotes the optimization of regional industrial structure and high-quality economic development. In addition, the level of export-oriented economic development is an important manifestation of social openness. It also helps to significantly improve the SMCL level, and its improvement coefficient reaches −0.147.

In terms of support systems, the level of scientific and technological development is negatively correlated, with the SMCL rate. This shows that technological innovation can help to improve the output of enterprises' construction land. Infrastructure construction can significantly reduce the efficiency of market operations and transaction costs, thereby improving the SMCL, with the improvement coefficients reaching −0.045 and −0.284, respectively.

Overall, except that the impact of land financial dependence is not in line with the expected judgment, other factors have played a significant role, thus confirming the validity of the GMSS analytical framework. Among the factors that exacerbate the misallocation of resources, the influence of local government intervention is the strongest, followed by the proportion of the secondary industry, and the influence of the financial credit scale is the weakest. Among the factors with corrective effects, urbanization has the strongest improvement effect, followed by road network density, openness to the outside world, consumption vitality, and level of technological innovation. Although the specific effects of different indicators cannot be comprehensively calculated based on the numerical distribution characteristics of the regression coefficients in each dimension, government power is the biggest reason for the SMCL in Shandong, followed by market power, and social power is still relatively weak. Owing to its diverse composition, the support system may exhibit a significant impact strength difference. However, transportation infrastructure has a stronger influence as a physical support system, and the level of scientific and technological innovation, as a soft factor, has a weak influence, which is in line with the actual situation of the current development of the Shandong's industrialization stage (Tan et al., 2021).

TABLE 3 | Regional heterogeneity effects of the multidimensional contributing factors of the SMCL.

Variable	LNR	JNR	JDR
	am_{it}	am_{it}	am_{it}
$land_{it}$	0.083	0.100	−0.045
	(0.07)	(0.07)	(0.03)
gov_{it}	4.430**	0.091*	1.525**
	(1.34)	(2.04)	(1.10)
ind_{it}	1.210**	0.602**	0.319**
	(0.00)	(0.00)	(0.00)
$urban_{it}$	−0.206*	−0.617**	−0.625*
	(0.47)	(0.24)	(0.29)
$lnfinan_{it}$	0.139	0.190	0.091
	(0.19)	(0.13)	(0.08)
$open_{it}$	−0.385	−0.285	−0.133
	(0.87)	(0.23)	(0.07)
$lnconsu_{it}$	−0.142	−0.133	−0.135
	(0.18)	(0.08)	(0.09)
$lntech_{it}$	−0.065	−0.087**	0.057
	(0.06)	(0.03)	(0.03)
$lnroad_{it}$	−0.666	−0.224**	−0.244*
	(0.29)	(0.07)	(0.12)
Constant	0.000	1.469	1.689*
	(0.00)	(0.80)	(0.61)
Observations	74	145	95
R-squared	0.646	0.461	0.381
Number of groups	4	8	5
FE	Yes	Yes	Yes
F	8.907	356.2	19.12

*Note: Standard errors in brackets, ***p < 0.01, **p < 0.05, *p < 0.1.*

TABLE 4 | Variable selection for the multidimensional contributing factors of the SMCL.

Variable properties	Variable dimension	Variable name	Variable meaning	Calculation method
Explained variable	Overall dimension	am_{it}	Misallocation of urban construction land in sub-regions	Absolute value of m_{it}
Explanatory variables	Government forces	$land_{it}$	The motivation of local government to intervene	Ratio of urban land leasing income to local public revenue
		gov_{it}	Level of local government intervention	Ratio of local public expenditure to GDP
	Market forces	ind_{it}	Industry structure of market forces	Proportion of the secondary industry to GDP
		$finan_{it}$	Level of capital supply	Loan balance of financial institution
		$urban_{it}$	Spatial structure of the market forces	Proportion of urban population
	Social forces	$consu_{it}$	Social vitality	Retail sales of consumer goods
		$open_{it}$	Degree of openness	Ratio of total value of imports and exports to GDP
	Supporting system	$tech_{it}$	Supply level of technological innovation	Expenditure on scientific and technological activities of industrial enterprises above the designated size
		$road_{it}$	Completeness of infrastructure	Highway mileage per 100 square kilometers

4.3 Robustness Test

To ensure the robustness of the measurement results, we choose the feasible general least squares model and mixed effects model for the test. The results show that the role and nature of each variable are completely consistent with the original model, which confirms the reliability of the analysis conclusion of each contributing factor. In particular, except for the weakening of the influence coefficient of the support system in the mixed effects model, the remaining variables still maintain the basic conclusion that the government has the most vital role, the market power is second, the social force is weak, and the support system exhibits type differentiation. This provides a credible empirical basis for the analysis of the contributing factors of the SMCL and subsequent governance.

5 HETEROGENEITY ANALYSIS

5.1 Temporal Heterogeneity Analysis

To study the changes in the effect of various factors on the SMCL at different stages, we used 2010 as the split point and regressed the data from 2001 to 2010 and 2011 to 2019, respectively. The results are presented in **Table 2**.

The results show that compared with the previous stage, the fitting efficiency of the model is significantly improved, indicating that the explanatory power of the GMSS analytical framework for the SMCL in Shandong is further enhanced. In particular, the intensification of the misallocation in the role of the government has weakened, the promoting role of market factors and social factors has increased, and the role of the support system has remained relatively stable, but compared with each other, the situation has not essentially changed.

Specifically, in terms of the role of the government, from 2011 to 2019, the impact of Shandong's land financial dependence on the SMCL has changed from an insignificant to a significant positive impact, which should be related to Shandong's active implementation of the policy, which means consolidation of fragmented rural land to shift newly obtained quotas to urban districts in the same region. Originally, this policy is in line with the industrialization and urbanization trends of Shandong, which is an effective way to improve the utilization efficiency of regional construction land. However, to a certain extent, it has also become a local government strategy that can prevent the national reduction in the scale of new construction land, which has exacerbated the degree of the SMCL (Chien, 2015). The weakening of the influence of government intervention on the SMCL rate should be related to the market-oriented reform of land transactions in China. During this period, the government paid more attention to the role of market supply and demand in the allocation of factors, and the proportion of construction land transferred by agreement decreased. However, an increasing number of market-oriented allocation methods, such as bidding, listing, and auction, have been adopted, which has slightly alleviated the distortion of construction land allocation.

In terms of market factors, the role of the industrial structure has weakened, and the roles of urbanization and financial credit have increased significantly. This is related to the rapid development of the tertiary industry and the industrial evolution trend that gradually exceed the proportion of the secondary industry in Shandong. In addition, in recent years, the development of emerging industries, such as big data and information technology, has accelerated, and the output efficiency of unit construction land in the secondary industry has significantly improved. Therefore, the negative contributions to the SMCL tend to be moderate. In 2011, the level of urbanization in Shandong exceeded 50%, the agglomeration economic effect produced by urbanization was released faster, and the improvement effect on the SMCL was also more obvious. Simultaneously, China issued an economic stimulus plan in response to the 2008 global financial crisis. The loose financing environment has enabled the rapid development of local traditional industries and backward production capacity and has aggravated the impact on the SMCL.

In terms of the social role, the correcting effect of the degree of opening to the outside world on the SMCL rate has weakened. This is related to the accelerated improvement of the socially open environment brought about by China's accession to the World Trade Organization in 2001 and the decline of marginal benefits

TABLE 5 | Economic statistics of Shandong province and its three sub-regions.

Region	GDP per capita (RMB yuan)	Proportion of urban population (%)	Industrial structures (%)	Urban construction land area (km^2)	Average growth rate of urban construction land between 2000 and 2019 (%)
Shandong	70,653	61.5	7.2:39.8:53.0	5129.91	6.16
JDR	94,405	67.0	6.4:39.0:54.6	2233.97	5.95
JNR	71,000	62.6	6.8:41.3:51.9	2006.81	6.18
LNR	44,346	54.8	9.9:40.4:49.6	889.13	6.68

TABLE 6 | Stepwise regression results of the econometric model for the effects of multidimensional contributing factors of the SMCL.

Variable	(1)	(2)	(3)	(4)	(5)
	am_{it}	am_{it}	am_{it}	am_{it}	am_{it}
$land_{it}$			0.020	0.019	0.022
			(0.02)	(0.03)	(0.03)
gov_{it}			1.119***	1.130***	1.728***
			(0.30)	(0.24)	(0.38)
ind_{it}	0.338***	0.349***	0.493***	0.358***	0.630***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$urban_{it}$		−0.302***	−0.226**	−0.069	−0.341***
		(0.09)	(0.10)	(0.07)	(0.06)
$lnfinan_{it}$					0.171***
					(0.06)
$lnconsu_{it}$				−0.036	−0.135**
				(0.03)	(0.05)
$open_{it}$		−0.022	−0.028	−0.032	−0.147***
		(0.05)	(0.06)	(0.05)	(0.03)
$lntech_{it}$				−0.016	−0.045**
				(0.02)	(0.02)
$lnroad_{it}$					−0.284***
					(0.04)
Constant	0.059	0.244**	−0.029	0.725***	1.276***
	(0.04)	(0.08)	(0.12)	(0.22)	(0.42)
Observations	314	314	314	314	314
R-squared	0.098	0.165	0.176	0.206	0.379
Number of groups	17	17	17	17	17
FE	Yes	Yes	Yes	Yes	Yes
F	1.489	11.06	16.64	183.9	187.3

*Note: Standard errors in brackets, ***p < 0.01, **p < 0.05, *p < 0.1.*

TABLE 7 | Robustness test of the econometric regression results *via* the FGLS model and mixed effects model.

Variable	FGLS test	Mixed effects test
	am_{it}	am_{it}
$land_{it}$	−0.018	−0.018
	(0.02)	(0.02)
gov_{it}	2.378***	1.858***
	(0.45)	(0.33)
ind_{it}	0.599***	0.675***
	(0.00)	(0.00)
$urban_{it}$	−0.341***	−0.183**
	(0.08)	(0.08)
$lnfinan_{it}$	0.180***	0.153**
	(0.02)	(0.05)
$open_{it}$	−0.169***	−0.102***
	(0.03)	(0.03)
$lnconsu_{it}$	−0.170***	−0.115**
	(0.02)	(0.05)
$lntech_{it}$	−0.016**	−0.047***
	(0.02)	(0.01)
$lnroad_{it}$	−0.318***	−0.064**
	(0.04)	(0.02)
Constant	1.396***	0.033
	(0.33)	(0.22)
Observations	314	314
Number of groups	17	0.281
FE	Yes	Yes
Wald/F	334.5	930.3

*Note: Standard errors in brackets, ***p < 0.01, **p < 0.05, *p < 0.1.*

in the later period. Reflecting that with the improvement in people's income level, the promotion effect of the vitality of private development on the utilization of construction land has been further enhanced.

The influence of the support system has not changed much, indicating that China's market-oriented reform has entered a critical period. The optimization relying on the external forces of the regional allocation of construction land has entered a stable stage, and in the future it will need to rely more on the changes in the system itself.

5.2 Regional Heterogeneity Analysis

According to the overall pattern of the regional economy in Shandong, the study area is divided into JNR, JDR, and LNR. Regression analysis is performed on three regions, and the results are shown in **Table 3**.

The heterogeneity of the GMSS system on the SMCL in the three regions is complex. Among them, the government's reliance on land finance exacerbates the misallocation in LNR and JNR. However, there is a certain misallocation improvement effect in JDR. This shows that economically developed areas are more inclined to adopt the strategy of sorting and excavating the potential of existing urban construction land, thereby helping to improve their SMCL level. The level of government intervention in urban development has a significant positive impact on all the three regions, consistent with the previous discussion in this study, but the influence coefficient in LNR is as high as 4.43, reflecting that government intervention in economically underdeveloped areas is an extremely important reason for the SMCL.

Among the market power factors, the proportion of the secondary industry still played a significant positive role in increasing the misallocation, but the role was weaker in regions with higher levels of economic development. This is consistent with the fact that the secondary industry's development level is relatively high, and the output efficiency of construction land is relatively more robust in economically developed areas. The level of urbanization is similar to this. The high level of urbanization in economically developed areas has a more apparent improvement effect on the SMCL, which reflects the necessity of continuing to accelerate the upgrading of the industrial structure and the urbanization process. The impact of the local financial environment is greatest in JNR, which is related to the centralized distribution of Chinese financial institutions in the provincial capital city as the administrative center and easy access to financial resources.

However, although the effects of the social force factors in the three regions are all improvement effects, the regression results are not significant. Among them, the regression coefficients of social openness and social consumption level in LNR are the smallest, indicating that although the social openness and social vitality of the underdeveloped areas are low, they tend to form stronger marginal improvement contributions because of their weak foundation.

In terms of the influence of the support system, the power of science and technology has a significant and the strongest improvement effect on JNR. This shows that the provincial capital has gathered a large number of educational technology resources due to its status as an administrative center and has formed a spillover effect on the surrounding areas through close-range scientific and technological cooperation, such that the role of scientific and technological innovation can be effectively played. The level of infrastructure construction represented by highway density has the strongest effect on the improvement of construction land mismatch in LNR, but it is not significant, which shows that infrastructure construction in LNR is still relatively lagging behind; thus, it has stronger improvement elasticity. However, while infrastructure improvement accelerates the flow of factors and alleviates the SMCL, the imperfect system and mechanism of promoting high-quality economic development in LNR may also lead to the transfer of low-end industries to the local area and aggravate the misallocation of land use. Therefore, although the improvement of infrastructure has a positive effect on improving the SMCL in LNR, it is clear that this effect is not sufficiently robust.

In general, the effects of various dimensions of the GMSS system in each region are still in line with theoretical expectations. Owing to the level of economic development and its structural characteristics, the role of the government is stronger and the role of market forces in promoting adaptation is lower than in backward regions, while social forces and support systems may have a stronger potential for improving misallocation. However, owing to the constraints of various factors, such as the imperfect system and mechanism, the degree of its role is not sufficiently stable.

6 CONCLUSION

Spatial misallocation among regions is an important contributor to the inefficient use of construction land. This study quantitatively measures and analyzes the spatial and temporal characteristics of the SMCL in Shandong, China. It also proposes and empirically tests the actual effects of the factors affecting the SMCL and its dynamic changes under the GMSS analytical framework. The main conclusions of this study are presented as follows:

(1) The calculation results based on the principle of equal marginal output can more accurately reflect the nature and intensity of the SMCL in the study area. During the study period, the urban construction land in the study area grows rapidly, but the overall level shows a downward trend. In most areas, the urban construction land significantly approaches the adaptation range. Overall, industrialization and urbanization remain as evident driving forces for local governments to compete for construction land resources. Cities with a moderate or low level of economic development, regions with a high proportion of agriculture or traditional industries, and regions with slower rates of industrialization and urbanization have a higher probability of shortage misallocation. The spatial pattern of the SMCL level in Shandong shifts from a numerical combination of the middle corridor and the north–south wings to a numerical combination of the central city as the core and the interlaced distribution of other regions.

(2) With the gradual improvement in developing countries' economic and social development levels, government forces, market forces, social forces, and their supporting systems will form a multi-agent symbiosis and coevolution regulation system. Under the management and control framework of the superior government, it adjusts the timing, structure, and efficiency of construction land utilization, which ultimately affects the SMCL status.

(3) The empirical results confirm the validity of the GMSS analytical framework for the contributing factors of the SMCL. Among them, government power not only aggravates the contradiction of the SMCL but also has the strongest effect. The role of social forces remains weak, and the nature and strength of the support system are internally differentiated. However, with the changes in the development stage, the intensification of misallocation in the role of the government has weakened, the role of market and social factors has been enhanced, and the role of the support system has remained relatively stable. However, the comparative situation has not fundamentally changed. The influence of different dimensions on the heterogeneity of the SMCL in the three major regions is more complex. In general, the role of the government in backward regions is stronger, the role of

market forces in adaptation promotion is lower, and social forces and supporting systems are not sufficiently steady.

The aforementioned conclusions not only have various policy implications for Shandong but also have rich reference values for other regions with rapid growth of construction land and significant internal differences. First, the fact that construction land in Shandong is growing rapidly but the level of SMCL is declining is closely related to the continuous promotion of the systematic reform of construction land allocation models in China and Shandong in recent years. This shows that in the future, relative regions should accelerate the construction of a policy environment, in which market and social forces can effectively participate in the allocation of construction land and constantly improve the mechanism design for multi-agents to play a coordinated role to avoid the risk of misallocation caused by improper government intervention. Second, the SMCL level is significantly related to factors such as the regional development level, industrial structure, spatial structure of agglomeration, and completeness of supporting systems. This means that the regional allocation of construction land should be fully integrated with the development characteristics of different regions. Nevertheless, it also reminds all regions to continuously improve their technological innovation system and infrastructure construction, actively promote the layout optimization of their industrial and spatial structures, and accelerate the transformation to high-quality development. Third, the process of improving the spatial misallocation of construction land in most regions is unstable and there may be large or small fluctuations. This requires that each region should also strengthen its statistical analysis, monitoring and early warning, and dynamic policy adjustment of construction land allocation to respond in a timely manner to the risk of loss of economic and social benefits caused by improper coordination of various dimensional factors.

Because the measurement method used in this study is a statistical estimation based on the ideal state, the measurement results may deviate from the actual situation in different regions. In addition, there are many contributing factors involved in the SMCL; therefore, this study cannot include more variables for a more systematic investigation, and the conclusions obtained also have certain limitations. Undoubtedly, the measurement ideas, analytical framework, and new discoveries of this study have theoretical and policy significance for understanding the evolution law of the SMCL pattern in rapid industrialization and urbanization areas, constructing a better regulatory framework, and improving the utilization efficiency of construction land (**Table 4**, **Table 5**, **Table 6**, **Table 7**).

DATA AVAILABILITY STATEMENT

Publicly available datasets are analyzed in this study. This data can be found here: https://data.cnki.net/, http://tjj.shandong.gov.cn/.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Conceptualization, SL and HC; methodology, SL and HC; software, HC and XW; validation, SL, HC, and XW; formal analysis, SL and HC; investigation, JW; resources, SL and HC; data curation, HC and XW; writing—original draft preparation, SL and HC; writing—review and editing, SL, HC, and XW; supervision, SL; project administration, SL. All authors read and approved the final manuscript.

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Resource and Environment Constraints and Promotion Strategies of Rural Vitality: An Empirical Analysis of Rural Revitalization Model Towns

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In response to the challenges of rural chronic poverty caused by insufficient self-development ability, establishing a development model conducive to poverty alleviation and stimulating rural development potential have become core tasks of deepening rural revitalization. Resources and environment play an important role in invigorating rural vitality. Based on symbiosis theory, we have constructed a new conceptual framework to analyze dynamic performance of rural areas in population, industry and facilities, and dynamic constraints in resources and environment. Using an improved TOPSIS evaluation method and panel Tobit model, we have selected 106 rural revitalization model towns from Shandong province as research samples, empirically analyzed the performance of rural vitality and its resources and environment constraints, explored differences of rural vitality performance and vitality constraints of different village types, and put forward long-term mechanisms to maintain rural vitality. Results show that from 2012 to 2019, rural vitality of rural revitalization model towns in Shandong province was gradually improved, among which industrial development had contributed the most; agriculture-tourism towns are more dynamic than industrialized agriculture towns and characteristic agricultural towns. Through analysis of resources and environment constraints on rural vitality, we found that resources had the greatest impact on rural vitality, and the short-term constraints of total amount restriction on rural vitality were not obvious; binding force of ecological environment on rural vitality changed from weak to strong and increasingly became the bottleneck restricting rural vitality. We have further proposed a long-term mechanism to stimulate rural vitality from the aspects of promoting comprehensive utilization of rural residential land, strengthening concept of ecological priority and green development, taking the road of urban–rural integration, and promoting integrated development of rural industries.

Keywords: resource and environment constraints, rural vitality status assessment, promotion strategies, rural revitalization model towns, Shandong, China

1 INTRODUCTION

With rapid expansion of world population, shortage of resources and energy, deterioration of ecological environment and intensification of social contradictions, and coordinated development of resources and environment has gradually become the consensus of all mankind. Regional development under resources and environment constraints has become a hot topic in recent years. Rural development is particularly dependent on resources and environment. Rural poverty, food security, and increasingly severe environmental degradation have posed challenges to realization of global sustainable development goals (SDGs) (Carr and Kefalas, 2009; Liu and Li, 2017; Barbier and Burgess, 2020; Diaz-Sarachaga, 2020; Yang et al., 2020). How to make better use of resources and environment to stimulate rural vitality has become a research hot spot to solve the problem of rural development and realize rural revitalization (Makkonen and Kahila, 2021; Pinilla and Sáez, 2021).

Revival of rural geography has started redefinition of rural areas, conceptualizing rural production space as a mixed and networked space (Woods, 2009; Yang et al., 2021). It is believed that material conditions and discourse power related to geographical environment of rural areas have an impact on rural development, creating diversification of interest subjects and industrial forms, multi-function of land use, and variability of land use modes (Liu et al., 2017; Li et al., 2019; Li et al., 2021; Long et al., 2019).

Resources and environment are important constraints for rural development. Some scholars have incorporated resource and environmental factors into analysis framework of agricultural total factor productivity and water use efficiency of food crops. For example, Ball et al. (2001) and Rezek and Richard (2004) measured TFP in US agriculture from the perspective of environmental constraints and found that the TFP index accounting for environmental pollution was lower than the TFP index without accounting for environmental pollution. Li (2014) concluded that agricultural green TFP was generally lower than agricultural TFP and that green TFP was higher in the eastern region than in the central and western regions. Gan and Li (2021) took discharge of major agricultural water pollutants as unexpected output to calculate the water use efficiency of grain crops in grain production areas. Some scholars have analyzed such issues as environmentally friendly and economically viable cropping systems, sustainable agriculture, and having sustainable livelihood under resource and environmental constraints. Deng et al. (2020) suggested that planting common vetch during the summer fallow period may be a productive and economically sound practice that has low energy requirements. Sarkar et al. (2021) considered that sustainable agriculture could play significant roles in facilitating the betterment of land, water, air, and the overall environment. In addition, sustainable livelihood had been fully utilized in solving the poverty problems (Dzanku, 2015), which is the ability to restore and confront pressure and shocks, to maintain capital and to remain growing based on conserving environmental resources (Chambers and Conway, 1992).

Previous studies have provided a good reference for explaining rural vitality under resources and environment constraints. In reality, rural areas carry multiple functions, such as agricultural production, rural cultural inheritance, social security, and ecological conservation. The endogenous development model embodied in rural vitality is pinned on a number of development goals, such as agricultural transformation and upgrading, sustained income increasing of farmers, and comprehensive rural progress, which is just in line with current needs to promote sustainable rural development and alleviate relative poverty. However, further stimulation of rural vitality is facing unprecedented pressure due to shortage of water resources, cultivated land resources, and labor resources as well as global climate change, agricultural non-point source pollution, and industrial exogenous pollution.

Based on this, we have tried to use the data obtained from 106 rural revitalization model towns in Shandong province in 2012, 2016, and 2019, constructed rural vitality index system, used an improved Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method to measure the vitality value of different village types and panel Tobit model to explore the impact of resource and environmental factors on rural vitality, and explored a feasible path to activate rural vitality, so as to fully explore development potential of rural areas and build a long-term mechanism to stimulate rural vitality. The main contributions of our study are summarized as follows: 1) a rural vitality index system based on "population–facility–industry" is proposed to analyze the performance of rural vitality of rural revitalization model towns in Shandong province and explore differences of rural vitality performance of different village types and 2) restricted by regional resources and environment have increasingly become a prominent contradiction perplexing rural revitalization. However, existing studies seldom analyze rural vitality from the perspective of resources and environment constraints. We creatively link the two and analyze the issue of stimulating rural vitality under resources and environment constraints.

2 CONCEPTUAL BACKGROUND

2.1 Literature Review of Rural Vitality

Vitality refers to vigorous vitality, which is generated in the exploration of life problems. Referring to general evolution law of life, vitality is used to express viability and development of social organizations, as well as the interaction between life and the external environment (Lan et al., 2020). In research on man-land relations, vitality is mainly used to express the attraction of space to people and its support for activities, especially in urban planning (Montgomery, 1995; Xia et al., 2020), which shows the economic and social development trends created by people on the basis of using natural resources and protecting environment (Lurie and Brekken, 2019).

Rural vitality is the embodiment of rural development and the potential of rural areas to overcome possible problems, such as rural hollowing out and backward development, which represents viability and development of rural social organizations, covering agricultural development, rural population employment, housing development, rural facilities improvement, traditional village protection, ecological governance, *etc*. Rural population, facilities, and industries are important components of rural vitality (Lampic and Potocnik-Slavic, 2007; Cheng, 2019; Cao et al., 2020).

Many scholars pay attention to rural vitality. Some of them concerned for rural vitality from a single perspective. Pearce (2005) analyzed the decisive role of natural resources in rural community vitality. Van Rij and Koomen (2010) concluded that there was no clear relationship between the construction of houses and different indicators of rural vitality such as employment and facility levels. Vujicic et al. (2013) studied local initiatives for rural vitality and social inclusion. Mihai et al. (2019) made a new assessment of the development status among the people living in rural areas. Lin et al. (2021) proposed a process for interactive participation to optimize green space in the peri-urban village from the demand-side perspective and enhance rural vitality. They have paid attention to rural vitality performance in specific fields but lacked a comprehensive understanding of rural vitality.

Therefore, some scholars have analyzed rural vitality from a comprehensive dimension and believed that rural vitality is the embodiment of comprehensive development of rural areas. Accordingly, evaluation system of rural vitality is mainly carried out from multiple dimensions. Cheng et al. (2019) proposed the personal rural development index (PRDI) from three socio-economic components, namely, economy, education, and health. Li et al. (2020) constructed the rural viability index from the aspects of infrastructure conditions, public services, health status, employment opportunities, and social participation, reflecting the ability of rural areas to achieve the quality of life desired by residents. In addition, some scholars have built index systems from the aspects of rural industrial development, living environment, cultural construction, governance capacity, and quality of life to measure the rural development level. Liu et al. (2022) established a traditional village vitality assessment index system as an integrated capacity to protect and develop rural sustainable revitalization.

2.2 Rural Vitality Based on Symbiosis Theory

Rural vitality is a comprehensive reflection of rural population activity, industrial output rate, and facility utilization rate. Rural population is the main body of the rural regional system. Number of farmers and their living standards are the most direct and realistic performance of rural vitality. Completeness of rural facilities is social performance of rural vitality. Convenient and high-quality infrastructure is conducive to promoting rural undertakings and the quality of life for farmers. Rural industrial development is economic performance of rural vitality, including agricultural production and the integrated development of agriculture, industry, and service industry, which is the power source of rural vitality.

Changes in any aspect of rural population, facilities, and industries may greatly impact rural vitality. The vitality state of rural areas is the result of the interaction of population, facilities, and industries. The changes in the quantity, quality, and structure of rural population are the main factors that determine the development of rural industries. The development of agricultural modernization has promoted the improvement of agricultural productivity, enhanced agricultural output capacity, and brought about the increase of rural population income. Industrial development is also inseparable from the support of production and living facilities. At the same time, benefits from industrial development lay the foundation for better upgrading the level of facilities. The development of infrastructure construction synchronized with or faster than rural development, which can well meet the needs of rural economic development and farmers' living, providing strong facilities guarantee for agricultural and rural development.

Through the interaction of population, facilities, and industries, rural vitality finally presents a state of population concentration, complete facilities, and prosperous industries. As for rural population, vibrant rural areas have high population density and income level. They attract population aggregation with stable employment and higher income and slowed down the overflow of rural population in rural areas. In the rural industry, dynamic rural areas have high agricultural production capacity and active entrepreneurial activities. Rural areas create a high-yield and low-consumption agricultural production system by the application of modern technology and industrial equipment and an entrepreneurial atmosphere of multi market players' competition and incorporation by adopting development mode of industrial integration, which is conducive to the development of agricultural industrialization. In rural infrastructure, rural areas with high vitality have sound infrastructure. Improving infrastructure construction to meet the needs of population and industrial development in rural areas will guide more rural people to change to a modern way of life, activate rural infrastructure vitality, and promote development of rural areas. The quantity and spatial combination of rural population, facilities, and industries constitute the rural regional system, which comprehensively shows rural vitality (**Figure 1**).

2.3 Resource and Environment Constraints on Rural Vitality

Meanwhile, basic pattern of social and economic activity spaces cannot cross the "hard threshold" jointly set by resource and environmental elements and geographical development conditions. Rural resources and environment and its development conditions constitute spatial carrier and natural base of rural vitality, which is the development foundation of rural vitality. Agriculture is highly dependent on resources and environment. The input of natural resources is essential. Appropriate natural ecological environment conditions are also very important.

Resources limitation mainly refers to land resources limitation. Land is material basis and spatial carrier of rural economic and social development, and plays a very important role in the process of activating rural internal vitality. Rural industrial structure adjustment, population agglomeration, and

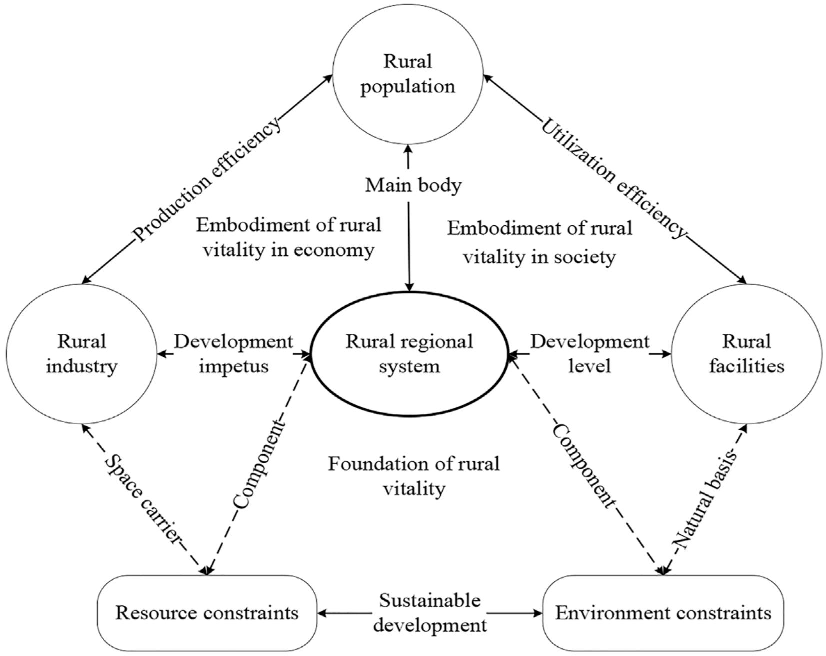

FIGURE 1 | Composition of rural vitality.

infrastructure construction all need to be realized through reallocation of land resources. Rational land use will play a good role in balanced distribution of resources and rural social and economic development. At present, imbalanced man-land relationship is basic contradiction in the process of stimulating rural vitality. Farmers are highly dependent on land, reflecting in spatial dependence of rural residents on living space (housing) and production space (arable land). However, man-land relationship in rural areas is facing conflicts such as village hollowing and extensive use of cultivated land. Land use change expressed by spatial expansion and contraction of different land use types has become an important driving force for rural vitality. Intensive land use has promoted change of input and output per unit land area, affected agricultural production efficiency, changed rural production system, and affected further stimulation of rural vitality.

Environmental constraints mainly refer to ecological environment constraints. A good ecological environment is basis for rural sustainable development. Under the condition of limited land resources, improving rural ecological environment helps to comprehensively stimulate rural vitality. Vegetation coverage, water resource abundance, and environmental quality are important indicators to indicate ecological environment change. Forest vegetation has the functions of regulating climate, conserving water, preventing soil erosion, and desertification in its adjacent areas, which will affect improvement of the farmers' living environment. It can also provide support to characteristic industries such as forest economy, natural eco-tourism, and forest health tourism. Water resource is a basic production factor of agriculture. Its abundance, shortage, and distribution directly determine the scale, type, and level of rural industrial development, which is essential in social and economic development. Water and soil pollution, air pollution, and excessive use of pesticides and fertilizers will lead to deterioration of rural living environment, resulting in a series of social and economic problems, including threat of food safety and human health, weakening of talent gathering capacity and low efficiency of agricultural production, which limits stimulation of rural vitality.

3 METHODS AND RESEARCH MATERIALS

3.1 Survey and Data

In 2013, the per capita disposable income of rural residents in Shandong province exceeded the 10,000 RMB for the first time, reaching 10,620 yuan. Since 2018, Shandong province has promoted flow of various resources and elements to the countryside, focused on building demonstration benchmarks for rural revitalization with different regional characteristics and different development types, and promoted overall momentum of rural revitalization by strengthening the top-level design and work implementation. Considering the availability of data, the three time points of 2012, 2016, and 2019 are finally determined, which can fully reflect dynamic characteristics of rural revitalization model towns in Shandong province at different development stages.

The data of population and industrial output value are from the third agricultural census, the sixth national census, County Statistical Yearbook for 2013, 2017, and 2020, and statistical bulletin on national economic and social development of counties for 2013, 2017, and 2020. Land use data are from

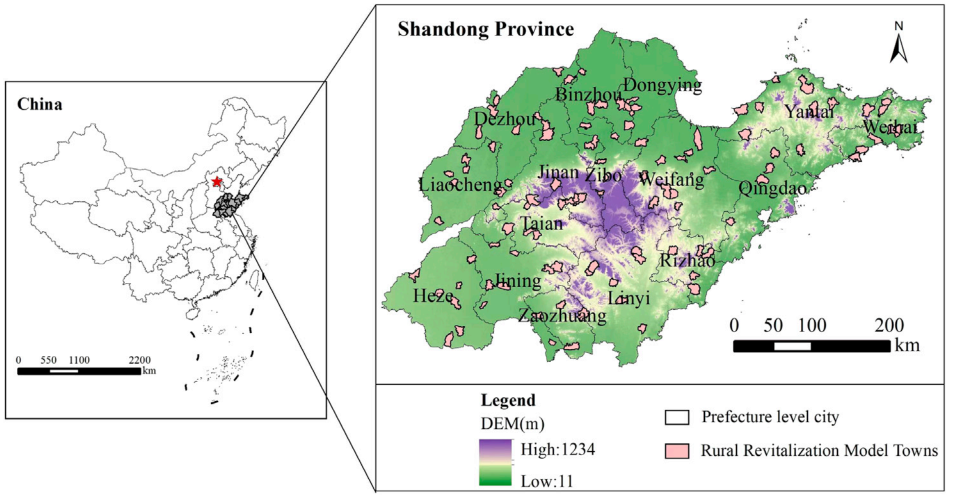

FIGURE 2 | Distribution of rural revitalization model towns.

Resource and Environment Science and Data Center of Chinese Academy of Sciences, (http://www.resdc.cn) providing land use data (spatial resolution: 100 m * 100 m) in 2012, 2016, and 2019. Through a large number of ground surveys and human–computer interpretation, the accuracy is not less than 85%. The number of rural household industry and township enterprises comes from local market survey.

3.2 Study Area

Rural revitalization model towns in Shandong province are selected as research samples (**Figure 2**). Shandong province is one of coastal provinces in East China. It is essential in national rural development for the following reasons. With 6% of arable land and 1% of fresh water resources in China, it contributes 8% of grain output, 9% of meat output, 12% of fruit output, 13% of vegetable output, 14% of aquatic product output, and 19% of peanut output; export volume of agricultural products accounts for 24% of the country; the rural population is 37.513 million, accounting for 36.95% of total population of Shandong province.

To further shoulder the responsibility of a major agricultural province, Shandong province has identified many rural revitalization model towns and explored multiple models and successful experience of building characteristic towns for rural revitalization. Thus, we have selected 106 towns with different resource endowments and location conditions as research samples. Industrial integration development is the fundamental path for the development of rural revitalization model towns in Shandong province. Through the investigation of whether the town adopts industrial integration development model and which industries the town mainly integrates with, these samples are divided into three types: characteristic agricultural towns, agriculture-tourism towns, and industrialized agriculture towns. Among them, there are 43 characteristic agricultural towns, accounting for 40.57%, 38 agriculture-tourism towns, accounting for 35.85%, and 25 industrialized agriculture towns, accounting for 23.58%.

Characteristic agriculture is a special agricultural industry developed on basis of regional resource advantages, which has more development advantages than conventional agriculture. It transforms the original natural resource advantage into scale, efficiency, and benefit advantage of agricultural development through agricultural science and modern management and then into economic advantage. It uses high-quality, high-value, and highly competitive agricultural products to meet people's growing diversified needs, obtain higher economic benefits and increase farmers' income. Compared with conventional agriculture, characteristic agriculture has the characteristics of strong regionality, high-quality products, high merchantability, and economic efficiency. Typical characteristic agricultural town is the standardized vegetable production town—Jitai town, Weifang city (**Figure 3**).

Integration of agriculture and tourism is mutual extension between agriculture and tourism, which can meet growing leisure and recreation needs of citizens and transfer agricultural surplus labor. Its essential attribute is industrial integration and urban–rural interaction based on agricultural resources. Agricultural resources formed by R&D, production, processing, and sales of the agricultural industry chain can be developed into tourism resources. Tourism mainly provides services and facilities. Through effective organization and development of corresponding projects, it organically combines elements such as food, housing, transportation, tourism, shopping, and entertainment with agricultural resources. Agriculture has changed from providing production factors for tourism to showing characteristics of tourism suppliers, which has optimized agricultural service industry development. Typical agriculture-tourism town is Longju town, Dongying city, which has a distinctive cultural and leisure tourism brand (**Figure 4**).

Industrialized agriculture refers to a modern advanced agricultural production mode that adopts industrialized production to achieve intensive, efficient, and sustainable

FIGURE 3 | Characteristic agricultural town.

FIGURE 4 | Agriculture-tourism town.

FIGURE 5 | Industrialized agriculture town.

development under relatively controllable environmental conditions. It is a production mode that combines advanced agricultural facilities with land, which has high technical specifications and high-efficiency intensive scale operation. Compared with traditional agriculture, industrialized agriculture based on the Internet can accurately control the problems of watering, fertilization and pesticide application in the process of agricultural production through the information-based intelligent monitoring system in real-time, so as to achieve the sustainable development goals of intensive, high-yield,

TABLE 1 | Rural vitality evaluation index system.

Target layer	Standard layer	Indicator level	Indicator characteristic	Action direction
Rural vitality	Population	Residential density of rural permanent population	Year-end resident population (person)/year-end area of rural settlements (hectare)	+
		Annual per capita net income of farmers	—	+
	Facilities	The level of agricultural mechanization	Annual agricultural machinery power (kW)/year-end total land area (hectare)	+
		Density of the highway network	Year-end area of roads (hectare)/year-end total land area (hectare)	+
	Industry	Agricultural output value per unit land area	Annual gross output value of agriculture (10,000 yuan)/year-end total land area (hectare)	+
		The number of rural household industries and township enterprises	—	+

efficient, and ecological agricultural production. Typical industrialized agriculture town is Baisha town, Rushan city, which uses industrial ideas to plan agricultural development (**Figure 5**).

3.3 Methods

3.3.1. Construction of Index System

Based on the aforementioned theoretical analysis, we have built the rural vitality evaluation index system from the dimensions of population, facilities, and industry (**Table 1**). Following principles of systematization, scientific nature, and data availability, we have screened representative indicators of each dimension. Population dimension includes residential density of rural permanent population and annual per capita net income of farmers, which represents distribution and wealth of rural populations. Facility dimension includes the level of agricultural mechanization and density of highway network, which reflects the level of agricultural modernization and regional highway development. Industrial dimension includes agricultural output value per unit land area and the number of rural household industries and township enterprises, which represents rural economic strength.

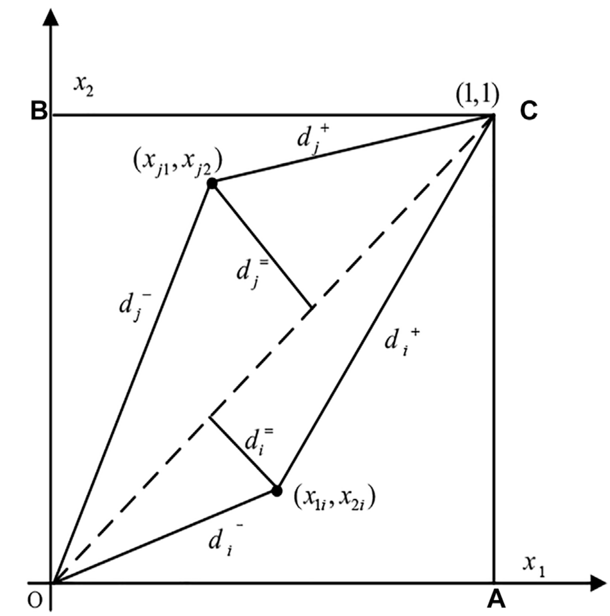

FIGURE 6 | Three distances of Program *i* and program *j*.

3.3.2. Improved TOPSIS Method

The traditional TOPSIS model only considers comprehensive level of indicators. But indicators can replace each other, that is, for a scheme, even if a small number of indicators have low scores and most indicators have high scores, comprehensive evaluation value of the scheme will be high. The requirement of coordinated development is that the scores of multiple development indicators should not be very different. The greater the difference, the lower is the comprehensive evaluation score. Based on this consideration, we have proposed the following improved TOPSIS method to calculate the comprehensive evaluation value and each dimension value of rural vitality.

First, positive and negative indicators are standardized according to the range variation method. Second, the equal weight method is adopted to give the index weight w_j. Considering unbalanced resource allocation of each town due to terrain and historical accumulation, if different weights are given to each indicator, development differences caused by uneven resource distribution will be amplified and the evaluation of rural vitality will be misled. Third, according to characteristics of standardization, the potential optimal and worst schemes (n-dimensional vectors) are (1, 1,. . ., 1) and (0, 0,. . ., 0), respectively. The Euclidean distance calculation formula is used to calculate distances between the scheme points y_{ij}, and the positive and negative ideal values are recorded as d_i^+ and d_i^- respectively. Fourth, we calculate the shortest weighted distance between the scheme point y_{ij} and the connection point y_i, which is recorded as $d_i^=$. Finally, the improved TOPSIS score e_i is calculated. e_i still varies between 0 and 1. The greater e_i is, the higher the score of the scheme is, and the more ideal the scheme is. e_i contains coordination information between indicators. When d_i^+ is equal to d_i^-, two objects can still compare vitality values.

$$e_i = \frac{d_i^-}{d_i^+ + d_i^- + d_i^=}. \tag{1}$$

Taking two indicators as examples to illustrate how to calculate, it can be seen from **Figure 6** that when index coordination is high, the scores of each index should be close, and the vertical distance from the scheme point y_{ij} to the diagonal of the unit square is close, otherwise it is far. When $d_i^=$ changes from 0 to 1, the coordination between indicators gradually decreases. The vertical distance from scheme point y_{ij} to the diagonal of the unit square can be used to indicate coordination between indicators.

When there are more than two evaluation indexes, the shortest distance from scheme point y_{ij} to spatial straight line needs to be calculated in the multi-index space. The calculation steps are as follows.

First, calculate square of the space distance d_i between the scheme point y_{ij} and the connection point y_i.

$$(d_i)^2 = \sum_{j=1}^{n} \left(y_{ij} - y_i\right)^2. \tag{2}$$

Second, calculate the derivative to get the coordinate value of the connection point y_i.

$$y_i = \frac{1}{n}\sum_{j=1}^{n} y_{ij}. \tag{3}$$

Finally, calculate the shortest weighted distance $d_i^=$ between the scheme point y_{ij} and the connection point $\frac{1}{n}\sum_{k=1}^{n} y_{ik}$. Where, w_j is the weight of the scheme point.

$$d_i^= = \sqrt{\sum_{j=1}^{n} w_j \left(y_{ij} - \frac{1}{n}\sum_{k=1}^{n} y_{ik} \right)^2}. \tag{4}$$

3.3.3. Model Construction

The value of rural vitality calculated by the improved TOPSIS method ranges from 0 to 1, which belongs to truncated data at both ends. If the OLS method is used to regression the model, the estimation of parameters will be biased and inconsistent. Therefore, we use the limited dependent variable model, namely, the panel Tobit model, to make an empirical analysis on rural vitality state under resources and environment constraints. Referring to Moffit and McDonald (1980), the model is as follows.

$$\begin{cases} y_i^* = \alpha^T X + \beta^T Z_i + \varepsilon_i \\ y_i = \max\left(y_i^*, 0\right) \end{cases}, \tag{5}$$

where, y_i represents the observed value of explained variable of town i, and y_i^* is an unobservable latent variable. X is the independent variable vector. Z_i is the control variable vector. α^T and β^T are the correlation coefficient vectors. ε_i is a random error term, which is independent and $\boldsymbol{\varepsilon_i} \sim N(0, \sigma)$. When $y_i^* > 0$, we select $y_i = y_i^* > 0$. y_i is the no-deletion observation. When $y_i^* \leq 0$, we select $y_i = 0$. y_i is the restricted observation.

3.3.4. Variable Selection

The explained variable is rural vitality index, which is calculated by the improved TOPSIS method; the core explanatory variable is the resource and environment constraints that affect rural vitality. The resource constraints mainly refer to land resource. In rural areas, cultivated land and rural residential land, accounting for the majority of land resource, are important social units because they reflect the relationships between people and land, the historical background, and the sociopolitical relationships (Robinson, 2003; Zhou et al., 2019). We have selected the per capita cultivated land area and the density of rural residential areas as the indicators. The indicators of environmental constraints are the ecological environment quality. With reference to Technical Criterion for Ecosystem Status Evaluation issued by the State Environmental Protection Administration and the theoretical analysis of **Section 2**, we have selected three indicators: vegetation cover index, water network density index, and the amount of solid waste discarded per unit area.

As to control variables, geographical location factors, urbanization level, policy inclination, and other factors are selected. 1) Geographical factors mainly include the distance from the county center. Compared with towns, the county has a high density of public facilities, a complete range of service industries and public activities. It is often an economically active and densely populated area and has a strong ability to drive vitality of surrounding areas. The closer the township is to the county center, the more convenient the transportation is, and the stronger the attraction of the township to people. 2) Urbanization drives development of rural areas in terms of scale, quality, and benefits by providing product sales markets and sharing of urban and rural facilities, which promotes expansion of the scale of agricultural products and rural tourism consumption markets, brings about an increase in farmers' income, drives the construction of rural infrastructure, leads to the agglomeration of rural development factors, and the improvement of comprehensive benefits. 3) Policy preference means that the government formulates fiscal and fixed asset investment policies conducive to rural development, which helps to guide more factors to gather in rural areas through capital investment, industrial layout, engineering projects, and supporting facilities construction. The meaning and calculation method of the selected variables are shown in **Table 2**.

4 RESULTS

4.1. Rural Vitality Status

To sum up, we have calculated measurement results of rural comprehensive vitality, industry vitality, facility vitality, and population vitality of 106 rural revitalization model towns in Shandong province from 2012 to 2019 (**Figure 7**; **Table 3**). The rural comprehensive vitality value showed a fluctuating upward trend during the study period. The average values in 2012 and 2019 were 0.4200 and 0.5245, respectively, and the average growth rate was 3.23%. According to the data of all dimensions, the average growth rate of industrial vitality was the highest, with a value of 3.97%, indicating that development of rural industries has made the greatest contribution to rural

TABLE 2 | Variable definition and descriptive statistics.

Variable	Calculation method of variable	Mean	Std. dev.	Min.	Max.
Rural vitality	Calculated according to the improved TOPSIS method	0.472	0.046	0.387	0.579
The per capita cultivated land area	Year-end area of cultivated land of the town (hectare)/total population of the town (person)	0.095	0.057	0.002	0.305
The density of rural residential areas	Year-end area of rural settlements of the town (hectare)/year-end total land area of the town (hectare)	0.104	0.079	0.005	0.607
Vegetation cover index	Year-end area of forest land of the town (hectare)/year-end total land area of the town (hectare)	0.122	0.168	0	0.762
Water network density index	Year-end water area of the town (hectare)/year-end total land area of the town (hectare)	0.056	0.076	0.001	0.605
The amount of solid waste discarded per unit area	Consumption of chemical fertilizer (convert to pure amount/ton)/Year-end area of cultivated land of the town (hectare)	0.624	0.53	0.1	0.525
Distance from the county center	Driving time from town to its county center (hours)	0.572	0.288	0.083	1.317
Urbanization rate	The number of permanent residents in urban areas (person)/total permanent population of the town (person)	0.132	0.187	0.006	0.652
Fiscal revenue	Revenue of government finance of the town (10,000 yuan)/total population of the town (person)	0.536	0.926	0.024	1.2

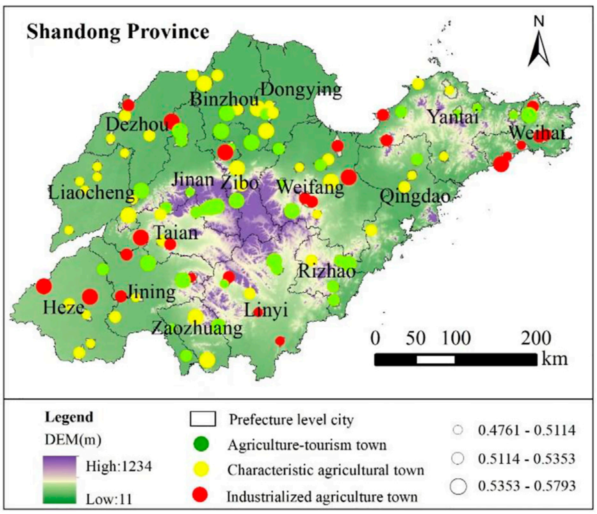

FIGURE 7 | Comprehensive vitality value of different village types in 2019.

vitality because rural areas are mainly based on production functions. In 2019, 88.68% of rural revitalization model towns in Shandong province had a comprehensive vitality index of more than 0.5, meaning that most towns can give relatively effective play to their resource advantages to achieve improvement of rural vitality. This is because the function of rural areas has changed from a single production function to a multi-functional one such as social security, economic development, and ecological conservation, which makes the relationship of population, industry, and facilities more harmonious. During the study period, the towns located around central cities in Shandong province had a high level of vitality and a rapid growth rate. This gets benefits from radiation and driving effect of a city on the surrounding villages and towns.

The trend of vitality values of various village types was consistent with an overall change trend. From 2012 to 2019, average growth rates of rural comprehensive vitality of industrialized agriculture towns, agriculture-tourism towns, and characteristic agricultural towns were 3.45, 3.31, and 3.01%, respectively. Average growth rate of industrial vitality of agriculture-tourism towns during 2012–2019 was 4.13%, which was higher than the growth rate of its comprehensive vitality. In 2019, its industrial vitality value reached 0.5335, indicating that industrial development is the main factor affecting rural vitality of such towns. From 2012 to 2019, its average growth rate of population vitality value was 2.79%. In 2019, the population vitality value reached 0.5261, slightly lower than its industrial vitality value of 0.5335 in the same year. Its average growth rate of facility vitality in 2012–2019 was 3.04%, and the facility vitality value in 2019 reached 0.5256, which is lower than the growth rate of its comprehensive vitality. Due to insufficient financial expenditure on rural infrastructure construction of the government, the weakness in infrastructure has, to some extent, lowered its vitality level.

Average growth rate of industrial vitality of industrialized agriculture towns during 2012–2019 was 4.14%, which was higher than the growth rate of its comprehensive vitality value. In 2019, its industrial vitality value reached 0.5582. Because, such towns relying on rich agricultural products and labor resources integrate industrial elements into rural industrial development, build an industrial chain of industrial and agricultural integration, and form a good trend of industrial and agricultural interaction to help development of towns. Its average growth rate of population vitality value from 2012 to 2019 was 2.98%. The population vitality in 2019 reached 0.5262, slightly lower than its industrial vitality value of the same year, and performed best among the three types. Benefiting from the development of agricultural product processing industry, farmers have expanded the channels of employment and income increase. Its average growth rate of the facility vitality value from 2012 to 2019 was 3.19%, which is lower than the growth rate of its comprehensive vitality value. In 2019, facility vitality value reached 0.4998, the worst among the three types, indicating that such towns should also increase investment in public infrastructure.

TABLE 3 | Vitality scores of different village types from 2012 to 2019.

Type	Year	Comprehensive vitality	Population vitality	Facility vitality	Industrial vitality
Industrialized agriculture towns	2012	0.4166	0.4283	0.4013	0.4202
	2016	0.4719	0.4703	0.4699	0.4705
	2019	0.5281	0.5262	0.4998	0.5582
Agriculture-tourism towns	2012	0.4207	0.4340	0.4261	0.4020
	2016	0.4802	0.4772	0.4765	0.4776
	2019	0.5284	0.5261	0.5256	0.5335
Characteristic agricultural towns	2012	0.4215	0.4351	0.4246	0.4047
	2016	0.4534	0.4740	0.4723	0.4685
	2019	0.5189	0.5177	0.5161	0.5229
All towns	2012	0.4200	0.4331	0.4196	0.4074
	2016	0.4822	0.4595	0.4608	0.4654
	2019	0.5245	0.5227	0.5157	0.5350

Average growth rate of industrial vitality value of characteristic agricultural towns during 2012–2019 was 3.73%, higher than its growth rate of the comprehensive vitality value. In 2019, the industrial vitality value reached 0.5229, the worst among the three types. This happens because there are still some problems, such as extensive land use and low land output efficiency in characteristic agricultural towns. Its average growth rate of the population vitality value during 2012–2019 was 2.51%, which was the worst in the three types because of the insufficient development of rural industries. Its average growth rate of the facility vitality value during 2012–2019 was 2.83% because most characteristic agricultural towns are located in traditional agricultural areas and have a certain amount of capital accumulation, which helps to complete public supporting facilities.

4.2. Resource and Environment Constraints of Rural Vitality

4.2.1. Basic Results

Through the aforementioned analysis, rural vitality values of 106 rural revitalization model towns in Shandong province in 2012, 2016, and 2019 were estimated. Here, the panel Tobit model was used to analyze resource and environmental constraints of their rural vitality values during the study period.

As is shown in column (1) of **Table 4**, the impact of the per capita cultivated land area, rural residential density, vegetation coverage index, water network density index, and the amount of solid waste discarded per unit area on rural comprehensive vitality value passed the significance test. The marginal effect of per capita cultivated land area was 0.314, which was significant at the level of 1%, indicating that the richer the per capita cultivated land area, the higher is rural comprehensive vitality value. Because in the areas rich in cultivated land resources in Shandong province, the degree of agricultural development is relatively high. The marginal effect of rural residential density was −0.042, which was significant at the level of 5%, indicating that scattered layout of rural settlements and low degree of intensive utilization limit stimulation of rural vitality. The marginal effect of vegetation cover index was 0.131, which was significant at the level of 10%, indicating that vegetation cover index has a certain positive effect on improvement of rural comprehensive vitality. The marginal effect of water network density index was 0.101, which was significant at the level of 1%, indicating that the more abundant the water resources, the better is the comprehensive vitality of a town. The marginal effect of the amount of solid waste discarded per unit area was 0.196, which indicates that improvement of comprehensive vitality of rural revitalization model towns in Shandong province is at the expense of the environment.

Comparing vitality values of different dimensions, the per capita cultivated land area and water network density index promoted population vitality, industrial vitality, and facility vitality and had a greater impact on industrial vitality. Promotion of facility vitality and industrial vitality was at the expense of environment while population vitality was not. Rural settlements density only had a negative effect on improvement of industrial vitality, with a marginal effect of −0.075, and had no significant impact on population vitality and facility vitality. Vegetation cover index only positively affected industrial vitality, with a marginal effect of 0.087, and had no significant impact on population vitality and facility vitality.

As for control variables, the impact of urbanization rate on rural comprehensive vitality value passed the significance test, and the marginal effect of urbanization rate was 0.117, indicating that urbanization positively impacts rural comprehensive vitality. Moreover, the urbanization rate had an increasing effect on vitality of three dimensions, but only had a significant positive effect on vitalities of population and industry.

4.2.2. Robustness Check

4.2.2.1 Add Control Variable

Previous studies have shown that cities have a radiating and driving effect on rural areas, and central cities with high levels of economic development and urbanization can better support rural development (Chen et al., 2018). Therefore, we added the per capita GDP index (10,000 yuan/person) as the control variable, which is the ratio of GDP (10,000 yuan) to total population of the town (person). The

TABLE 4 | Resource and environment constraints of rural vitality.

Variable	(1) Comprehensive vitality	(2) Population vitality	(3) Facility vitality	(4) Industrial vitality
The per capita cultivated land area	0.314*** (0.030)	0.196*** (0.075)	0.118*** (0.011)	0.596** (0.286)
The density of rural residential areas	−0.042** (0.020)	0.031 (0.031)	−0.163 (0.142)	−0.075** (0.037)
Vegetation cover index	0.131* (0.079)	0.015 (0.023)	0.139 (0.104)	0.087*** (0.014)
Water network density index	0.101*** (0.025)	0.027*** (0.007)	0.011*** (0.002)	0.141*** (0.027)
The amount of solid waste discarded per unit area	0.196* (0.105)	−0.136** (0.0685)	0.0632 (0.055)	0.229*** (0.0766)
Distance from the county center	0.012 (0.012)	−0.073 (0.056)	0.017 (0.110)	0.01 (0.008)
Urbanization rate	0.117*** (0.031)	0.120*** (0.031)	0.025 (0.021)	0.192*** (0.033)
Fiscal revenue	0.011 (0.012)	−0.011 (0.022)	0.014 (0.022)	0.005 (0.040)
N	318	318	318	318

*Note: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively; Std. err. values in parentheses.*

TABLE 5 | Estimation results of robustness analysis.

Variable	(1) Add control variable	(2) Eliminate abnormal value	(3) CLAD
The per capita cultivated land area	0.331* (0.181)	0.314*** (0.030)	0.224*** (0.076)
The density of rural residential areas	−0.053* (0.028)	−0.042** (0.020)	−0.075* (0.042)
Vegetation cover index	0.139** (0.068)	0.131* (0.079)	0.118 (0.075)
Water network density index	0.011 (0.009)	0.101*** (0.025)	0.242*** (0.066)
The amount of solid waste discarded per unit area	0.035 (0.024)	0.196* (0.105)	0.133 (0.482)
Distance from the county center	0.012 (0.022)	0.012 (0.012)	0.040 (0.032)
Urbanization rate	0.012 (0.022)	0.117*** (0.031)	0.109*** (0.031)
Fiscal revenue	0.011 (0.009)	0.011 (0.012)	0.014 (0.012)
Per capita GDP	0.134* (0.078)		
N	318	318	318

*Note: *, **, and *** represent 10%, 5%, and 1% significance levels, respectively; Std. err. values in parentheses.*

results in column (1) of **Table 5** showed that after adding control variables, the estimated results of core explanatory variables did not change in the direction of influence compared with benchmark regression results, but only changed in the significance level, which verifies the robustness of benchmark regression results.

4.2.2.2 Eliminate Abnormal Values

In order to eliminate interference of a small number of outliers caused by special areas, it is necessary to deal with outliers through bilateral tailing. Comprehensive vitality index of rural areas was treated by bilateral tailing at the 1% quantile. It was not difficult to find from column (2) of **Table 5** that symbol of the coefficient of core explanatory variables had not changed and all passed the significance test, which showed that after bilateral tailing treatment of 1% quantile of rural comprehensive vitality index, the effect of core explanatory variables on rural comprehensive vitality index should still be consistent with benchmark regression.

4.2.2.3 Transform Estimation Method

The Tobit model is highly dependent on the distribution of disturbance terms. If the disturbance terms do not obey the normal distribution or have heteroscedasticity, the estimation results will be biased. In view of this, we used the more robust merged least absolute deviations (censored least absolute deviations, CLAD) method for semi-parameter estimation, and the results are shown in column (3) of **Table 5**. Compared with benchmark regression results, the estimated results of core explanatory variables did not change in the direction of influence, but only changed in the significance level. It can be seen that estimated results using the CLAD method were basically consistent with benchmark regression results.

4.2.3 Heterogeneity Analysis: the Impact of Industrial Convergence Development

The impact of resource and environment constraints on rural comprehensive vitality index depends on efficiency of resource and environment utilization. Towns with agriculture as the leading industry have the following characteristics: low productivity level, extensive production mode, and poor ecological environment quality. Resource and environmental constraints have certain restrictions on stimulating rural vitality. With the gradual integration of agriculture and the secondary and tertiary industries, the level of intensive and economical utilization of rural land resources and water resources has increased, habitat environment has gradually improved, and resource and environmental constraints have gradually weakened, contributing to the improvement of rural vitality.

TABLE 6 | Results of heterogeneity analysis.

Variable	Industrial integration town		Non-industrial integration town	
	(1)	(2)	(3)	(4)
The per capita cultivated land area	0.465** (0.191)	0.411** (0.166)	0.150** (0.062)	0.147* (0.080)
The density of rural residential areas	−0.311** (0.153)	−0.264* (0.155)	−0.101 (0.068)	−0.189 (0.150)
Vegetation cover index	0.174** (0.072)	0.147* (0.080)	0.108*** (0.031)	0.131* (0.079)
Water network density index	0.113*** (0.031)	0.126** (0.062)	0.348** (0.165)	0.217** (0.100)
The amount of solid waste discarded per unit area	−0.063** (0.028)	−0.052* (0.028)	0.210** (0.100)	0.133** (0.062)
Distance from the county center		0.023 (0.481)		0.013 (0.029)
Urbanization rate		0.326 (0.287)		0.329 (0.321)
Fiscal revenue		−0.158 (0.225)		0.045 (0.077)
N	189	189	129	129

*Note: *, **, and *** represent 10, 5, and 1% significance levels, respectively; Std. err. values in parentheses.*

In order to test the aforementioned conjecture, we classified characteristic agricultural towns as the non-industrial integration type and industrialized agriculture towns and agriculture-tourism towns as the industrial integration type and carried on the regression test again. **Table 6** shows the results, while rural vitality of industrial integration towns improved, the amount of solid waste discarded per unit area decreased, but non-industrial integration towns did not achieve such a result, indicating that the task of ecological protection in characteristic agricultural towns is more arduous. Rural settlements density strengthened the constraints on industrial integration towns but weakened the constraints on non-industrial integration towns. The per capita cultivated land area, vegetation cover index, and water network density index all positively affected the vitality of each type, but industrial integration towns were more affected by the per capita cultivated land area and vegetation cover index, and non-industrial integration towns were more affected by water network density index.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on symbiosis theory, we have creatively put forward the "population–facility–industry" theoretical framework of rural vitality, constructed rural vitality index system, selected 106 rural revitalization model towns from Shandong province as research samples, empirically tested rural vitality of 106 rural revitalization model towns by using an improved TOPSIS method, and measured resource and environmental constraints of rural vitality by using the panel Tobit model.

Overall, during the study period, the comprehensive vitality value of 106 rural revitalization model towns in Shandong province showed a fluctuating upward trend, with an average growth rate of 3.23%. Industrial vitality had the fastest growth rate, with an average growth rate of 3.97%, indicating that rural industries have the greatest contribution to promotion of rural vitality. In 2019, 88.68% of the towns' comprehensive vitality values were above 0.5, indicating that the overall vitality level of rural revitalization towns in Shandong province was high, especially towns around central cities benefitting from the radiation and driving effect of cities.

Average growth rates of comprehensive vitality of industrialized agriculture towns, agriculture-tourism towns, and characteristic agricultural towns during the study period were 3.45, 3.31, and 3.01%, respectively. From 2012 to 2019, average growth rates of industrial vitality of industrialized agriculture towns, agriculture-tourism towns, and characteristic agricultural towns were 4.14, 4.13, and 3.73%, respectively, which were higher than average growth rates of their respective comprehensive vitality indexes, indicating industrial development is also the main factor affecting rural vitality of different village types. From 2012 to 2019, average growth rates of population vitality of industrialized agriculture towns, agriculture-tourism towns, and characteristic agricultural towns were 2.98, 2.79, and 2.51%, respectively, which were lower than average growth rates of their respective comprehensive vitality indexes, indicating that improvement of rural vitality do not bring about a rapid increase in farmers' income, reflecting current situation of insufficient development of rural towns in Shandong province. The public infrastructure of various types of towns had different degrees of disadvantages. Taking data of 2019 as an example, facility vitality of industrialized agriculture towns, agriculture-tourism towns, and characteristic agricultural towns were 0.4998, 0.5256, and 0.5161, respectively, which were lower than their respective comprehensive vitality index values, lowering rural vitality level to a certain extent. It is necessary to increase investment in infrastructure construction in towns to ensure the infrastructure guarantee for internal dynamic development of rural areas.

Benchmark regression results showed that the per capita cultivated land area and water network density positively impacted comprehensive vitality and population vitality, facility vitality, and industry vitality. The result was related to rich cultivated land resources and water resources and the high level of economical and intensive utilization; rural settlements density negatively impacted comprehensive vitality and industrial vitality, indicating that rural settlements have problems such as hollow population and single land use function. It is necessary to integrate rural settlements and improve the mixed utilization of rural residential land; improvement of vegetation cover index promoted comprehensive vitality and industrial vitality, indicating that vegetation cover has played a positive role in the development of rural industries. To a large extent, the promotion of vitality level of rural revitalization model towns in Shandong province was at the expense of the environment, and there is an urgent need to walk out of the old road of "pollution before treatment." As for control variables, urbanization positively impacted comprehensive vitality, population vitality, and industry vitality. We should further play the role of urbanization in promoting rural vitality.

Heterogeneity analysis showed that the per capita cultivated land area played a greater role in promoting rural vitality of industrial integration towns than that of non-industrial integration towns because high level of economical and intensive utilization of cultivated land resources in industrial integration towns will have a strong role in promoting rural industrial development. Rural settlement density negatively impacted industrial integration towns but had no significant impact on non-industrial integration towns, indicating that industrial integration towns are more constrained by rural settlement density. Vegetation cover index had a greater positive impact on the vitality level of industrial integrated towns but a smaller impact on non-industrial integrated towns. Forest resources provide a good ecological environment and production factors for rural secondary and tertiary industries. Water network density index played a greater role in promoting rural vitality of non-industrial integration towns than that of industrial integration towns. Water demand of characteristic agricultural towns is large, and the change of water resources significantly affects their agricultural development. Improvement of vitality of non-industrial integration towns had brought about environmental problems to varying degrees. However, while industrial integration towns improved vitality of towns, the amount of solid waste discarded per unit area decreased.

5.2 Recommendations

According to the previous research conclusions, the following suggestions are put forward.

Further promote comprehensive utilization of rural residential land. The research showed that the density of rural residential areas had a negative impact on comprehensive vitality and industrial vitality. Therefore, we should take rural revitalization as strategic goal and village planning as means to guide the mixed layout of rural residential land, promoting rural residential land from single to diverse, from diverse to complex, and making rural residential land become a multi-functional complex integrating residence, industry, commercial services, and tourism reception. Accelerate adjustment of land use structure of rural residential areas, reduce the proportion of residential areas, increase the proportion of industrial land and public service land, provide space for industrial development and public infrastructure construction, improve compatibility of adjacent plots, and attract capital, industry, population, and other factors. This can stimulate land factors to promote industrial upgrading, promote diversification and interaction of rural resource factors, and realize a virtuous circle of various factors, so as to enhance vitality and attractiveness of rural areas.

Further strengthen the concept of ecological priority and green development. The research conclusion showed that the promotion of vitality level of rural revitalization model towns in Shandong province was at the expense of the environment. Therefore, we should further improve green development in rural areas, promote green production in agriculture, green living of farmers, and rural ecological environment protection. Reduce the use of chemical fertilizers and pesticides and promote organic fertilizers and biological pesticides; realize resource utilization of agricultural wastes, such as realizing straw resource utilization and waste plastic film and packaging waste recycling; improve quality and safety level of agricultural products, and the proportion of brand agricultural products. Promote the rural living environment, with the treatment of rural garbage, sewage and toilets as the main content, it is recommended to establish a system for the collection, transportation, and disposal of rural domestic garbage, promote local classification and resource utilization of rural garbage, extend coverage of urban sewage pipe network to surrounding villages, achieve sewage treatment and resource utilization, and popularize sanitary toilets in rural areas.

Rural development should take the road of urban–rural integration. The empirical test results showed that the increase of urbanization rate promoted rural vitality. Therefore, it is suggested to promote two-way flow of urban–rural spatial elements and cultivate symbiotic mechanism of endogenous driving force of rural development through complementing regional resource advantages. In the connection and interaction between urban and rural areas, we should clarify prominent position of villages in social and economic construction and their equal position in urban–rural relations, fundamentally change the development path of unifying agriculture by industry, unifying villages by cities, and reducing farmers in rural areas by expanding cities, promote mutual integration and common development of urban and rural areas in planning layout, industrial development, public services, ecological protection, etc., and gradually narrow development gap between urban and rural areas. The establishment of a good interactive relationship between urban and rural areas can further promote rural development and enable rural areas to produce economic and social values synchronized with cities.

Continue to promote integrated development of rural industries. Based on the aforementioned analysis, we understand that rural industrial integration is conducive to promoting rural vitality. Therefore, it is advised to further innovate development mode of rural industrial integration and improve the rural industrial integration level. Encourage new agricultural management organizations to carry out integrated development of rural industries in various forms and promote integrated process of "production, processing, storage, transportation, and sales" of advantageous and characteristic agricultural products, so as to promote natural extension of the primary industry to the secondary and tertiary industries; use agricultural production and operation activities, rural natural ecological environment and rural unique local culture to attract tourists, develop rural ecological sightseeing tourism and leisure experience agriculture, fully exploit potentialities of agricultural natural resources, and expand agricultural functions, so as to promote integration of the primary industry to the tertiary industries.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the data that support the findings of this study are available from Statistical Yearbooks and local market survey, but restrictions apply to the availability of these data, which were used under supervision. Requests to access the datasets should be directed to zhihengyang@163.com.

AUTHOR CONTRIBUTIONS

ZY: conceptualization, formal analysis, methodology, and writing original draft. TL: validation and writing—original draft. NS: investigation, validation, and writing—original draft. MG: conceptualization, data collection and collation, and formal analysis. YZ: investigation, validation, data collection and collation, and formal analysis. HJ: investigation, validation, data collection and collation, and formal analysis.

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New Form of Economic Development in Highly Urbanized Area and Its Effect on Green Development

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The balanced and stable development among economy, society and environment is an important research topic for any region. Given the gap between urban and rural areas, further improving the social security system is a key issue that China urgently needs to solve. This paper uses the autoregressive distributed lag (ARDL) model to evaluate the implementation effect of the two-tier social security system in the Macao Special Administrative Region (MSAR), and discusses the effect of social security expenditure on green development. The results show that: in the long run, social security expenditure is negatively correlated with regional economic development, but the two-tier social security system has significantly promoted the development of the regional economy. This shows that Macao's two-tier social security system can be a new form of economic development. The coupling coordinating relationship between economic growth and green development fluctuated from 2010 to 2020. Compared to economic growth, social security expenditure has a significant negative lag effect on green development. Therefore, the effect of social security on promoting environmental protection and green development needs to be optimized. Through the discussion of the relationship between Macao's social security, economic growth and green development, this study provides relevant practical experience and inspiration for the economic and social green development of other region.

Keywords: economic growth, social security, green development, high urbanization, ARDL model, Macao

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1 INTRODUCTION

Urbanization is a phenomenon accompanying economic and social development (Zarghami et al., 2020). From 1978 to 2021, China's urban residential population increased from 172 million to 914 million, and the urbanization rate grew from 17.92 to 64.72%. The high degree of urbanization has become an obvious characteristic in China's economy and society. Meanwhile, a large population of laborers is concentrated in cities and towns, which creates clear population structure differences between urban and rural areas, especially China's aging population (Li and Lin, 2016; Li and Qin, 2020; Jiang et al., 2022). According to data from the Seventh National Population Census of China, the proportions of the elderly aged 60 and over, and 65 and over in rural areas are 23.81 and 17.72%, respectively; these values are 7.99 and 6.61 percentage points higher than in urban areas in China. Meanwhile, due to the need for urban construction, cities have expropriated part of the rural land, which has resulted in some farmers left behind in the countryside losing their main source of income (Hong et al., 2021). However, the rural migrant population is difficult to fully enjoy the urban social security system (Cai and Yue, 2020). Differences in population structure and economic income have aggravated the social inequality and uneven development among urban and rural areas (Ding and Xu, 2013).

Social security adapted to the development of urbanization is one of the most effective means to improve the above situation (Yu and Li, 2021). This system includes social insurance, social assistance, and social welfare, among others (Han, 2021). Social security provides people with basic life security through wealth redistribution, which plays an important role in adjusting residents' income distribution, reducing income gaps, and guaranteeing social fairness and stability (Lu and Du, 2021). However, just as China's economic development is facing severe regional disparities, there are also imbalances in the level of social security among regions, and groups (Yu, 2018; Liu and Wang, 2021). Although urbanization can provide strong economic security and human support for the construction of social security system, the social situation presented by urbanization development correspondingly puts forward new requirements for the improvement of social security system. That is, urbanization not only provides great opportunities for the construction of social security system, but also brings severe challenges.

In terms of the development of China's social security system, social security level is closely related to economic development (Li et al., 2020). The level of social security expenditure, which is usually expressed as the ratio of social security expenditure to gross domestic product (GDP) in the current year, is the core indicator used to measure how much importance a government attaches to national social welfare (Qi and Sun, 2020). The structure and scale of social security contributions and expenditure have an important impact on improving people's sense of acquisition and happiness. This can promote stable economic and social development and ensure that all people can share the fruits of this growth with dignity. In related studies, social security and regional economic growth have been found to have synergistic effects (Wang et al., 2018), constituting a synergistic system (Feng and Gao, 2020). As for the mechanism of social security and economic growth, some early scholars (Laitner, 1988; Kotlikoff, 1996; Mitchell and Zeldes, 1996) argued that social security first acts on material capital and then influences economic growth. Later, some scholars (Jia et al., 2011; Guo and Gong, 2012; Sun and Xiao, 2013) carried out research on this basis to further verify this view. At present, some academics believe that social security is conducive to educational investment and can improve human capital thereby promoting economic growth (Li and Zhao, 2016). However, some Chinese scholars (Chen et al., 2018; Mou, 2020) reached the opposite conclusion through model analysis. They found that under the pay-as-you-go social security system, an increase of social security payments will reduce investments of human capital and hinder economic growth (Jia et al., 2018). In light of the effect of social security on regional economic growth, different scholars have obtained opposite findings based on their respective perspectives. Fan et al. (Zhu et al., 2015; Fan and Feng, 2017) showed that social security expenditure can promote economic growth. Zhang et al. (Zhang and Qiu, 2019) argued that social security spending inhibits economic growth. Moreover, some scholars (Wang and Li, 2019) established a model to analyze the interactions among social security expenditure, economic growth, and the income gap, and found that economic growth can promote social security expenditure, but the level of social security expenditure cannot significantly promote economic growth. (Li et al., 2021) found that the benign interaction between the two was unstable when exploring their coupling and coordination relationship. Throughout these studies, research on the mechanism and effect between social security level and economic growth are abundant, but there is no consistent conclusion. Empirical studies on regions with multiple characteristics need to be further enriched. Meanwhile, the studies mostly explore the one-to-one relationship between the two variables from a single perspective. There are few studies that bring the evaluation of social security policy and relationships of variables into one framework. Moreover, most of the existing studies are based on cross-sectional data, ignoring the influence of time.

Highly urbanized Macao, as one of the regions with the highest per capita GDP in the world, has developed an aging society earlier than mainland China. Since its official operation in 1990, Macao's social security fund has been increasing its expenditure level with the increasing aging population. To cope with this problem, the government of the Macao Special Administrative Region (MSAR) proposed a two-tier social security system in 2008 based on its own practical experience. This new system includes the first layer of the social security system and the second layer of the non-mandatory Central Provident Fund system, which is a new idea for the construction of the social security system. This two-tier social security system has been implemented in Macao since 2010. Has this policy achieved the expected results in terms of economic development? What mechanism is used to achieve its impact? Do social security expenditure promote or hinder the development of the regional economy?

In order to answer the questions mentioned above, this study explores the relationship between the social security fund and the regional economic development of Macao and evaluates the overall implementation effect of Macao's two-tier social security policy creatively and objectively by using the Autoregressive Distributed Lag (ARDL) model and time series data from 1990 to 2019. The findings help us to fully understand the policy choices of the Macao government in terms of social security expenditure during the period of the rapid increase in the aging population. Meanwhile, it is expected to improve the understanding of the relationship between social security system, economic development and green development through the research results. This is of great significance to provide experience for the improvement of the mainland's social security system, and can help narrow the gap between urban and rural areas and promote green and sustainable economic development.

2 RESEARCH FRAMEWORK AND METHOD

2.1 Research Framework

Green development is a mode of economic growth and social development that aims at efficiency, harmony and sustainability under the constraints of resources and the environment. Green development takes "greenization" and "ecologicalization" as the main content of the process and results of economic activities and emphasizes environmental protection. However, for a long time,

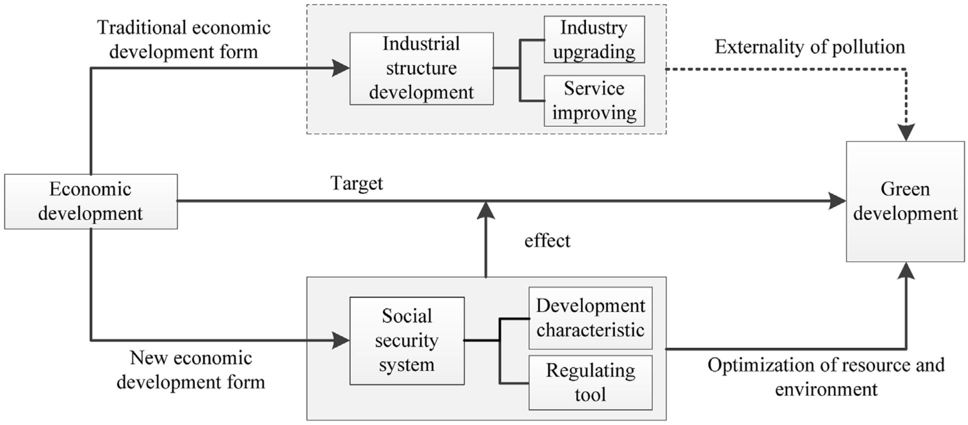

FIGURE 1 | Research framework.

there have been contradictions and conflicts between economic growth and environmental protection (Luo and Zhang, 2020). From the perspective of traditional economic growth forms, industrial structure upgrading and benefit output are the main manifestations (Li and Zou, 2018). Different industries regulate the output of material goods or services based on market supply and demand to influence economic development. In the production process, the traditional economic growth mode, while realizing multiple benefits, is often accompanied by the consumption of material resources and the discharge of pollutants, which has a negative impact on resources and the environment, and then affects the transformation of society to green development (Su and Fan, 2022) (**Figure 1**)

Green development needs to give priority to the transformation of economic growth mode (Li et al., 2022). As a social policy, social security system is not only the product of economic and social development, but also has an important effect on economic growth. Compared with traditional economic growth form, social security system plays a special role in economic growth and environmental protection. In terms of the attribute, the social security system itself in addition to social, fairness, but also has the developmental characteristic. Its developmental characteristic is not only to guarantee and improve the basic living ability of residents, but also to enhance the stable development ability of economy and society. The social security system optimizes the allocation of social resources, adjusts the balance of supply and demand and provides a stable development environment by providing specific funds. The effective social security system actually provides a regulatory tool for the economic towards green development. This tool can help reduce the depletion of material resources, promote environmental protection and sustainable economic development.

2.2 Research Method

2.2.1 The Relationship Between the Development of Social Security Fund and Economic Growth

1) Variable setting

The abbreviation *AGDP* represents the explained variable of regional economic growth. Based on existing studies, the growth rate of the per capita regional GDP is used to measure regional economic growth (Lv and Liu, 2017). The total expenditure scale on social security (*FSS*) is set as core explanatory variable and is measured using the proportion of the MSAR's expenditure on the social security fund to Macao's GDP in the same year. In addition, D_{0T} is the dummy variable for time; 2010–2019 are policy implementation years for which D_{0T} is coded 1; 1990 to 2009 are the years when the policy was not implemented, for which D_{0T} is coded 0. The influence of the time trend on economic growth after the implementation of the two-tier social security policy in the MSAR is controlled for using this dummy variable. The coefficient on the dummy variable represents the implementation effect of the policy and is the focus of this model. Some other important factors also affect the development of the regional economy, so it is necessary to introduce control variables to the model. In view of the situation in the MSAR and the need to reduce the loss of freedom in model construction, human capital (*HUM*) is introduced into the model. This variable is measured by the proportion of college students in the MSAR out of the total regional population. Fixed capital stock (*CAP*) is used to measure the impact of capital factors on economic growth; the variables for the unemployment rate (*JR*) and industrial structure (*STR*) indicate the economic growth pattern reflected by the industrial structure to a certain extent. In this paper, the index of industrial structure upgrading is expressed by the ratio of the added value of the tertiary industry to that of the secondary industry (Gan et al., 2011). Additional control variables are not choosed because too many control variables may cause multicollinearity problems. In addition, the lag time of the regional economic growth parameters is introduced into the model, so the influence of factors not included in the control variables on economic growth can be considered (Gan et al., 2011).

2) Model construction

This paper studies the influence of the social security fund of Macao on the region's economy. The Macao's social security fund was established only recently, so the data span is short. Therefore, the problem of a small sample size must be considered when selecting the econometric model used for the analysis. In addition, regional economic growth is dynamic. Changes in one factor can lead to changes in other factors, and the influence of the former factor will be strengthened. The economy develops following the direction of change of the initial factors and forms a cyclic cumulative causality through the echo effect and diffusion effect (Pesaran et al., 1996); that is, economic growth during the early stage will affect current economic growth. Therefore, this paper introduces dynamic factors to explore the time effect of the economic variables. In this study, the ARDL model was used for the empirical analysis. The model can avoid the autocorrelation problem of a random disturbance term due to the omission of other important measurable and unpredictable factors (Ifa and Guetat, 2018). It is very suitable for small-sample data (Torruam and Abur, 2014) and its estimator is consistent and effective (Li and Shang, 2014).

The ARDL model was proposed by Pesaran, in 1996. Then in 2001, Pesaran, Shin and Smith and further improved by introducing the boundary co-integration test period, which was developed by constructing an autoregressive distributed hysteresis-error correction model (ARDL-ECM) (Wang, 2009). Therefore, this paper selects the ARDL-ECM model for the analysis based on previous research. The ARDL model is a least-squares regression model in which the lag values of one or more explained variables are added as explanatory variables. The model can usually be expressed by ARDL (p, q_1, q_2 ..., q_k), where k is the number of explanatory variables. The general expression of the ARDL model is as follows:

$$y_t = c_0 + \sum_{i=1}^{p}\alpha_i y_{t-i} + \sum_{j=0}^{q}\beta_j x_{t-j} + \varepsilon_t \quad (1)$$

where p is the lag order of the explained variable, q is the lag order of the explanatory variable, α_i, and β_j is the coefficient, respectively.

The ARDL (p, q_1, q_2, q_3, q_4, q_5, q_6) model of the effect of Macao's social security on its regional economy is as follows:

$$\begin{aligned} AGDP_t = c &+ \sum_{i=1}^{p}\alpha_i AGDP_{t-i} + \sum_{j=0}^{q_1}\beta_{1,j}\ln(FSS_{t-j}) + \sum_{j=0}^{q_2}\beta_2 D_{0T} + \sum_{j=0}^{q_3}\beta_{3,j}\ln(HUM_{t-j}) \\ &+ \sum_{j=0}^{q_4}\beta_{4,j}\ln(CAP_{t-j}) + \sum_{j=0}^{q_5}\beta_{5,j}\ln(JR_{t-j}) + \sum_{j=0}^{q_6}\beta_{6,j}\ln(STR_{t-j}) + \varepsilon_t \end{aligned} \quad (2)$$

To test whether there is a long-term stable relationship between variables in **Eqs. 2**, a long-term equilibrium equation was established as follows:

$$\begin{aligned} AGDP_t = \theta_0 + \theta_1 \ln(FSS_t) + \theta_2 D_{0T} + \theta_3 \ln(HUM_t) \\ +\theta_4 \ln(CAP_t) + \theta_5 \ln(JR_t) + \theta_6 \ln(STR_t) + \mu_t \end{aligned} \quad (3)$$

Within this,

$$\theta_1 = \frac{\sum_{j=0}^{q_1}\beta_{1,j}}{1-\sum_{i=1}^{p}\alpha_i}, \theta_2 = \frac{\sum_{j=0}^{q_2}\beta_{2,j}}{1-\sum_{i=1}^{p}\alpha_i}, ..., \theta_6 = \frac{\sum_{j=0}^{q_6}\beta_{6,j}}{1-\sum_{i=1}^{p}\alpha_i}$$

The long-term equilibrium relationship among variables reflected in **Eq. 3** does not always exist. Due to the comprehensive effect of various random factors, the deviation from the long-term equilibrium relationship will occur in the short term. However, the internal relationship and mechanism of action of the system will correct such deviation (Qamruzzaman and Jianguo, 2017). Therefore, a corresponding ECM should be established:

$$\begin{aligned} \Delta AGDP_t = &-\sum_{i=1}^{p-1}\alpha_i^*\Delta AGDP + \sum_{j=0}^{q_1-1}\beta_{1,j}^*\Delta\ln(FSS_{t-j}) + \sum_{j=0}^{q_2-1}\beta_2^*\Delta D_{0T} \\ &+ \sum_{j=0}^{q_3-1}\beta_{3,j}^*\Delta\ln(HUM_{t-j}) + \sum_{j=0}^{q_4-1}\beta_{4,j}^*\Delta\ln(CAP_{t-j}) + \sum_{j=0}^{q_5-1}\beta_{5,j}^*\Delta\ln(JR_{t-j}) \\ &+ \sum_{j=0}^{q_6-1}\beta_{6,j}^*\Delta\ln(STR_{t-j}) + \varphi EC_{t-1} + \varepsilon_t \end{aligned} \quad (4)$$

where the error correction term at t−1 is:

$$EC_t = AGDP_t - \begin{bmatrix} \theta_0 + \theta_1 \ln(FSS_t) + \theta_2 D_{0T} + \theta_3 \ln(HUM_t) \\ +\theta_4 \ln(CAP_t) + \theta_5 \ln(JR_t) + \theta_6 \ln(STR_t) \end{bmatrix} \quad (5)$$

The premise of the above equation is that there is a co-integration relationship between variables, so it is necessary to establish the boundary co-integration test regression equation of the ARDL model (Pesaran et al., 1996):

$$\begin{aligned} \Delta AGDP_t = &-\sum_{i=1}^{p-1}\alpha_i^*\Delta AGDP + \sum_{j=0}^{q_1-1}\beta_{1,j}^*\Delta\ln(FSS_{t-j}) + \sum_{j=0}^{q_2-1}\beta_2^*\Delta D_{0T} \\ &+ \sum_{j=0}^{q_3-1}\beta_{3,j}^*\Delta\ln(HUM_{t-j}) + \sum_{j=0}^{q_4-1}\beta_{4,j}^*\Delta\ln(CAP_{t-j}) + \sum_{j=0}^{q_5-1}\beta_{5,j}^*\Delta\ln(JR_{t-j}) \\ &+ \sum_{j=0}^{q_6-1}\beta_{6,j}^*\Delta\ln(STR_{t-j}) - \delta_0 AGDP_{t-1} - \alpha - \delta_1\ln(FSS_{t-1}) - \delta_2 D_{0T} \\ &-\delta_3\ln(HUM_{t-1}) - \delta_4\ln(CAP_{t-1}) - \delta_5\ln(JR_{t-1}) - \delta_6\ln(STR_{t-1}) + \varepsilon_t \end{aligned} \quad (6)$$

The assumptions of the boundary co-integration test are:

$$H_0: \delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_6$$
$$H_1: \delta_1 \neq \delta_2 \neq \delta_3 \neq \delta_4 \neq \delta_5 \neq \delta_6$$

If the sample value of the test statistic F is higher than the larger critical value, the null hypothesis is rejected and there is a long-term co-integration relationship between variables. If the sample value of the test statistic F is lower than the small critical value, the null hypothesis cannot be rejected and there is no co-integration relationship between variables. If the sample value of the test statistic F is between the two critical values, it is impossible to determine whether or not there is a co-integration relationship between variables (Pesaran et al., 1996).

It can be seen that the boundary co-integration test of the ARDL model breaks through the limitation that the variables involved in the traditional co-integration test (such as the Engle and Granger method,; the Johansen method, and the Johansen and Juselius method, etc.) must be in the same order of integration (Qamruzzaman and Jianguo, 2017). It also can be seen that the variables of the ARDL model can be an $I(0)$ sequence or an $I(1)$ sequence, or a mixture of the two. Meanwhile, the ARDL model should ensure that the order of integration of variables does not exceed 1 to avoid regression bias

TABLE 1 | Economic growth and green development evaluation index system of MSAR.

Target	First Grade Indexes	Second Grade Indexes	Unit of Index	Index Weight	Index Direction
Economic development	Economic growth strength	Economic density	Millions of Macau Pataca/km^2	0.15	+
		Growth rate of GDP	%	0.13	+
		Tertiary industry/total value of out-put	%	0.10	+
		Fiscal revenue	Thousands of Macau Pataca	0.08	+
	Economic growth benefit	Per capital GDP	Macau Pataca	0.14	+
		Per capita disposable income	Macau Pataca	0.14	+
	Economic growth mode	Import index	Point (2016 = 100)	0.13	+
		Export index	Point (2016 = 100)	0.13	+
Green development	Resource input	Average water resources input per unit land area	m^3/km^2	0.15	-
		Average electricity power resources input per unit land area	kilostere/km^2	0.15	-
		Average capital investment per unit land area	Thousands of Macau Pataca/km^2	0.12	-
		Average labour input per unit land area	Thousands of population/km^2	0.08	-
	Green output	Growth rate of sulfur oxide emissions	%	0.15	-
		Growth rate of greenhouse gas emissions	%	0.15	-
		carbon emissions/gross value of production	t/Millions of Macau Pataca	0.2	-

(Yi et al., 2015). Therefore, the first step of applying the ARDL model is to conduct a unit root test on the variables.

2.2.2 The Effect of Social Security on the Green Development

In order to further test the green development effect of the new economic growth form, this study first identifies the coupling coordination relationship between economic growth and green development. On this basis, the OLS model is introduced to analyze the effect of social security development on the green development.

1) The coupling coordination degree between economic growth and green development

Economic growth is the key to sustainable economic development. Most scholars believe that the connotation of economic growth can be better reflected from the effectiveness, stability, sustainability, innovation and sharing of economic growth (Zhu, 2019). Therefore, the selection of indexes mainly focuses on three aspects: economic growth strength, growth benefit and growth mode (**Table 1**). Green development is a development mode that achieves multi-target and reaches the optimal status under certain constraints. Green development needs not only to increase the output intensity of resources, but also to consider reducing pollutant emission levels under the constraints of energy conservation and emission reduction, so as to achieve sustainable use of resources and green sustainable development (Hu et al., 2018). The selection of indexes is based on the improvement of ecological ability in the process of land use, the degree of green development is mainly measured focuses on two aspects of resource input and green output (**Table 1**). Meanwhile, this study uses entropy weight method and coupling coordination degree model to divide the coupling coordination level of Macao's economic growth and green development into 10 levels with 0.1 as equal spacing (Huang et al., 2018; Liang et al., 2019; Liang et al., 2020): extreme imbalance, serious imbalance, moderate imbalance, mild imbalance, imminent imbalance, reluctant coordination, primary coordination, moderate coordination, good coordination and high quality coordination, so as to explore the coupling coordination level of Macao's economic growth and green development since the implementation of the two-tier social security system in 2010.

2) Effect of social security fund development

Social security function is mainly embodied in social function and economic function. Among them, the economic function is "explicit function", which is the expected and visible function of the social security plan (Shen et al., 2022). This function can balance supply, regulate investment and financing, redistribute national income, and protect and allocate labour force; social function is "implicit function", which is unpredictable and invisible. Social security improves individual fairness perception by promoting the improvement of infrastructure and public services, and promotes population aggregation and urban function. However, the "implicit function" of social security cannot be ignored. On the basis of introducing factors of social security expenditure and economic development, this study also introduces the interaction term of social security expenditure and economic growth to examine whether the effect of economic growth on green development will be affected by the level of social security expenditure. In order to explore whether the effect of social security expenditure on green development will lag, we introduce the lagged term of social security expenditure into the regression model (**Formula 7**). The definitions and explanations of each variable are shown in **Table 2**.

$$Sys\_GL = \alpha + \beta_1 Sys\_EN + \beta_2 Sys\_EN * FSS + \beta_3 FSS + \beta_4 FSS_{t-1} + e_3 \quad (7)$$

TABLE 2 | Variable definition and explanation.

Variable	Definition	Explanation
Sys_EN	Economic growth level	Calculation of economic development index by entropy method
Sys_GL	Green debelopment level	Calculation of green development index by entropy method
FSS	Social security development level	Proportion of social security expenditure in GDP
*Sys_EN*FSS*	Interaction term between economic development and social security	Multiplication of economic growth level and social security development level

TABLE 3 | Variables and their descriptive statistics.

Variables	Description	Data Resource
AGDP	Per capita GDP growth rate of MSAR	World Development Indicators database of the World Bank
FSS	The proportion of Macao's social security fund expenditure in regional GDP	International Monetary Fund Database of Government Finance Statistics
D_{0T}	Dummy variable of policy implementation time	2010–2019 are the years of policy implementation, D_{0T} = 1; 1990–2009 are the years when the policy was not implemented, D_{0T} = 0
HUM	Proportion of college students in Macao to regional population	Macao statistics and Investigation Bureau
CAP	Fixed capital stock	World Development Indicators database of the World Bank
JR	The proportion of the unemployed population in labor force	Macao statistics and Investigation Bureau
STR	Added value ratio of tertiary industry to secondary industry in Macao	Macao statistics and Investigation Bureau

	Mean	Standard Deviation	Min	Max
AGDP	3.7937	9.0977	–23.0421	23.5581
FSS	0.4103	0.2979	0.0900	1.0483
HUM	3.3673	1.3641	1.4789	5.3130
CAP	3.36E+10	2.78E+10	5.07E+09	8.92E+10
JR	3.4363	1.5991	1.7000	6.8000
STR	11.3385	6.9382	4.3609	25.8661

2.3 Data Resources

Taking into account the official operation of the Macao's social security fund in 1990, the data selected cover the period from 1990 to 2019. Among the selected data and indices, the growth rate of per capita GDP, fixed capital stock, and other data come from the World Development Indicators database of the World Bank. Social security expenditure data are derived from the International Monetary Fund Database of Government Finance Statistics; the data of human capital, industrial structure, the unemployment rate, economic density, regional GDP growth rate and other economic growth variables, as well as average water resources input per unit land area, average electricity power resources input per unit land area and other green development variables are come from the Macao Statistics and Investigation Bureau; the data of sulfur oxide emission growth rate, greenhouse gas emission growth rate and carbon emission in the green development index system are from the annual environmental status report of Macao environmental protection agency. The descriptive statistics for each variable are shown in **Table 3**. According to the mean and standard deviation of each variable, the data are evenly distributed and can carry out good empirical test.

3 RESULT ANALYSIS

3.1 Analysis of the Contribution to Economic Growth

Considering that the selected variables are constructed using time series data and most are economic data, we first take the logarithm of the selected data before conducting the empirical analysis to eliminate the influence of heteroscedasticity. Therefore, part of the data in this ARDL model are calculated as the logarithm of the original data.

3.1.1 Unit Root Test

Before analyzing the data, a unit root test should be carried out to verify the data's stability. In large samples, the Augmented Dickey-Fuller (ADF) test is effective (because of the limit distribution); in small samples, however, the test effect decreases significantly (Fang and Zou, 2007). In view of the small sample size of this study, the method suggested by Zhang Hui is used (Zhang, 2020). The unit root test is mainly based on the Dickey-Fuller Test with GLS Detredding (DF-GLS test), and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS)

TABLE 4 | DF-GLS unit root test.

Variable	Original Sequence		First-Order Difference Sequence		
	Test Type (C, T, N)	Statistic	Test Type (C, T, N)	Statistic	Conclusion
AGDP	(1,0,0)	−3.3960**	(1,0,0)	−5.9317***	I (0)
	(1,1,0)	−3.3949**	(1,1,4)	−4.5620***	
Ln(FSS)	(1,0,0)	−3.2678***	(1,0,0)	−5.6141***	I (0)
	(1,1,0)	−3.2705**	(1,1,0)	−5.8488***	
Ln(HUM)	(1,0,4)	−0.6595	(1,0,4)	−2.0211**	I (1)
	(1,0,4)	−1.0492	(1,0,3)	−4.9819**	
Ln(CAP)	(1,0,0)	−2.4011**	(1,0,0)	−5.2131***	I (1)
	(1,1,0)	−2.4763	(1,1,0)	−5.2531***	
Ln(JR)	(1,0,0)	−3.9415***	(1,0,0)	−6.0901***	I (0)
	(1,1,0)	−4.1002***	(1,1,0)	−6.6520***	
Ln(STR)	(1,0,1)	−4.1023***	(1,0,0)	−5.5711***	I (0)
	(1,1,1)	−4.1301***	(1,1,0)	−4.5331***	

*Note: The components in (C, T, N) represent the constant term, trend term, and lag order, respectively. A value of 1 denotes that there is a constant term or trend term, and a value of 0 denotes no constant or trend term. The lag order is determined by the SIC, minimum criterion; the null hypothesis of the DF-GLS, unit root test is that there is a unit root in the variable. *, **, and *** represent rejection of the null hypothesis at the 10, 5, and 1% significance levels, respectively.*

TABLE 5 | KPSS unit root test.

Variable	Original Sequence		First-Order Difference Sequence		
	Test Type (C, T, W)	Statistic	Test Type (C, T, W)	Statistic	Conclusion
AGDP	(1,0,2)	0.1130	(1,0,10)	0.1677	I (0)
	(1,1,2)	0.1136	(1,1,10)	0.1508**	
Ln(FSS)	(1,0,0)	0.1045	(1,0,27)	0.5000**	I (0)
	(1,1,0)	0.1054	(1,1,27)	0.5000***	
Ln(HUM)	(1,0,2)	0.2250	(1,0,1)	0.1088	I (1)
	(1,0,2)	0.1700**	(1,0,0)	0.0203	
Ln(CAP)	(1,0,2)	0.0711	(1,0,5)	0.0955	I (0)
	(1,1,2)	0.0736	(1,1,5)	0.0946	
Ln(JR)	(1,0,0)	0.2641	(1,0,15)	0.2737	I (0)
	(1,1,2)	0.0847	(1,1,15)	0.2624***	
Ln(STR)	(1,0,4)	0.0555	(1,0,11)	0.1898	I (0)
	(1,1,4)	0.0545	(1,1,10)	0.1603**	

*Note: The components in (C, T, W) represent the constant term, trend term, and width of band, respectively. A value of 1 denotes that there is a constant term or trend term, and a value of 0 denotes no constant or trend term. The lag order is determined by the SIC, minimum criterion; the null hypothesis of the KPSS, unit root test is that the variables are stable. *, **, and *** represent rejection of the null hypothesis at the 10, 5, and 1% significance levels, respectively.*

method is used as an auxiliary and supplementary explanation. The results of the DF-GLS unit root test (**Tables 4**)and the KPSS unit root test (**Table 5**) show that the variables are stationary sequences that can be used for further empirical analysis.

3.1.2 Autoregressive Distributed Lag Model Estimation

This study uses Eviews 9.0 for the empirical analysis. The specific operations are as follows. First, the error correction model (ECM) corresponding to the ARDL model is established, and the F-statistics in the ECM model are calculated to determine whether there is a long-term stable relationship between variables. Then ARDL model is used to estimate the coefficient of the long-term relationship between variables. In addition, the study shows that in the case of large samples, the selection of the lag term of the ARDL model should be based on the SBC criterion; but in the case of small samples, the AIC criterion is better (Yi et al., 2015). Considering the small sample size of the data used in this study, according to the AIC criterion set, the optimal ARDL model is ARDL (2, 2, 1, 2, 2, 2, 1). To further determine the fitting effect of the model, the autocorrelation test of its residual sequence is needed. If the residual sequence is a white noise sequence—that is, the sequence shows the characteristic of pure randomness—this indicates that the model has a high fitting degree and can fully extract the relevant information in the sequence without a need for secondary information extraction of the residual. On the contrary, if there is a significant autocorrelation in the residual sequence, it is necessary to extract the secondary information of the residual to improve the accuracy of the model's fit.

Based on this, the Breusch–Godfrey method is used to test the residual autocorrelation of ARDL (2, 2, 1, 2, 2, 2, 1). The null hypothesis is that there is no residual autocorrelation in the sequence. The test results (**Tables 6** and **7**) show that the Chi-square distribution of the *p*-value is 0.6305, greater than the 5%

TABLE 6 | Breusch–Godfrey test.

F-Statistic	0.106,131	Prob. F (2,6)	0.9010
Obs*R^2	0.922,540	Prob. Chi-square (2)	0.6305

TABLE 7 | Bounds testing approach to co-integration.

Significance Level	10%		5%		1%	
Critical value	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
	2.12	3.23	2.45	3.61	3.15	4.43
F-value			5.1931***			
Conclusion			Long-term co-integration relationship exists			

*Note: *** indicates that the null hypothesis is rejected at the 1% significance level.*

TABLE 8 | Error correction and short-term adjustment.

Variable	Coefficient	Std. Error	t-statistic	Prob
D(AGDP(-1))	−0.5445***	0.1524	−3.5721	0.0073
D(Ln(FSS))	−0.0438	0.0580	−0.7555	0.4716
D(Ln(FSS(-1)))	0.1835**	0.0640	2.8683	0.0209
D(D_{0T})	6.2752	7.0163	0.8944	0.3972
D(Ln(HUM))	−13.9636***	0.1215	−114.9285	0.0000
D(Ln(HUM(-1)))	−0.1515	0.0995	−1.5225	0.1664
D(Ln(CAP))	−0.1438	0.0874	−1.6462	0.1384
D(Ln(CAP(-1)))	0.0861	0.0587	1.4665	0.1807
D(Ln(JR))	0.2097*	0.1109	1.8914	0.0952
D(Ln(JR(-1)))	−0.0860	0.1431	−0.6009	0.5646
D(Ln(STR))	0.5244***	0.0639	8.2123	0.0000
CointEq(-1)	−0.8675**	0.2690	−3.2248	0.0122

Note: D *represents the first-order difference; *, **, and *** represent significance levels of 10, 5, and 1%, respectively; CointEq (−1) is the error correction term.* CointEq = AGDP – *(−0.2481**DFSS + *20.1058**D_{0T} *−15.3247**DHUM *−0.6706**DCAP + *0.6173**DJR + *1.1075**DSTR + *0.1929).*

significant level. Therefore, we cannot reject the null hypothesis. The model residual is a white noise sequence, indicating that ARDL (2, 2, 1, 2, 2, 2, 1) has extracted most of the data information, and the model has high accuracy. The F-statistic of the tested sample is 5.1931, which is greater than the upper limit of the critical value of the 1% significance level; therefore, the null hypothesis (that there is no long-term co-integration relationship between variables) is rejected.

The ARDL-ECM model estimation (**Table 8**) for the short-term deviation adjustment of the long-term equilibrium relationship of the response system also shows the impact and influence of the short-term changes of the independent variables on the regional economy. Meanwhile, the coefficient of the long-term equilibrium relationship between per capita GDP and the other variables (**Table 9**) further shows that: in the process of using the ECM for short-term adjustment, the coefficients on the explained variable lagged by one period are significant. This shows that regional economic growth has a significant lag effect, and that the dynamic model used in this paper is appropriate. The coefficient on the virtual variable (D_{0T}), used to measure the policy effect, is not obvious, indicating that the economic growth has not improved significantly in the short term after the implementation of the two-tier social security system. In addition, the coefficient on the error correction term (CointEq (−1)) is negative and significant, indicating that the deviation of the system from the long-term equilibrium is significantly adjusted to the equilibrium position, which also proves the existence of a long-term equilibrium relationship between variables.

TABLE 9 | Long-term equilibrium coefficient.

Variable	Coefficient	Std. Error	t-statistic	Prob
Ln(FSS)	−0.2481**	0.1023	−2.4252	0.0415
D_{0T}	20.1058**	7.5909	2.64866	0.0293
Ln (HUM)	−15.3248**	4.7571	−3.2214	0.0122
Ln(CAP)	−0.6706*	0.3042	−2.2045	0.0586
Ln(JR)	0.6173	0.3627	1.7023	0.1271
Ln(STR)	1.1075**	0.2888	3.8344	0.0050
C	0.1929	2.7533	0.0701	0.9459

*Note: *, **, and *** represent significance levels of 10, 5, and 1%, respectively.*

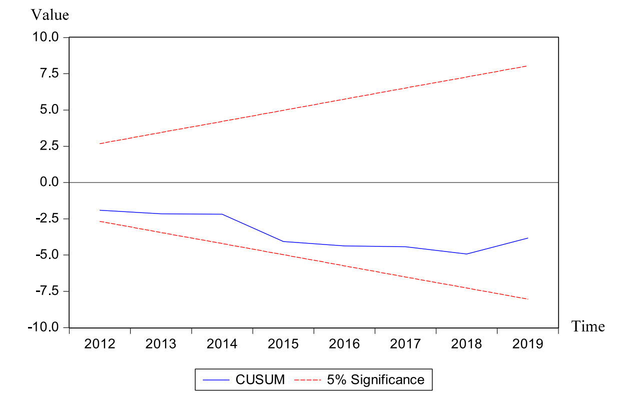

FIGURE 2 | CUSUM test results.

3.1.3 Stability Test

The stability of the model parameters is tested using the residual cumulative sum (CUSUM) test and the residual cumulative sum of squares (CUSUM of squares) test. CUSUM was proposed by Page based on maximum likelihood ratio (Page, 1954). CUSUM uses representative approximate value to replace the original data, mean value, range or standard deviation to record data. By continuously accumulating deviations, CUSUM continuously enlarges small changes, so as to give early warning of model deviations. CUSUM can more sensitively detect the small deviation of the model, which is particularly advantageous when the number of samples is small (Wang et al., 2021). The CUSUM and CUSUM of squares test results drawn by Eviews 9.0 are shown in **Figures 2**, **3**. The horizontal axis represents the specific year of the time interval of the investigation period, and the vertical axis represents the cumulative deviation of the sample. The red dotted line represents the boundary interval of the 5% significance level. It can be intuitively seen from the two figures that the sum of sample residuals did not deviate from the boundary range in the whole study period. The results show that

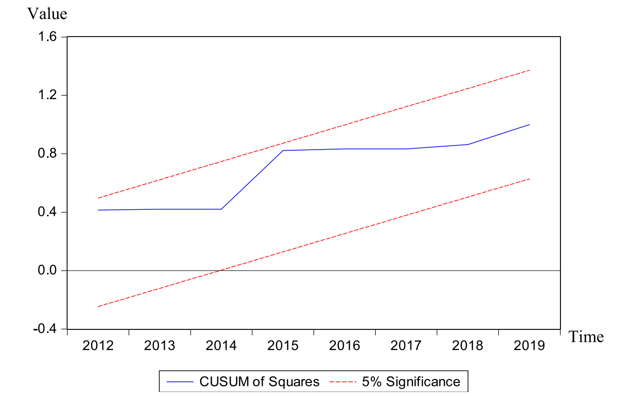

FIGURE 3 | CUSUM of squares test results.

the regression parameters estimated by the model are reliable in study period, and the deviation is relatively small; that is, the regression coefficients are stable in the study period.

3.1.4 Effect of Social Security Fund Development on Economic Growth

In the estimation results of the long-term equilibrium relationship, the most important coefficient to measure the policy effect—the coefficient on the time dummy variable D_{0T}—is positive and significant, indicating that the economic growth rate has significantly improved after the implementation of the two-tier social security policy in the MSAR. In addition, through the piecewise regression of data before and after the implementation of the policy, the results show that, before the implementation of Macao's two-tier social security system in 2010, the coefficient between Macao's social security fund expenditure and per capita GDP is negative and significant. This suggests that, before the implementation of the policy, social security expenditure hindered economic development, a conclusion that is consistent with previous studies (Chen et al., 2018; Mou, 2020). After the implementation of the policy, the coefficient between social security fund expenditure and per capita GDP is positive, which further verifies the estimation results of the long-term relationship. The two-tier social security system can promote economic growth as a new form of economic development.

The continuous optimization and upgrading of industrial structure are important parts of modern economic growth. The coefficient on industrial structure in the estimation results is positive and significant, indicating that the relative growth of the service industry in the MSAR is mainly due to the modern service industry. At the same time, the modern service industry has greatly stimulated the economic growth of the region, with gambling and tourism as the pillars. The structural optimization degree of human capital as a kind of production factor also affects the speed of economic development. With faster economic development, advanced human capital has not only higher labor productivity, but also greater knowledge spillover. Because of the stronger ability to benefit from element agglomeration, upgrading human capital structures can promote economic growth (Zong and Zhou, 2015). However, human capital cannot promote the economy independently, but needs to be matched dynamically with the industrial structure to take effect. Industrial structure has a demand effect on the human capital structure, and different industries have different demands on the quality and quantity of human capital. The optimization of the human capital structure should be driven by the demand of industrial structure and the supply of education and training. This demand and supply are relatively independent of each other, leading to a possible mismatch between the two (Chen and He, 2020). Therefore, the human capital coefficient in **Table 9** is negative and significant, indicating two possible problems. First, with the expansion of human capital, the input of other production factors failed to expand synchronously. Second, with the upgrading of the industrial structure, the market demand for innovative and technical talents increased, while the current human capital structure struggles to adapt to market demands, thus dragging down economic growth.

Fixed capital stock is an important factor affecting socio-economic efficiency; it reflects the degree of government's material capital input. Under the law of the diminishing marginal effect, material capital cannot maintain sustained economic growth, and technological innovation can promote sustained economic prosperity. The empirical results show that the fixed capital stock has a significant negative effect on economic growth in the MSAR, indicating that the mode of driving growth through material capital input has become invalid and even hindered the improvement of economic growth to a certain extent. The unemployment rate has no significant impact on the regional economy, suggesting that fluctuations of the regional economy can break through the constraint of "Okun's Law" when high social welfare is present. The rise of the unemployment rate will not lead to an economic recession, which also proves the superiority of the two-tier social security system in the MSAR.

3.2 Analysis of Green Development Effect

3.2.1 Change of Coupling Coordination Relationship Between Economic Growth and Green Development

As can be seen from **Table 10**, the coupling coordination degree index of Macao's economic growth and green development from 2010 to 2020 shows an overall trend of first increasing and then decreasing, with obvious volatility. Specifically, Macao's economic growth and green development in 2010, 2014 and 2018 was moderate coordination. The relationship between the two was good coordination from 2011 to 2013. Moderate imbalance was observed in 2015, and the situation improved in the following 2 years. After 2018, the coupling coordination degree between the two systems declined sharply. Although it briefly reached reluctant coordination in 2019, the coupling coordination degree in 2020 was only 0.236, the lowest level in the study period. This also shows that Macao's economic growth is rising but not accompanied by green and sustainable development. It is also affected by the traditional economy in terms of resource input and green output, and needs to seek new economic forms in the future.

3.2.2 Effect of Social Security Fund Development

It can be seen from **Table 11** that the impact of social security expenditure on green development is not significant in the current period, but its lag term is negatively significant, indicating that the

TABLE 10 | Changes of coupling coordination degree between Macao's economic growth and green development.

Year	Coupling Degree	Coordination Degree	Coupling Coordination Degree	Relationship
2010	0.892	0.682	0.780	moderate coordination
2011	0.995	0.679	0.822	good coordination
2012	0.990	0.692	0.828	good coordination
2013	0.966	0.787	0.872	good coordination
2014	0.874	0.628	0.741	moderate coordination
2015	0.318	0.193	0.248	moderate imbalance
2016	0.646	0.244	0.397	mild imbalance
2017	0.643	0.356	0.478	imminent imbalance
2018	0.921	0.579	0.730	moderate coordination
2019	0.862	0.410	0.594	reluctant coordination
2020	0.347	0.161	0.236	moderate imbalance

TABLE 11 | Regression results.

Variable	Regression Coefficient
Constant	-0.099 (-1.048)
*Sys_EN*FSS*	-0.065** (-2.860)
Sys_EN	0.880** (5.038)
FSS_{t-1}	-0.454** (-3.868)
FSS	0.029 (0.563)

Note: Sys_GL, *is the dependent variable; *, ** and ** are significant levels of 10, 5 and 1% respectively.*

negative effect of Macao's two-tier social security system on green development is lagging. Economic growth has a significant positive effect on green development, and the effect is large. It can be concluded that there are significant differences between the effect of social security expenditure and economic growth on green development. At the same time, the interaction term between social security expenditure and economic growth has a significant negative effect on green development, but the influence coefficient is small, indicating that with economic growth, the increase of social security expenditure will hinder green development to some extent. Therefore, it is urgent to optimize the regulation of social security system in order to give full play to its green development effect.

Limited by natural conditions, Macao presents the characteristics of resource scarcity, limited carrying capacity and highly compatible and high-density land resource utilization (Cui et al., 2014). With the rapid social and economic development, the living standard of residents is constantly improved, so the requirements for ecological environment quality are also increased. Therefore, economic growth plays a positive role in the protection of ecological space. However, the neglect of environmental protection by social security expenditure to some extent is not conducive to green development in the long run.

4 DISCUSSION

4.1 Research Findings

This study uses ARDL model to discuss the relationship between social security fund and economic development, and objectively test the economic green development effect of the two-tier social security policy in Macao Special Administrative Region. The results show that the two-tier social security system can promote green development as a new form of regional social and economic development. This is a strong supplement to the existing research system on the development of social security system, and provides a theoretical basis for solving the problems associated with the fundraising and operation mode in the integration of urban and rural social security in China. At the same time, it can also provide important reference for China and even other regions in the world to shape the new form of economic development with social security system.

One of the important means to improve regional ecological environment and achieve green development is to increase government expenditure on environmental protection (Jiang, 2018). According to the results, it can be found that social security has a negative lag effect on green development. The main reason may be that social security has the characteristics of "rigidity". This characteristic is that social security expenditure is easy to rise and not easy to fall, and does not depend on the economic cycle and fluctuates with a rising long-term trend, that is, "welfare rigidity" (Shaoan et al., 2019). Social security projects in the MSAR are numerous and the level of payment continues to rise. Excessive social security expenditure will inevitably have a crowding-out effect on other public expenditure, which makes insufficient expenditure on ecological environment protection and economic green development. This deficiency is reflected in the negative correlation between social security and green development. Social security allocates public resources rationally by means of national legislation to ensure that the basic livelihood of workers is not affected in the face of unemployment, old age, illness, childbirth, industrial injury, and natural disasters. Moreover, social security also guarantees the basic survival of people with no or low income in order to maintain social fairness and welfare and improve quality of life (Lv and Liu, 2017). At present, China's economic and social development has shifted from a stage of high-speed growth to one of high-quality development. It is urgent to establish a social security system compatible with economic and social development. And Macao's two-tier social security system also inspires us to attach importance to the needs of different groups and coordinate different levels of social security.

There are also some limitations in this study. First, there is a lack of analysis on the path of two-tier social security system affecting economic development, and a lack of discussion on the interactive effects of different factors on economic development. Second, the mechanism of social security system green promoting economic development has not been deeply explored. In the future, further research will focus on the coordinated development of social security, economic growth and ecological environmental protection.

4.2 Policy Implications

According to the results of this study, the following policy suggestions are proposed for implementing social security as a new form of economic development for the rapid urbanization of mainland China and even the world.

First, governments should establish a non-mandatory social security fund to supplement the current social security system. Individual funding is open to residents and managed by eligible fund management entities. Investment in the non-mandatory social security fund can provide more adequate protection for urban and rural residents.

Second, it is important to regulating the scale of social security revenue and expenditure, and reduce the burden of government fiscal expenditure on the premise of playing its role in promoting economic growth. Meanwhile, the government should increase support for the green development of urban environment and formulate a scientific budget for environmental protection. Give full play to the regulating role of social security expenditure on regional economy and green development to promote the coordinated development of economy and environment.

Third, leaders should optimize the industrial structure and capital investment direction. They should reduce financial support for outdated industries to gradually eliminate excess backward production capacity. Combined with the regional advantages of different regions, resources should be concentrated in the direction of refinement, service, and green development.

In addition, different cities have different problems and advantages in coordinating the relationship between regional economy and ecology due to their differences in resources, location and environmental conditions. Therefore, the city should take corresponding solutions according to its own actual situation.

5 CONCLUSION

Based on the time-series data of the MSAR from 1990 to 2019, this paper constructs an ARDL model to quantitatively analyze the effect of social security expenditure on economic growth. The empirical results indicate several findings. First, the influence of the two-tier social security policy, social security expenditure, and other control variables on economic growth has a time lag. Second, in the long run, social security expenditure has a negative and significant impact on the per capita economic growth rate, while the two-tier social security policy has a positive and significant effect on economic growth. This demonstrates the effectiveness of the two-tier social security policy. Third, Macao's industrial structure is positively correlated with economic growth, indicating the necessity of China's reform and optimization of industrial structures. Fourth, fixed capital stock has a significant negative impact on Macao's economic growth; that is, material capital investment has been unable to promote economic development. The effects of technological innovation on promoting economic development should be emphasized. Fifth, human capital has a significant inhibitory effect on economic development. A possible reason is the asymmetry between the supply side and the demand side of the labor market and the weak matching of other production factors. Sixth, the coupling coordination relationship between economic growth and green development fluctuates from 2010 to 2020. The implementation of the two-tier social security system has a negative lag effect on green development to a certain extent. The positive role of social security in green development should be further activated in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, BW and YQ; methodology, BW and QR; formal analysis, BW and XD; data curation, BW and YL; writing—original draft preparation, BW and XD; writing—review and editing, XD and YQ; visualization, BW and YL; supervision, YZ and ZX. All authors have read and agreed to the published version of the manuscript.

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The production function socialization trend of rural housing land and its response to rural land planning in metropolitan suburbs from the perspective of rural space commodification

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An investigation of the changing production function of rural housing land can help to guide appropriate land use adjustment and rural land planning. Taking into account the layout characteristics from 2005 to 2018, we employed the structural equation model and the theory of planned behavior to analyze the differentiation mechanism of rural housing land production function based on survey data of 613 typical farmers in Pinggu District of Beijing. Our results show that, first, the production function intensity of rural housing land in Pinggu District fell from 0.327 to 0.126, and the coefficient of variation increased from 0.15 to 0.54. This indicates that the overall production function decreased but the spatial heterogeneity increased. Second, the production function of rural housing land gradually withdrew and socialized in villages, following the socialization evolution process of agricultural production function, industrial and commercial service function, and public service function. Third, the internal land use pattern of rural housing land is significantly influenced by the subjective norms and perceptual behavior control of farmers. The demonstrative norms of family and the prescriptive norms of village collective have significant effects on subjective norms, and the perceived behavioral control is significantly affected by income scale and structure, family size, and employment type. Finally, to further promote rural housing land management, it is necessary to optimize its prescriptive norms of the village collective, improve the farmers' income level and employment structure, and weaken the farmers' perceived difficulties. According to the different function socialization stages of rural housing land, rural land planning should coordinate the relationship between the production function socialization of rural housing land and the commercialization of rural space, and boost the revitalization of rural industry.

KEYWORDS

rural housing land, production function socialization of rural housing land, internal land use, commodification of rural space, rural land planning

1 Introduction

Land is a core element of urban and rural development (Long and Chen, 2021), and the improvement of land use function is an important way to implement the rural revitalization strategy. It is also an important perspective to measure the implementation effect of rural revitalization (Zhang and Li, 2020). Exploring the impact of micro-subject land use behavior on land use function change and clarifying the behavior response mechanism of actors have become important research directions of land system science, driven by the Global Land Project (GLP) (Tang et al., 2009; Verburg et al., 2009; Liang et al., 2019). Rural housing land is a multifunctional compound space that the rural population relies on for survival and development. It is also the core of the interaction and coupling of the man-land relationship in the rural regional system, presenting function diversity with different human needs (Jiang et al., 2016; Zhou et al., 2017). Clarifying the multifunctional characteristics of rural housing land is of great significance for promoting intensive and economical use of rural land, and for urban-rural integration development (Cloke and Edwards, 1986; MLRPRC, 2016; Liu, 2018; Yang et al., 2018).

Rural housing land is an important land use type and the traditional living form of farmers in the countryside (Long and Li, 2005; Jiang et al., 2007; Whittemore and BenDor, 2019), meeting the production and living needs of farmers (Wegren et al., 2008; Jiang et al., 2016; Qi et al., 2020), and occupying a large proportion of urban and rural construction land in developing countries with a large agricultural population (Liu and Li., 2017; The Department of Economic and Social Affairs of the United Nations Secretariat (UN DESA), 2018). Social and economic development; the accelerative flow of the urban and rural population, capital, and other factors (Liu, 2018); and the rapid change of rural land planning, peasant household structure, and personal characteristics have forced the unprecedented morphological evolution and function transformation of rural housing land (Skowronek et al., 2005; Long et al., 2007; Long et al., 2011; Zhou et al., 2019). The simple functions of agricultural production and villagers' residence have gradually shift to multiple and complex functions of production, processing, trade, sightseeing and leisure, and recuperation and vacation. The dominant function is gradually moving from social security to asset, which presents regional and individual differentiation. As the rural collective construction land with the largest area, the widest audience, and the most direct impact on interests, rural housing land has attracted increased attention from management departments and academic circles (Qu et al., 2021; Yuan et al., 2021).

Existing studies generally suggest that rural housing land has two basic functions: production and living. Meanwhile, some studies demonstrate usufruct function (Banski and Wesolowska, 2010; Song, 2012; Zhang, 2015). The function of rural housing land has mainly been studied by constructing evaluation models or according to the proportion of land use structure (Dahms, 1995; Fang, 2014; Jiang et al., 2022). Understanding the nature of rural housing land as a means of production is the basis for a breakthrough in the next-stage reform (Alger, 1993; Cohen, 2001; Jerzy and Monika, 2010; Zhu et al., 2017; Zhang and Liu, 2021). The function of rural housing land presents the evolution of "simple living function to both production and living function to regional differentiation of production and living function" (Feng and Yang, 2015). Comparative analysis has examined the function spatial differences of rural housing land in counties at different stages of industrialization but they have not analyzed the differences within counties (Jiang et al., 2016). The evolution of functional differentiation is the main aim of social and institutional change, citizens' property rights consciousness, and farmers' interest (Cobb, 1984; Chaney and Sherwood, 2000; Wasilewski and Krukowski, 2004; Nepal, 2007; Domon, 2011; Xia, 2017), which in turn has an impact on the environment (Hansen and Brown, 2005; Lambin and Meyfroidt, 2010). The functional evolution of rural housing land is influenced by the external environment, internal subjects, and their characteristics. External institutions and economic environment are background factors, while the internal subjects (i.e., the characteristics of farmers) are the direct factors (Qu et al., 2012; Zhao et al., 2019). However, a micro-mechanism analysis from the perspective of the farmers is still lacking. The existing studies mostly employ traditional logistic regression, which can analyze the dominant factors but is difficult to use to measure the potential variables related to farmer willingness.

This study takes the Pinggu District of Beijing as the research area. It analyzes the temporal and spatial variation characteristics of rural housing land production function based on the survey data of typical households, constructs the theoretical analysis framework of planning behavior (TPB), and employs a structural equation model (SEM) to analyze the factors that influence the production function of rural housing land from the perspective of bottom-up peasant household behavior. This study aims to introduce the theory of rural space commercialization to discuss the optimization path of the production function space of rural housing land in the process of rural land planning. It also aims to promote the function structure adjustment of rural housing land and alleviate the problem of land for village development.

2 Theoretical underpinning

2.1 Land function

Land is a multifunctional complex problem and the concept of "production-living-ecological" space has been proposed from the perspective of land use function (De Groot, 2006; Liu et al., 2017). The land surface is commonly characterized by distinguishing different land cover types. The capacity of land to provide goods and services is referred to as land use functions, or ecosystem functions. The function division from the perspective of land use is economically oriented, which refers to people's arrangement, activities, input and acquisition of production, transformation and maintenance capacity for specific land use and cover types (Foley et al., 2005; Verburg et al., 2009). The function space of production, living, and ecology, covering biophysical processes, direct and indirect production, spiritual, cultural, leisure and aesthetic needs, and so on are the products of the synergistic coupling of natural system and social economic system (Li and Fang, 2016; Ghosh, 2021). Although the capacity of the land to provide goods and services is related to land cover, many other factors (including the spatial arrangement and temporal intensity of land use in the landscape) may be important. Therefore, land function change may not only result from local changes in land cover but can also be the result of changes in the broader context of the location without changes inland cover at the location itself (Verburg et al., 2009).

2.2 Production function identification of rural housing land

The rural courtyard is the center of the farmers' production and life, and was formed during the development of traditional farming and small-scale peasant economy. The function of rural housing land refers to the combination of the potency, property, efficacy in the farmers' land use process (Jiang et al., 2016). The deepening system reform of rural housing land is of great significance to the realization of the rural revitalization strategy. Understanding the nature of rural housing land as a means of production is the basis of the next step in promoting the breakthrough of rural housing land system reform. According to Marx, rural housing land provides laborers with a foothold and a place for activities. Rural housing land is a general means of labor and belongs to the means of production—without it, the labor process cannot be carried out (Zhang and Liu, 2021).

Rural housing land also has an important production function. For example, farmers can deposit grain, agricultural materials, and tools, do some farm work and production repair tools, develop a courtyard economy (e.g., the cultivation of grapes and other fruits, and development in the family sideline businesses such as raising pigs and chickens), and grow fruit and tea trees behind the house (Qu, 2020).

After the reform and opening up process, especially since the beginning of the twenty-first century, the rising demand of urban residents to return to nature, and travel to the countryside to relax and experience the interests of farming has led a large number of rural housing land in rural areas, especially in the suburbs of cities, to become an important place to operate "farmhouse entertainment" and develop the leisure tourism industry. China's rural housing land system reform since the 18th Congress has taken a substantial step forward and the central government has proposed the separation of ownership, qualification, and use rights of rural housing land. It has also explored the transfer system of use rights, and made every effort to revitalize idle rural housing land and idle agricultural houses. The series of policies that have been issued for this purpose is consistent with the property that rural housing land is a means of production (Zhang and Liu, 2021).

There is an intrinsic relationship between the function and land use structure of rural housing land. Furthermore, the evolution of internal land use structure is continuously adapting to the demand for function changes. The change of internal land use structure can be used to illustrate the function change of rural housing land. Drawing on the connotation of land use function (Liang et al., 2019), the production function of rural housing land can be divided into six subclasses based on the perspective of internal land use (Table 1).

2.3 The stages of the production function change of rural housing land and the commercialization of rural space

Production function socialization within village of rural housing land refers to the phenomenon that the production land of rural housing land has been gradually withdrawn and transferred to the village due to the changing livelihood characteristics of peasant households, thus reducing the production function of rural housing land and socializing in the rural areas by land planning. This process has developed gradually rather than overnight. The rural courtyard is the basic place for the farmers' production and life, and was formed by the development of Chinese traditional farming civilization and small-scale peasant economy. With the intensification of marketization, urbanization, and urban-rural population flow, the economic location of villages has changed and the social security system has been gradually improved. This has led many farmers to a non-agricultural livelihood and to the structural differentiation of family members. The property attributes of rural housing land are gradually highlighted, especially in those rural areas that have significant radiation effects from big cities.

According to studies on the commodification of rural space, one of the paths to realizing the commercialization of rural space

TABLE 1 The production function identification of rural housing land based on the perspective of internal land use.

1st level classes	subclasses	function description	internal land use
production function	planting (PPF)	engaged in fruit trees, vegetables, crops, and other cultivation	garden, fruits orchards
	breeding (PBF)	engaged in livestock and poultry breeding	animal house
	airing (PAF)	used for drying clothes, food crops, etc.	courtyard space
	productive storage (PPSF)	storage of agricultural products, agricultural machinery, goods, and other productive supplies	wing-room, a yard or gate
	rental (PRF)	the lease part of the land for profit	mainly wing rooms
	industry and commerce (PICF)	processing industry, barber, hotel, express service point, and other lands	mainly wing rooms

is the consumption of rural space by urban residents that is brought by reverse urbanization. In particular, rural tourism can attract people's imaginations (Wang, 2013). Under the influence of the commercialization of rural space, the requirements for value realization and value appreciation are becoming stronger (Wang, 2013). The farmer's quality of life has improved and the demand for improving the housing environment is increasingly strong.

According to the changing characteristics of the farmers' livelihood and the transformation process of utilization mode, the agricultural production land has first withdrawn from rural housing land and socializing the village, and has formed centralized and socialized functional spaces (e.g., breeding plants, plantations, and agricultural machinery stations) in the village. Later, non-agricultural production functions have also faced a similar path. Storefront houses, small processing industries, shops, barbershops, express delivery points, and other street layouts will be subject to unified planning and construction specifically for the development of industry and commerce, which forms a large-scale effect. The function of rural housing land is constantly differentiated, which shows a tendency of mixing to specialization. In addition, this rural housing land undertakes the residential function but not the production function thanks to the unified layout of rural land planning.

2.4 The evolution of the production function of rural housing land

Function change of rural housing land refers to the change of property rights, land use methods, and output capacity of rural housing land, which belongs to the change of recessive morphology of land use. This is an important reflection of land use morphological change, and is an important source of rural development and land use transformation (Dong et al., 2022).

The initial function state of rural housing land is social security. From the perspective of land use, there are two function transformation situations of rural housing land that are caused by land marginalization (Zhu F. K. et al., 2017). First, the economic benefits of agricultural production have been significantly lower than those of migrant workers in cities. Consequently, large numbers of the rural labor force have moved into towns looking for job opportunities as the farmers' opportunity costs rise. The number of part-time households and non-households in rural areas have gradually increased, which reduces the intensity of internal land use under the residential security function of rural housing. The utilization rate of rural housing land decreases or is even abandoned, thus forming the situation of lien function. Second, following the changing location conditions and land policy, the changing relationship between land supply and demand, and the asset properties of rural housing land gradually falling under the stimulation of the market, it is increasingly common to use rural housing land for industry and commerce, and the opportunity cost of self-occupation will increase. Thanks to the attraction of comparative income, some "rational farmers" will automatically change their livelihood mode and obtain an operating income from rural housing land, thus forming the production function and causing the change of the internal land use structure of rural housing land.

2.5 Planned behavior theory

In the theory of planned behavior (TPB), Ajzen added perceptual behavior control factors as prefactors affecting individual behavior intention based on rational behavior theory in 1985 and predicted an individual's actual actions for certain behaviors. The individual behavioral intention is jointly influenced by attitude, subjective norms, and perceived behavioral control, and there may be a related influence among these three factors. The individual's behavior is jointly determined by behavioral intention and perceived behavioral control (Ajzen, 1985; Zhong et al., 2013; Huang et al., 2014; Zhao et al., 2016).

The factors influencing attitudes in the theory of planned behavior can be divided into behavioral belief and results

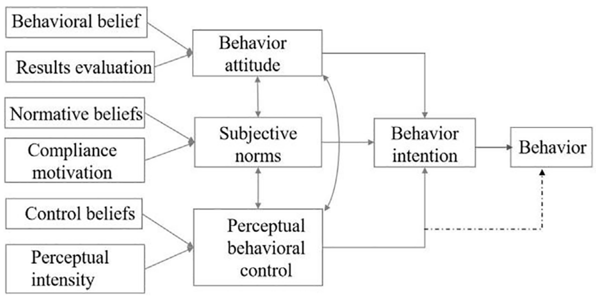

FIGURE 1
Conceptual model of the theory of planned behavior.

evaluation, which are used to measure the individual's recognition of behavior effects and the importance of these effects to individuals (Figure 1). Subjective norms can be divided into normative beliefs and compliance motivation. Perceptual behavioral control consists of two dimensions: control belief and perceptual intensity (Duan and Jiang, 2008). In recent years, the theoretical model of planned behavior has been widely studied and applied by social researchers to explain the characteristics of farmers' land use behavior, including farmland transfer and rural housing land withdrawal (Wan et al., 2017).

In this study, the production function intensity of rural housing land reflects the results of the farmers' land use behaviors. The influence of the farmers' attitudes, subjective norms, and perceived behavioral control on their intentions and behaviors is analyzed according to the conceptual model of TPB, which is the research hypothesis of this study.

1) The impact of behavior and attitude on production function intensity of rural housing land. Behavioral attitude refers to a person's positive or negative feelings toward the implementation of a certain behavior (i.e., an individual's conceptualized attitude toward the evaluation and definition of the determined behavior). Farmers mainly arrange all kinds of land in the rural housing land based on the actual demand of individuals and the family. When farmers think that production land can obtain more economic benefits, they will adjust the internal land use structure and thus enhance the function intensity.
2) The impact of subjective norms on the production function intensity of rural housing land. Subjective norms are the social pressures that are perceived by individuals to perform a particular behavior. A certain land use behavior of farmers will be affected by the family, neighbors, friends, and so on. The village collective also plays an important role in this behavior of the farmers.
3) The influence of perceptual behavioral control on the production function intensity of rural housing land. Perceptual behavioral control refers to the perceived difficulty of performing a particular behavior. Government policies have a guiding effect on household rural housing land use behavior. Household characteristics (e.g., age, occupation, education level, household size, household income, the proportion of non-agricultural income, rural housing land location, and other family conditions) may directly affect the farmers' perceptions of difficulty.

3 Materials and methods

3.1 Study area

Pinggu District is located in the Northeast of Beijing, between 40°02'~40°22′N and 116°55′21"~117°24′07″E. The area is located at the junction of Beijing, Tianjin, and Hebei provinces, with unique geographical conditions. It is an important node of the eastern development belt of Beijing and one of the important channels for the coordinated development of the Beijing-Tianjin-Hebei Urban Agglomeration (Zhou T. et al., 2018). It is 38.5 km from north to south and 40.25 km from east to west, covering a total area of 950 km^2, including 14 towns and two townships, and 275 administrative villages. The terrain is high in the north and low in the south, with the highest altitude of 1234 m (Figure 2).

According to the different geomorphic characteristics, the whole region can be divided into plain, mid-level mountains, and mountainous areas. Each area accounts for about 1/3 of the total area under the jurisdiction. In 2018, the number of rural households is 109,000, and the proportion of the agricultural population in the corresponding landform is 0.22:0.59:0.19. Mountain scenery is beautiful, forestry, and tourism is more developed; mid-levels are the fruit production base; the plain area is the economic and cultural center of the whole region, and is the main producing area of grain and vegetables. In 2020, the GDP of Pinggu District was 28.41 billion yuan, and the tertiary industrial structure was 4.5:25.1:70.4. In the process of urbanization and industrialization, as the peri-urban area of the Beijing metropolis, Pinggu District has undergone a remarkable social and economic transformation. From 2005 to 2015, the total rural population decreased from 228,000 to 185,000, a decrease of 18.86%, while the area of rural residential land decreased from 6,180.12 ha to 5,713.96 ha, a decrease of 9.12% (Liu and Li, 2017). There is a significant transition phenomenon both in the rural settlements and population in this area.

3.2 Data sources

The data sources in this study include geospatial data, social and economic data, and farmer survey data. The geospatial data came from the geospatial data cloud and the Pinggu Branch of Beijing Municipal Planning and Natural Resources Commission, the socioeconomic data came from socioeconomic statistical Yearbook

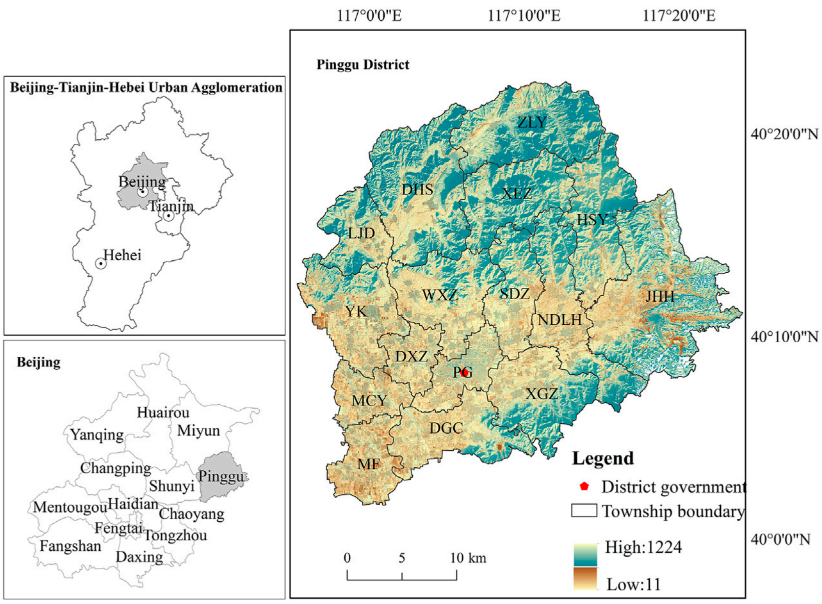

FIGURE 2
Location of Pinggu, Beijing, China (PG, DXZ, DGC, MCY, MF, WXZ, YK, LJY, DHS, XEZ, ZLY, HSY, SDZ, NDLH, XG-Z, and JHH are the name abbreviations of the townships in Pinggu, Daxingzhuang, Donggaocun, Machangy-ing, Mafang, Wangxinzhuang, Yukou, Liujiaying, Dahuashan, Xiongerzhai, Zhenluoying, Huangsongyu, Shandongzhuang, Nandulehe, Xiagezhuang, and Jinhaihu, respectively).

of the Pinggu District and rural economic management station, and the data of villages, farmers, and rural housing land came from survey interviews. A stratified random sampling method was adopted to select the interviewed farmers. The proportion of surveyed farmers in the corresponding topographic area was determined according to the proportion of agricultural households in the plain, mid-level, and mountainous areas (0.22:0.59:0.19).

Typical farmers were randomly selected from each layer in each topographic area according to the proportion of household rural housing land utilization obtained in the pre-survey. The sample points of peasant households have a better representation, reflect the utilization state of rural housing land in the whole region, and cover relatively comprehensive household housing characteristics. The questionnaire was established according to the theoretical model and a pre-survey was conducted for the specific situation of Pinggu District.

In 2005, the research group adopted participatory rural assessment (PRA) to carry out the field survey of farmers according to the differences of landform and location in Pinggu District. We employed a stratified sampling method in the town to select sample villages according to the level of geographical location and socioeconomic development. On the basis of the village survey in 2005, the research group went into the same typical villages in Pinggu District again in August and September of 2018, and selected the same number of household sites by sampling method as in 2005, and then conducted household survey in the form of semi-structured interviews. Through a questionnaire survey and interviews with village cadres and typical household farmers, relevant data of village, household and rural housing land were obtained, and the realistic performance of rural housing land function was observed and recognized.

Village research content: 1) characteristics of rural housing land in a village (i.e., the total scale of rural housing land, the proportion of farmers using rural housing land by self-occupancy, rental, idle, concurrently commercial and industrial operation, and multiple houses in one household); and 2) background conditions of the village (i.e., the distance between the village and the urban area, the geographical characteristics of the village, the economic characteristics of the village industry, the annual income, the total population, the proportion of non-agricultural population, the proportion of permanent population, and other population characteristics).

The contents of the household survey are as follows: 1) characteristics of household rural housing land (i.e., location, area, construction age, land use status, and construction cost of rural housing land); 2) household characteristics (i.e., total population, annual income, the proportion of non-agricultural income, and cultivated area); 3) the characteristics of the head of the household (i.e., the head of the household age, education level and occupation; Table 2); and 4) and the rural households' willingness to use the land for rural housing lands, their behavioral attitudes, and subjective norms.

Finally, approximately three typical villages were selected in each town, and 43 villages were effectively investigated,

TABLE 2 Measurement variable selection and descriptive statistics.

Latent variables	Serial number	Measured variable	Mean value	Standard deviation
Behavior attitude	BA1	I think the production function should be one of the important functions of rural housing land	3.68	0.91
	BA2	I think more productive land can improve the quality of living	4.63	0.97
	BA3	I think the separation of production function from rural housing land is beneficial to rural land planning	3.57	0.87
Subjective norms	SN1	The family thinks more land should be used for production	4.81	0.82
	SN2	Relatives and friends support the enhancement of productive land	4.25	0.79
	SN3	Village collectives encourage to engage in production activities on rural housing land	3.96	0.94
Perceptual behavioral control	PBC1	There are plenty of funds	3.79	0.83
	PBC2	Family population	4.78	1.71
	PBC3	Household non-farm income share	0.76	0.27
	PBC4	Household head education level	2.87	2.09
	PBC5	The householder age	55.22	12.51
	PBC6	Householder job type	3.56	2.93
Householder intend	HI	I think we should increase the area of production land in the rural housing land	4.16	0.85
Householder behavior decision	HB	The production function intensity of household rural housing land	9.34	5.98

Note: Household head education level: primary school and below = 1, junior middle school = 2, high school or special secondary school = 3, junior college or above = 4; type of work: fallow at home = 1, farmer = 2, part-time farming = 3, temporary worker = 4, individualization = 5, officer = 6.

covering 16 townships. Based on the characteristic of rural housing land, a typical survey method was adopted to select 15 households from each village to carry out the household survey to investigate the basic situation of farmers' families and the area and utilization of rural housing land, and a total of 613 households were effectively investigated, 132 in the plain area, 362 in the mid-level area and 119 in the mountainous area.

3.3 Methods

3.3.1 Production function calculation of rural housing land

From the perspective of internal land use, farmers conduct production and operation activities in the courtyards, and the production function can be measured by the proportion of profitable land area, such as planting land, breeding land, industrial and commercial land, and productive storage land, airing land and lease land.

$$F_P = \sum_{i=1}^{6} A_{Pi} \Big/ A, \tag{1}$$

where $F_P$is the production function intensity of rural housing land to illustrate the scale benefit, $A_{P\rangle}$ is the area of subclasses, and A is the total area of farmer's rural housing land (Eq. 1).

3.3.2 The production function evolution type judgment of rural housing land

The utilization rate of rural housing land is introduced to judge the utilization degree of the first case; namely, the residential security function of rural housing land:

$$\Delta EU = EU_i - EU_{i-1} \leq 0, \tag{2}$$

where EU_i is the utilization rate of rural housing land in a year i, EU_{i-1} is the utilization rate of rural housing land in year i-1, and $\triangle EU$ is the change of land utilization rate under the condition that the use or function of rural housing land remains unchanged.

The rural housing land own-occupancy rate is introduced to analyze the structural characteristics of internal land use under the change of rural housing land use or function:

$$\Delta L = L_i - L_{i-1} \leq 0, \tag{3}$$

where L_i is the owner-occupancy rate of rural housing land in a year i (the proportion of internal owner-occupancy area), L_{i-1} is the rural housing land owner-occupancy rate in year i-1, and $\triangle L$ is the change amount of rural housing land owner-occupancy rate under the change of use or function of rural housing land.

3.3.3 Factors influencing the production function of rural housing land under the characteristics of peasant households

(1) Model specification

The attitudes, subjective norms, and perceived behavioral control that affect farmers' land use behavior are latent variables, which are not convenient for direct observation. Structural equation modeling (SEM) is a statistical analysis method that can be used to establish, estimate, and test causal relationship models, which includes manifest variables—it also contains latent variables that cannot be directly observed (Hou et al., 2014).

The SEM was constructed based on the above assumptions. To test the causality in the model, an empirical test analysis was conducted on the model through a structural equation. The SEM with latent variables is composed of a measurement model and a structural model. Wherein, the measurement model expresses the relationship between indicators and potential variables, which is usually expressed as:

$$X = \Lambda x\xi + \delta,$$
$$Y = \Lambda y\eta + \varepsilon, \tag{4}$$

where $X$is the vector composed of exogenous observation variables, and ξrepresents exogenous latent variables; $Y$is the vector composed of endogenous observed variables, and ηrepresents endogenous latent variables; Λ§represents the factor load matrix of exogenous observation variables on exogenous latent variables, $\Lambda y$is the factor load matrix of endogenous observation variables on endogenous latent variables, and the two matrices represent the relationship between latent variables and observed variables. $\delta\, and\, \varepsilon$ are the residual matrices of the measurement model.

The relationship between latent variables is usually expressed as in the following structural equation:

$$\eta = \beta\eta + \Gamma\xi + \zeta, \tag{5}$$

where $\beta$is the mutual effect coefficient of endogenous latent variables; $\Gamma$is the effect coefficient of exogenous latent variables on endogenous latent variables; and ζrepresents the residual term of the structural equation, reflecting the unexplained part of η in the equation.

(2) Scale design

Based on the theoretical analysis framework of planned behavior, this study refers to relevant research results (Fang, 2014; Wan et al., 2017; Zhao et al., 2019) that are based on field research and interviews with farmers, and three latent variables. Their corresponding observable variables were designed and established from the perspectives of representativeness of driving factors and regional differences. Measurement methods adopt the Likert-scale scoring method, options are "completely disagree," "not agree," "not sure," "agree," and "completely agree," adopt positive assignment, respectively 1, 2, 3, 4, and 5 (including family population, the proportion of non-agricultural income, household culture degree, age and head of the household heads work types for actual values). The specific items are shown in Table 2.

4 Results and analysis

4.1 Temporal and spatial characteristics of rural housing land production function

4.1.1 Overall characteristic

According to the analysis, from 2005 to 2018, the production function decreased from 0.327 to 0.126 at a rate of 62%, and the coefficient of variation increased from 0.15 to 0.54 at a rate of 260%. This indicates that the overall production function decreased but the spatial heterogeneity increased. The productive storage function is the highest in 2005, followed by the function of airing and breeding. The total proportion was 95.4%. Airing was the highest among the production functions in 2018, followed by leasing, commercial, and industrial functions, which account for 80% of the total. From 2005 to 2018, the decrease in rural housing land production function in Pinggu District was mainly caused by the decrease of the productive storage, breeding and airing functions, while the rental, concurrently commercial and commercial functions, and planting functions showed an increasing trend (Figure 3).

The six sub-functions show a different change process, which reflects the change in regional industrial development and the farmers' livelihood. Specific analysis shows that the planting function was enhanced but the spatial heterogeneity was reduced, and the high-value area was transferred from the mid-level mountains to the mountainous areas and suburbs. This may be caused by the decrease in the area of cultivated land in the region and the farmers use the rural housing land to grow some vegetables for food. The breeding function and spatial heterogeneity decreased, and the high-value area shifted from mountainous areas and urban areas to mid-mountain areas.

On the one hand, this was due to the government's pollution control policies for livestock and poultry breeding, which limits breeding activities in rural housing land; on the other hand, it was also due to the upgrading of farmers' livelihood and their demand for a good living environment. The airing function decreased but the spatial heterogeneity increased, and the high-value area shifted from the mountainous area to the urban plain. This was mainly due to the decrease of the arable land area that was used by the farmers, the diversification of livelihood from single farming, coupled with the increasing number and area of housing. The productive storage function is reduced, the spatial heterogeneity is significant, and the high-value areas are still mountainous and mid-mountainous.

This is mainly due to the transformation of the mode of production, which led to a decrease in the proportion of agricultural production activities, and the changes in the

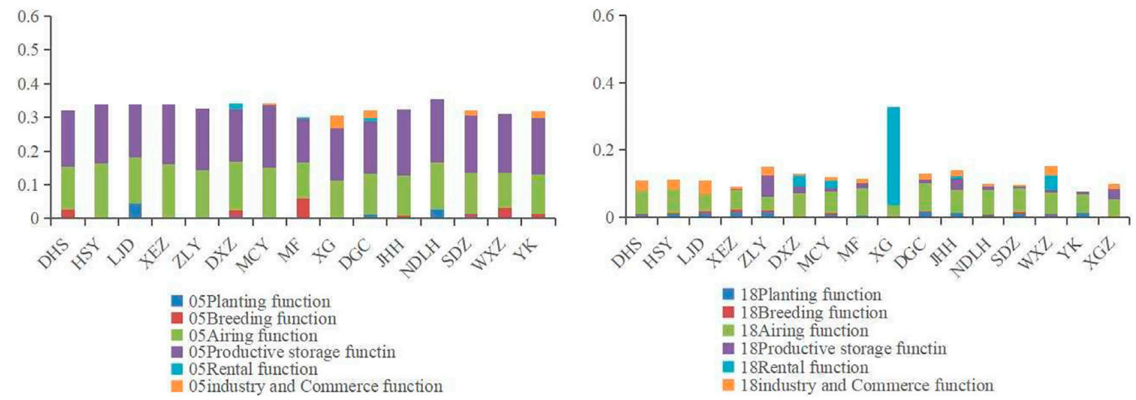

FIGURE 3
Internal sub-production functions of rural housing land in each town of Pinggu District.

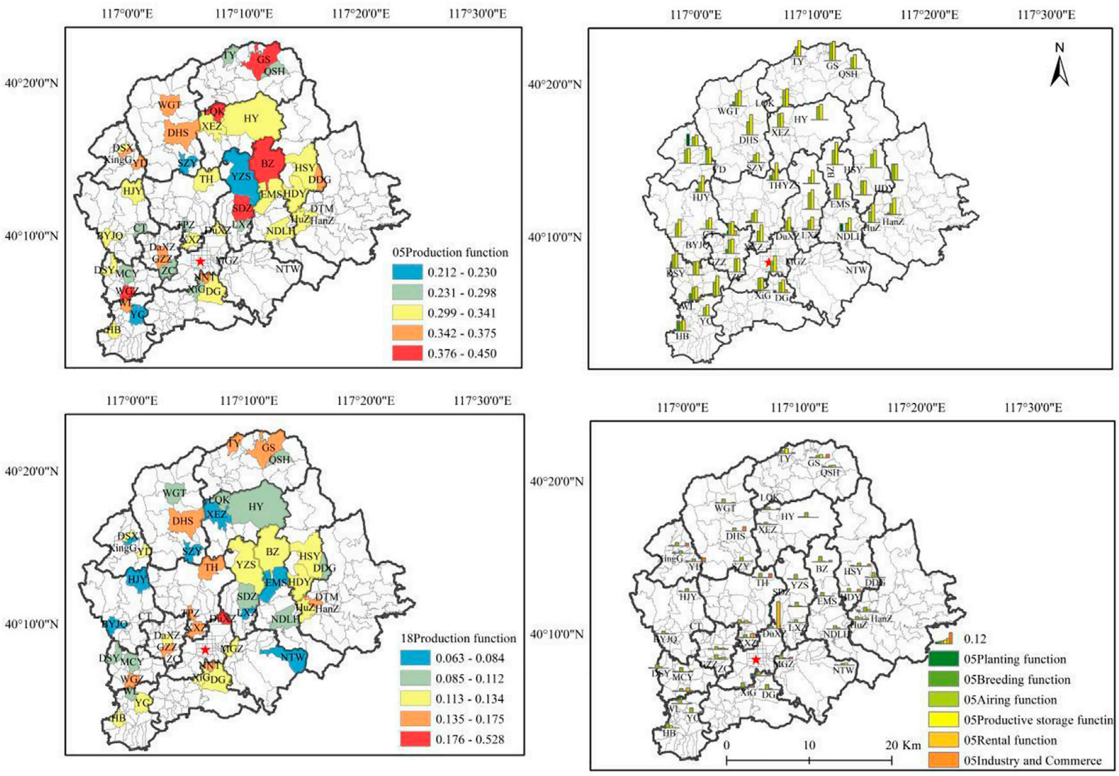

FIGURE 4
Production function and its sub-function space distribution.

economically developed plain areas are more drastic than those in the economically-backward mountainous areas. The leasing function was enhanced and the spatial heterogeneity increased. The high-value area is still near the urban area. This is mainly due to the rapid development of the suburban economy, which attracts the employment of migrants, resulting in frequent rental activities. The high-value area transferred from urban areas to mountainous areas. This was mainly due to the development of tourism in some villages in mountainous areas and the increase in rural entertainment.

Due to the superior location, the leasing and commercial functions of rural housing land appear and strengthen in the developed plain area, near the industrial park or in the mountain tourist area. In the less developed areas, farmers have lower income and are more dependent on agricultural production (e.g., planting, breeding, productive storage, and airing) in the housing, and the land is relatively large. In the developed plain suburbs, while the agricultural production function weakened, the non-agricultural production function (concurrently as industry and commerce, lease) strengthened (Figure 4). This is consistent with the results of Qu and Zhu (2015), but different from those of Song (2012). This study also found that the production function of individual household rural housing land may be very low in the inner suburbs of the plain and high in the mountainous area or the outer suburbs. Therefore, in addition to the spatial differences, the functional ratio of rural housing land may be related to the characteristics of the farmers, which requires further analysis.

4.1.2 Typical evolutionary process

The production function evolution types of rural housing land can be identified by the changes in the characteristics of the internal land use structure at the beginning and end of the study. From 2005 to 2018, the production function change process of rural housing land in Pinggu District can be divided into three typical types: T1, T2, and T3. There are 22 households in T1 type, accounting for 3.59% of the total number of surveyed households. The utilization rate of the rural housing land improved; that is, $\triangle EU \geq 0$. There are only two households in the T2 type, accounting for 0.33% of the total number of surveyed households. In this type, the rural housing land is generally used for industrial and commercial activities from the idle and abandoned state. Therefore, $\triangle EU = EUi > 0$, but the proportion of the internal self-occupied area is still 0; that is, $Li=Li\text{-}1 = \triangle L = 0$. There are 42 households in T3 type, accounting for 6.85% of the total number of surveyed households. Both the rural housing land utilization rate and the owner-occupancy rate may increase or decrease, but the utilization rate is not 0 and the owner-occupancy rate is not 100%.

From the perspective of topographic differences, the proportion of T3 type in the plain area is 10.61%, which higher than the regional average and other topographic areas. The proportion of T1 type also reaches 4.55%, which is mainly distributed in Daxingzhuang, Duxinzhuang, and Machangying. From 2005 to 2018, the proportion of rural housing land production function showed an upward trend, increasing by 5.3%. The proportion of T1 type was the lowest among the topographical areas in the mid-level mountains, mainly distributed in Taihou village, Donggao village, and Xiaoxinzhai village, while the proportion of T2 type was 0.

From 2005 to 2018, the proportion of production functional rural housing land in the mid-levels increased by 2.48%. The proportions of T1 and T2 in mountainous areas were 5.88 and 0.85%, respectively, which were the largest among all topographic areas. T1 is mainly distributed in Heidouyu, Dahuashan, and Guancun, while T2 is located in Huayu village, and the proportions of T3 were the smallest among all topographic areas. The proportion of production functional rural housing land in mountainous areas increased by 5.89% (Table 3).

The main feature of the T1 type is that rural housing land produces a production function under the original residential security function. From the perspective of internal land use, it is reflected in the proportion reduction of the internal self-occupied area based on the improvement of the utilization rate of the rural housing land. The utilization rate of rural housing land increased by 6.7%, and the proportion of the internal self-occupied area decreased by 42.8% (Figure 5).

The inousing land changed, and the intensity of productive storage, lease, and industrial and commercial land increased by 0.9, 32.4, and 10.4%, respectively. The location conditions of such rural housing land are good, the labor force of peasant households is sufficient, and the property of rural housing land has the objective conditions to realize. The types of land used in rural housing land are rich and the conversion between the types of land used occurs, which is mainly reflected in the conversion of land space originally used for living and living storage to goods storage, house rental, and industrial and commercial operation for operating profit. The internal living land space is compressed and profitable land space gradually manifests. The T1-type marked land inside the rural housing land is used for both industry and commerce, which is rented and represented by a farmhouse.

The main feature of the T2 type is that the rural housing land is revitalized from the idle and abandoned state to stimulate the realization of its asset value, thus forming the profit function. From the perspective of internal land use, the rural housing land utilization rate increases from 0 to a value between 0 and 1, but the proportion of self-occupied areas generally remains at 0. According to the analysis of the change of the internal land use structure of the rural housing land in Pinggu District, under this type, the utilization rate of the rural housing land increased by 45.4%, while the intensity of rental land increased by 45.4%. The general location conditions of this type of rural housing land are superior and the overall construction quality is good. In addition, the internal land type is rich, which has the conditions for direct utilization. This is mainly reflected in land types leased out and used by the tenants for living or engaging in goods storage, industrial and commercial operation, and other activities, and the profitable land space gradually becomes obvious. Therefore, it can be concluded from this analysis that T2-type homelands in Pinggu District are mainly distributed in Yingcheng village, Xigao village, Magezhuang village, and other villages in the

TABLE 3 Basic information on conversion type of rural housing land production function.

	T1	T2	T3
Criteria	$\triangle EU \geq 0$, $\triangle L < 0$	$\triangle EU > 0$, $Li=Li\text{-}1 = \triangle L = 0$	$EU \neq 0$, $L \neq 100\%$
The amount and proportion of changes in plain areas	6, 4.55%	1, 0.75%	14, 10.61%
The number and proportion of changes in mid-levels	9, 2.48%	—	22, 6.08%
The number and proportion of changes in mountainous areas	7, 5.88%	1, 0.85%	6, 5.04%
The number and proportion of changes in the whole district	22, 3.59%	2, 0.33%	42, 6.85%

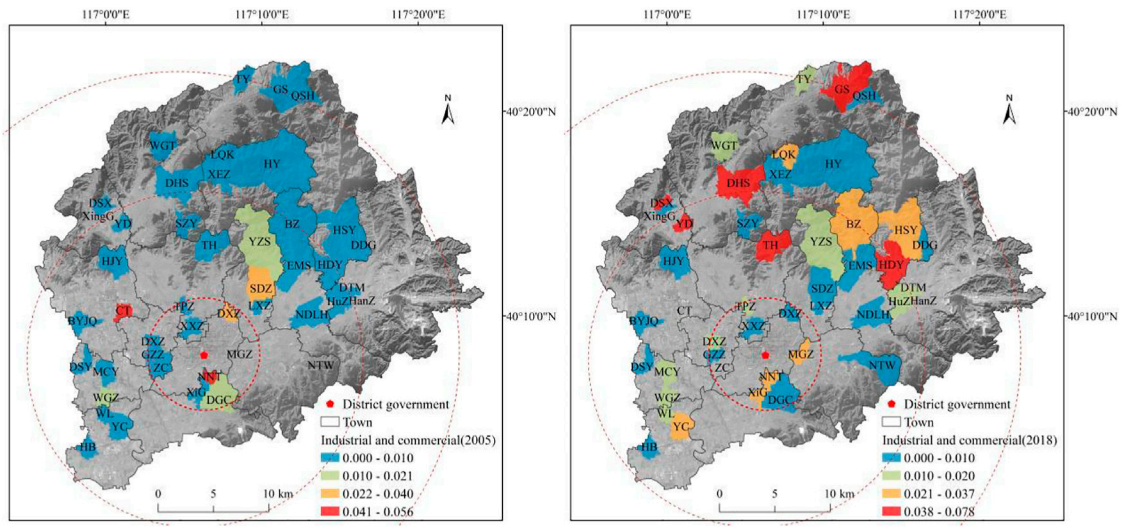

FIGURE 5
The change of the signalized land class inside the rural housing land under the type T1.

TABLE 4 The change of the signalized land class inside the rural housing land under the type T3.

Type of land use		In 2005		In 2018		△EU, △L (%)
		Area (m^2)	Proportion (%)	Area (m^2)	Proportion (%)	
Utility room	Productive storage land	16	7.13	6	2.50	$\triangle EU = 4.52$, $\triangle L = -6.77$
Facility	Dry land	30	13.37	9	3.74	
Land for planting		1.6	0.72	2.8	1.17	
Land for farming		8	3.57	3	1.25	
Lease the land		2	0.89	30	12.48	
Industrial and commercial land		3	1.34	25	10.40	

suburbs of the urban area. The internal marked land type is the emergence and enhancement of leased land.

The main characteristic of the T3 type is that the functional type attribute of rural housing land keeps the profit function unchanged. From the perspective of internal land use, it reflects that the utilization rate of rural housing land and the proportion of owner-occupied area may fluctuate, but the utilization rate is not 0 and the proportion of the owner-occupied area is less than 100%. According to the change analysis of land use structure inside the rural housing land in Pinggu District, under this type, the utilization rate of rural housing land increased by 4.52% and the intensity of planting land increased by 75%, which may be

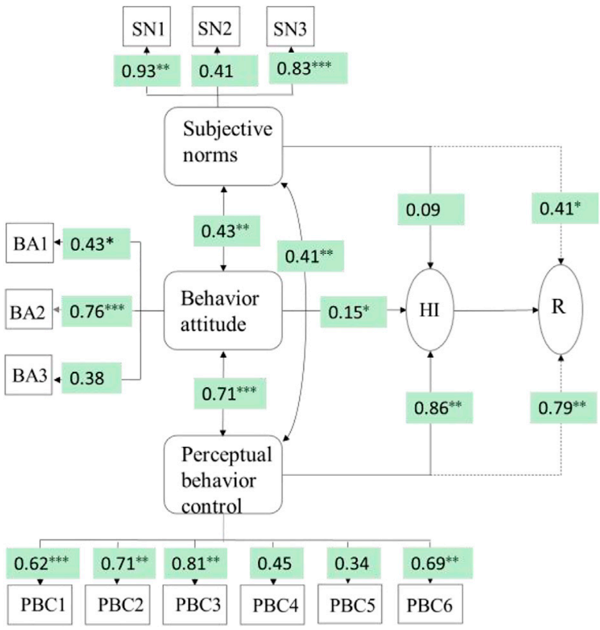

FIGURE 6
Measure the standard factor load of the model and the path coefficient of the structural model. (***, ** and * significant at the level of 1, 5, and 10%, respectively; χ^2/df = 1.021 (is the chi-square test of goodness of fit, and its value ranges from 1 to 3), RMSEA = 0.025 (root mean square of the approximation error, the value range is < 0.08), GFI = 0.907 (is the goodness of fit index, and the value range is > 0.9), CFI = 0.974 (comparison fitting index, value range >0.9), IFI = 0.912 (incremental fitting index, value range >0.9).

caused by the fall of the area of cultivated land in the region, and the farmers used the rural housing land to grow some vegetables for food (Table 4).

The intensity of land used for breeding decreased by 62.5%. On the one hand, this was due to the government's pollution control policies on livestock and poultry breeding, which restricted breeding activities in rural housing land. On the other hand, it was due to the upgrading of farmers' livelihood and their demand for a good living environment. Airing land use intensity fell by 70% and productive storage land intensity fell by 62.5%. This was mainly due to the change from single farming to diversification. In addition, it was due to the squeeze caused by the increase in the number and area of housing, while the transformation of the mode of production caused the reduction of the proportion of agricultural production activities. The productive storage of farmers mainly consists of farm tools and grain storage, and the change of economically developed plain area is more severe than that of economically-backward mountainous area. The intensity of the land used for leasing increased by 15 times, while the intensity of the land used for industry and commerce increased more than 8 times. This is mainly due to the rapid development of the suburban economy, which attracts the employment of the migrant population, resulting in frequent rental activities, the development of tourism in some villages in the mountainous areas, and the increase in rural entertainment.

4.2 Influencing factors and change mechanism of rural housing land production function

4.2.1 Influencing factors of rural housing land production function

Many factors affect land use structure, such as village location, village environment, and peasant household characteristics. As the actual users of rural housing land, farmers play a direct role in the use and function change of rural housing land (Yang et al., 2019; Kong et al., 2021). Therefore, this section focuses on the impact of household behavior characteristics on the production function of rural housing land. To quantitatively analyze the relationship between them, this chapter constructs a SEM based on TPB.

(1) Model test

Reliability refers to the dependability, stability, and consistency of scale test results. The internal consistency coefficient Cronbach's α was used for the reliability test.

$$\alpha = \frac{k}{k-1}\left[1 - \frac{\sum_{i=1}^{k} s_i^2}{s_x^2}\right], \tag{6}$$

where K is the total number of questions tested, s_x is the variance of the total number of tests, and s_i is the variance of the value of question i. SPSS19.0 software was used to analyze the reliability of observable variables of behavioral attitude, subjective norms, and perceived behavioral control. The results showed that Cronbach's α value was between 0.765 and 0.886, and the overall α value of the questionnaire was 0.914. Therefore, the data used in this study have good internal consistency.

Validity refers to the accuracy and reliability of the questionnaire, which can generally be analyzed from two aspects: convergence validity and discriminant validity. The KMO value of the analyzed data was 0.742, and the Bartlett sphericity test value was less than 0.001, which indicates that the sample data had the condition of factor analysis. In this study, principal component analysis (PCA) was used to perform exploratory factor analysis on the data. The convergence validity and discriminant validity of the observed variables were judged by the load value. The results show that the standard factor load of each observation variable is above 0.5, which indicates that the structure validity of each potential variable is good.

(2) Identifying the influencing factors

According to the analytical framework of TPB in the final model figure, path coefficients of behavioral attitude, subjective norms and perceived behavior control, and load coefficients of observation variables were obtained (Figure 6).

1) Behavior and attitude. Figure 6 shows that behavioral attitude has a positive impact on farmers' willingness, with a direct effect of 0.15. This indicates that the more positive the behavioral attitude of farmers is, the more significant their willingness to increase the production land will be. Among the three observed variables, the load coefficient of BA2 is 0.76, which is significantly greater than the other two variables, while BA3 is not significant. This indicates that in their behavior and attitude, farmers pay more attention to the improvement of living quality than the efficiency of rural housing land use and village planning. Behavior attitude has no significant effect on the land use suitability index. The analysis shows that the behavior and attitude may only affect the willingness of farmers, and there is no direct effect on whether or not to increase the production function of land.

2) Subjective norms. The social group pressure that farmers feel when deciding whether to increase the productive land still plays a certain role. As can be seen from Figure 6, the load coefficient of subjective norms' impact on farmers' willingness is 0.09, while the impact on the intensity of rural housing land production land is 0.41. This shows that social groups have little influence on the farmers' will but have more influence on their behavior. According to the specific analysis, the load coefficients of SN1 and SN3 are higher than 0.8, while the influence of SN2 is not significant. This reflects that family members play a greater role in the model norms, while relatives and friends have no significant influence. The prescriptive norms brought by the village collective have a great influence on farmers. This reflects the farmers' obedience to the government's advocacy behavior, and also indicates that the government's role of the village collective, as the owner of the rural housing land, plays a leading role in the change of the intensity of production land in the rural housing land.

3) Perceptual behavioral control. When farmers perceive that they have insufficient capacity and resources to implement the behavior of increasing production function land for rural housing land, their behavior will be hindered. The load coefficient of perceived behavioral control on farmers' willingness was 0.86, and the load coefficient of perceived behavioral control on farmers' behavior was 0.79. This shows that perceived behavioral control not only has an impact on intention but also has a direct effect on behavior. It can be seen from Figure 6 that PBC1, PBC2, PBC3, and PBC6 show significant effects, in which the load coefficient of PBC3 reaches 0.81, which is larger than other observed variables. PBC4 and PBC5 had no significant effect. This indicates that the household size, economic conditions, income structure, and other factors have a significant impact on the changed behavior of rural housing land production function intensity, while the characteristics of household owners have no significant effect.

4) It can also be seen from Figure 6 that behavioral attitude, subjective norms, and perceived behavioral control interact. Among them, the interaction force between behavioral attitude and perceptual behavioral control was larger, and the load coefficient was 0.71. This indicates that farmers with a positive attitude toward the increase of functional land for rural housing land are generally more willing to create more conditions for it, and thus have relatively high perceptual and behavioral control in the process of internal function change. In contrast, farmers with higher perceptual behavioral control have a stronger pursuit of a comfortable living environment and have a stronger behavioral attitude toward the increase of productive land on rural housing land. Meanwhile, the load coefficients between subjective norms and behavioral attitude and perceived behavioral control are 0.43 and 0.41, respectively, which shows that there is a certain mutual influence.

4.2.2 The change mechanism of rural housing land production function

Access to adequate housing is a basic human right and the provision of facilities essential for safety, comfort, health, and nutrition is considered to be central to human welfare. With the integrated development of urban and rural areas, the production function of rural housing land also changes to varying degrees. Relevant policies, village positioning, family conditions, and other factors affect the farmers' land use behavior. As micro-independent decision-making individuals, farmers have the characteristics of rational economic people. The occurrence of their idea-decision-behavior is a complex process, which plays a core role in the change of land use structure inside rural housing land.

1) The rationalization of the farmers' behavior decisions is the direct influencing factor of the internal land use change of rural housing land. Farmers have certain characteristics of "rational smallholder farmers," and their rational behavioral decisions can constantly adjust the use of rural housing land, driving its change in the direction of maximum land use efficiency, and efficient and reasonable land use structure. At the same time, affected by individual cognitive ability, family capital, and their selfishness and narrowness, the decision-making behavior of farmers is not completely rational. Unreasonable behavior may cause the inefficient

phenomenon, such as large courtyards and disorderly parking. To effectively guide and correct farmers' irrational behavior, we should further exert the prescriptive and normative role of the village collective.

2) Peasant household differentiation fundamentally affects the formation and change of rural housing land production function. With the rapid development of urbanization, the flow of urban and rural populations is more frequent. Depending on the difference in the family size, education level and other resource endowments of farmers, the livelihood mode of farmers has changed to different degrees, which further increases the existing differences among farmers. The differentiation of peasant households leads to the diversified characteristics of their understanding, demand, and choice of rural housing land, thus forming the diversified use of rural housing land with different functions and characteristics.
3) The macroeconomic, social, and institutional environment often takes farmers as the carrier and indirectly affects the internal land use change process of rural housing land. Regional land policy, village environment, and location characteristics are the external factors for the change in rural housing land use. The rapid development of society and economy makes the types of farmers increasingly abundant and the differentiation of farmers more complex, which also leads to the strengthening of the diversity and difference in rural housing land use. At present, the coordinated development of urban and rural areas continues to be promoted, various factors flow to rural areas, exchanges between urban and rural areas are frequent, institutional and policy barriers to rural development are gradually broken, and farmers' various land use behaviors show a diversified trend. However, the land use structure of residential land should urgently be reconstructed under the requirements of the rural revitalization strategy.

4.2.3 Explanation of production function changes of rural housing land from the perspective of bid rent and the theory of rent dissipation

Based on location theory, Wilhelm Alonso put forward a theoretical model of bid rent. The difference in land use in rural housing land comes from the difference in regional land prices and the difference in land rent payment ability of different economic activities. Restricted by property rights arrangement, rural housing land cannot be freely transferred and traded, so it is difficult to form a specific price. However, with the change in village economy and location, the asset property of rural housing land becomes increasingly obvious. It is quite common for farmers to use their rural housing land for industrial and commercial activities. Rural housing land occupies a large proportion of rural collective construction land, and the function change of rural housing land has an important impact on the overall land use form of rural areas (Zhu and Zhang, 2016).

Rural residents apply for rural housing land as collective members and allocate it for free. The initial allocation is based on welfare and security purposes. Theoretically, this is a completely planned allocation and is not affected by the market. However, as the spillover of urban residential function to the suburbs and urban property prices soar, the study area of house-sites in the countryside, and industrial and commercial activities and rent phenomenon is widespread, the market is increasingly obvious, and the influence of land asset attributes gradually appear. This can be seen in the following ways: the houses inside the rural housing land other than self-occupancy are rented out or engaged in industrial and commercial operations by themselves. Among them, rental for residential use, and mixed commercial and residential income along the street have little impact on the farmers' quality of life and are the main regional manifestation. However, the residential sites rented as industrial factories or warehouses significantly affect the farmers' quality of life, accounting for a small proportion, generally occurring in "one family with multiple houses" or in the idle residential sites of farmers living in cities. It can be seen that the expression form of rural housing land asset attribute is affected by village, location of rural housing land, and rural housing land ownership rate.

The theory of bid rent studies the distribution of land resources in different locations from the demand perspective of economic activities for land resources. Its premise is that land is homogeneous and can be bought and sold freely, and (actually) the property rights of rural housing land are separated; that is, collective ownership belongs to the village, and the use right for farmers, affected by the property rights system has the effect of rent dissipation, in entering the market and inevitable problems in the circulation. Its layout and construction are restricted by many factors. Therefore, the study of functional spatial differentiation of rural housing must take into account the role of property rights and institutions in the allocation of rural housing land.

According to Zhang Wuchang's two propositions about the dissipation of rent value, the difference between rural housing land and urban land property right arrangement leads to the restriction of the use and transaction of the rural housing land, and the value of rural housing land will inevitably decline. As the actual users of rural housing land, the farmers will not helplessly look at land rent dissipation, see their economic interests damaged and indifferent, but will take appropriate action to minimize the degree of dissipation. The function transformation of rural housing land from security to an asset is the result of the actions that farmers can take to reduce the dissipation of rural housing land rent under the constraints of the existing system. House rental, small family workshops, and farmhouse management are all typical methods of intensive use of rural housing land and reduce the rent dissipation of rural housing land. At the same time, under the same institutional arrangement, the opportunity cost of farmers in villages with different location conditions to maintain the original residential security function of rural housing land is different, which will cause regional heterogeneity in the dissipation degree of rural housing land rent.

5 Discussion

5.1.1 Rural housing land production function

During the study period, the decrease in agricultural production activities resulted in a decrease of land space for productive storage, breeding, and airing, while the land for planting was preserved and strengthened because of its agricultural culture and ecological value. At the same time, the change of livelihood mode makes the amount of leased and commercial land rise. The rapid economic development of some areas in the suburbs (such as Pinggu Town) has attracted the employment of migrants, resulting in frequent rental activities. Part of the mid-level area has convenient transportation and beautiful scenery, which promotes the development of village tourism and family entertainment.

The production function of rural housing land tends to be imbalanced. It fosters the spatial evolution from multi-use to single-use land, and the dominant development from balanced to single-use land type. With the continuous improvement the economy and social development, when the traditional profit land such as planting and breeding is no longer a necessary type of rural housing land, the area standard of rural housing land can be moderately reduced to strengthen the intensive use of rural housing land. Previously, scholars believed that farmers in economically developed areas have higher income, and the production function of rural housing land is weak, so the area of land use should be less (Song, 2012). However, this study found that the agricultural production function (e.g., the subclass function of planting, breeding, and airing) in economically developed areas is weakening, while the production function strengthens thanks to the appearance and enhancement of non-agricultural production function (e.g., the subclass function of industrial, commercial, and rental use).

5.1.2 The embodiment of land use in the production function socialization of rural housing land

From the historical change and the trend of the farmers' independent choice, the production function can be separated from rural housing land and socialized within the village through rural land planning. The function of space separation and socialization of rural housing land is an important basis for the commercialization of rural spaces and provides the source of land use (Figure 8). The commodification of rural space is a process of re-resourcing in rural areas, which emphasizes the role of modern rural space as material production is declining, while the role of consumption space as non-material products is gradually increasing. The commercialization of rural space is one of the most important factors to promote rural change and prevent rural economic decline (Wang, 2013). It emphasizes the role of capital and power in rural change, which is the theoretical advantage of an international Frontier perspective of rural geography.

The commercialization of rural space pays more attention to the non-material goods that are attached to concrete resources. Immaterial "goods" created by material entities can be consumed repeatedly and consumers pay for and gain access to immaterial goods, rather than ownership. According to studies on the commodification of rural space, one of the paths to realizing the commercialization of rural space is the consumption of rural space by urban residents brought by reverse urbanization. In particular, rural tourism can attract people's imaginations (Wang, 2013).

5.1.3 The production function socialization within village of rural housing land is an important prerequisite to realizing the commercialization of rural space

Rural environment, population, rural housing land, and its ownership status are the foundation of rural land development and planning (Tusting et al., 2019). In 2019, the CPC Central Committee and The State Council issued "Several Opinions on Establishing and Supervising the Implementation of the Territorial Space Planning System," which required the formulation of practical village planning integrating multiple plans. Beijing Municipal Commission of Planning and Natural Resources promulgated the "Revised Guidelines for Village Planning in Beijing." In the same year, the General Office of Land and Resources issued the "Notice of the General Office of Natural Resources on Strengthening Village Planning and Promoting Rural Revitalization," stipulating that by the end of 2020, village layout at the county level should be complete under the national spatial planning. The implementation of these plans has significantly and gradually affected the state of rural land use in the region (Ma et al., 2022; Yao et al., 2022).

According to the data of the third national land survey, the area of rural housing land in Pinggu District is 4,682.17 hm^2, which is mainly distributed in the central and southwest mid-level mountains and plains. In the village, the agricultural land for facilities is 587.80 hm^2, and the pit and pond for breeding are 550.18 hm^2, which reflects the centralized function of agricultural land in the village. There are 1,335.85 hm^2 of industrial land, 1,043.37 hm^2 of facility land for commercial service, and 720.78 hm^2 of logistics and storage land in the village. This indicates that the industrial and commercial service land functions in the village have appeared to agglomerate. From a relatively regular distribution pattern, a certain unified layout and arrangement of land use have been made. In the village, the

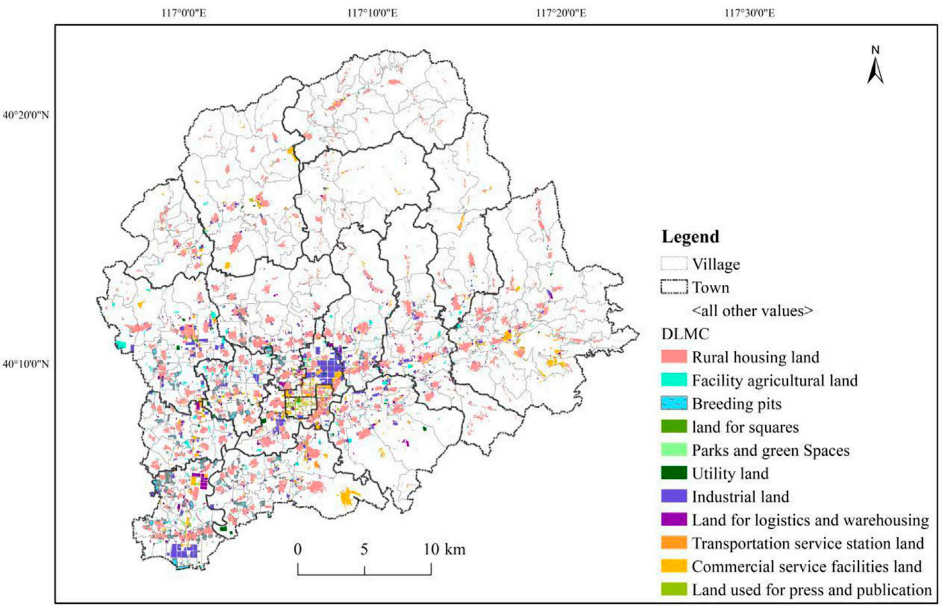

FIGURE 7
Present rural land use in the third national land survey in Pinggu District.

land for public facilities is 182.53 hm^2, the land for the traffic service station is 114.10 hm^2, and the land for the square is 25.52 hm^2. To some extent, this kind of land for public service has emerged and become an essential part of the village (Figure 7).

The analysis shows that the land for industry, commercial services, and some public facilities in villages of Pinggu District has gradually separated from the rural housing land, and has become centralized and socialized in villages. The layout of village land is changing toward zoning, classification, and is moving in a more reasonable direction. The development of village collective industries should conform to the functions and industrial development direction of the capital; highlight the industrial characteristics; rely on the resources of rural green mountains, rural scenery, and local culture; and promote the integrated development of primary, secondary, and tertiary industries under the principle of suitability. Based on sorting out the current situation of the collective industry and investigating the development intention of villagers, the types, goals, and paths of collective industry development should be proposed in combination with the requirements of superior planning (Serra et al., 2014; Qu et al., 2022).

On the premise of ecological protection and according to different location conditions and resource endowments, the characteristic industries of "suitable for agriculture and suitable for a green" should be developed in the villages with enhanced features and improved regulation located in the exurb plain and mountainous areas. In addition, leisure agriculture and rural tourism should be guided to develop. Based on sorting out the current situation of the collective industry and investigating the development intention of villagers, the development path of the collective industry before urbanization or relocation should be clarified in combination with the relevant arrangements for future development and construction of superior planning.

The distribution of land for collective industrial use in villages should meet the requirements of "two lines and three zones," and should encourage appropriate concentration by industrial characteristics through the overall planning and rational distribution of townships. Priority should be given to the use of existing industrial land for construction, and diversified forms of appropriate scale operation should be developed to achieve an organic link between the development of small farmers and modern industries. This will not only regulate the land but also meet the function demands of farmers and save land space. In the future, institutional innovation in rural housing land should be implemented based on region and type (Zhang et al., 2019). Rural housing land with strong production capacity in the plain can expand use rights, enter the market subject to rural land planning and land use control, and have the same right as state-owned residential land, allowing rent, sale, and mortgage and thus internalizing external profit (Ghosh, 2021).

5.1.4 Policy implications for rural land planning

General Secretary Xi Jinping pointed out in his report to the 19th National Congress of the Communist Party of China that we will implement the rural revitalization strategy and deepen reform of the rural land system. Land is the core element of urban and rural development, and the diversification and compounding of land use functions is an important way to implement the rural revitalization strategy. Diversified use of rural housing land and effective activation of "sleeping" land assets are new driving forces for accelerating agricultural and rural modernization, and promoting integrated development of urban and rural areas. As the largest proportion of collective construction land, the system reform of rural housing land involves a huge number of farmers and is also an important link to rural revitalization.

Since 2003, the "No. 1 Document" for 19 consecutive years has focused on "agriculture, rural areas, and farmers." In 2018, the "No. 1 Central Document" laid out the reform idea of "separation of the three rights of rural housing land" in principle within the strategic framework of rural revitalization, which indicates the important significance of rural housing land system reform for rural revitalization. The first document of the CPC Central Committee in 2022 stressed the importance of steadily and prudently advancing the pilot reform of the rural housing land system and supporting the development of country inn and agritainment that are directly or jointly operated by farmers. In the process of urbanization in China, the functional transformation of rural housing land is not smooth, the value is not balanced, and the withdrawal mechanism is missing. This forms the paradox of the decrease in the rural population and the increase of rural housing land, and it is behind the conflict between the rural housing land system and the functional change of rural housing land, creating the dilemma between the government and farmers (Lv et al., 2021).

Under the guidance of industrial parks and urban industrial development, the degree of public service facilities in villages should be improved, attention should be given to maintaining and repairing the rural ecological environment, renovation of the living environment should be carried out, and the quality of life should be improved. At the same time, the disorderly expansion of rural housing land should be controlled, the social security function of rural housing land should be strengthened, and better basic conditions for the development of the production function should be created. Among them, for some villages who are close to urban areas and have a strong desire for urbanization, farmers can be settled by building centralized living communities with relatively complete basic conditions (Guo et al., 2020). The original rural housing land or house yard can be reclaimed for farming, planting vegetables or trees, or developing secondary and tertiary industries. Some of the rural housing land with protection value or utilization value can be retained. At the same time, as the production function of this area is relatively strengthened, the residential sites that were previously close to roads or concurrently used for industry and commerce can be directly demarcated as industrial development land and not demolished. The land will be centrally planned along the streets. In this way, the functional demand can be guaranteed, the farmer's quality of life can be improved, and the intensive use of rural housing land can be realized (Figure 8).

New city fringe areas and the center towns surrounding mid-levels district can lead to the construction of the new urbanization, put the village and town planning and construction together, take advantage of the town's population, improve industrial land utilization rate, reduce the proportion of idle land, and it can also relieve some farmers employment and avoid the contradiction of phase separation. The state should also accelerate the construction of the rural housing land system, especially the withdrawal mechanism, strengthen the social security system of rural villagers, and promote the stable withdrawal of farmers' rural housing land. Efforts to improve the living environment in villages should be made on an equal footing with those in cities and towns. The unused rural housing land can be reclaimed as farmland or built into public facilities, such as park green spaces, elderly houses, and parking lots, according to their different locations in the village.

In remote mountainous areas far away from new towns and central towns, the focus of rural land planning should be to optimize the living conditions of the farmers and improve the housing security function of rural housing land through renovation policies of dilapidated houses. It is necessary to strengthen the construction of auxiliary land for agricultural production in villages and guide the withdrawal of some functional structures in rural housing land according to the actual livelihood mode of rural households, promote the separation of agricultural production and living space, adjust and optimize the pattern of villages and rural housing land use, and improve functional specialization and rationalization of utility structure.

Typical rural villages with non-agricultural industry development should speed up rural land planning and construction and establish a unified village brand, such as the regional characteristics of the farmhouse management model. Furthermore, the regional landscape and cultural differences are fully reflected to make the production function of rural housing land sustainable. Because most of these villages are located in mountainous and mid-level areas, traffic conditions and local infrastructure conditions play an important role in attracting tourists and benefiting rural housing land. Therefore, a sound system of public service facilities should be established, including transportation, supermarkets, express delivery points, medical clinics, and other facilities. In addition, the rural social security system should be improved, such as providing an old-age pension and assistance, refine the policy of "mortgage of two rights," and guide the transformation of rural housing land into a profit function.

The rural housing land management system should be improved and its prescriptive norms of the village collective should be optimized. The management system of rural housing land should be placed based on guaranteeing farmers' rights, fairness, and social stability to realize the reasonable and effective use of resources. To improve the system of rural housing land, we must introduce the concept of public participation, allow farmers to appeal for their interests, and let farmers themselves become the best

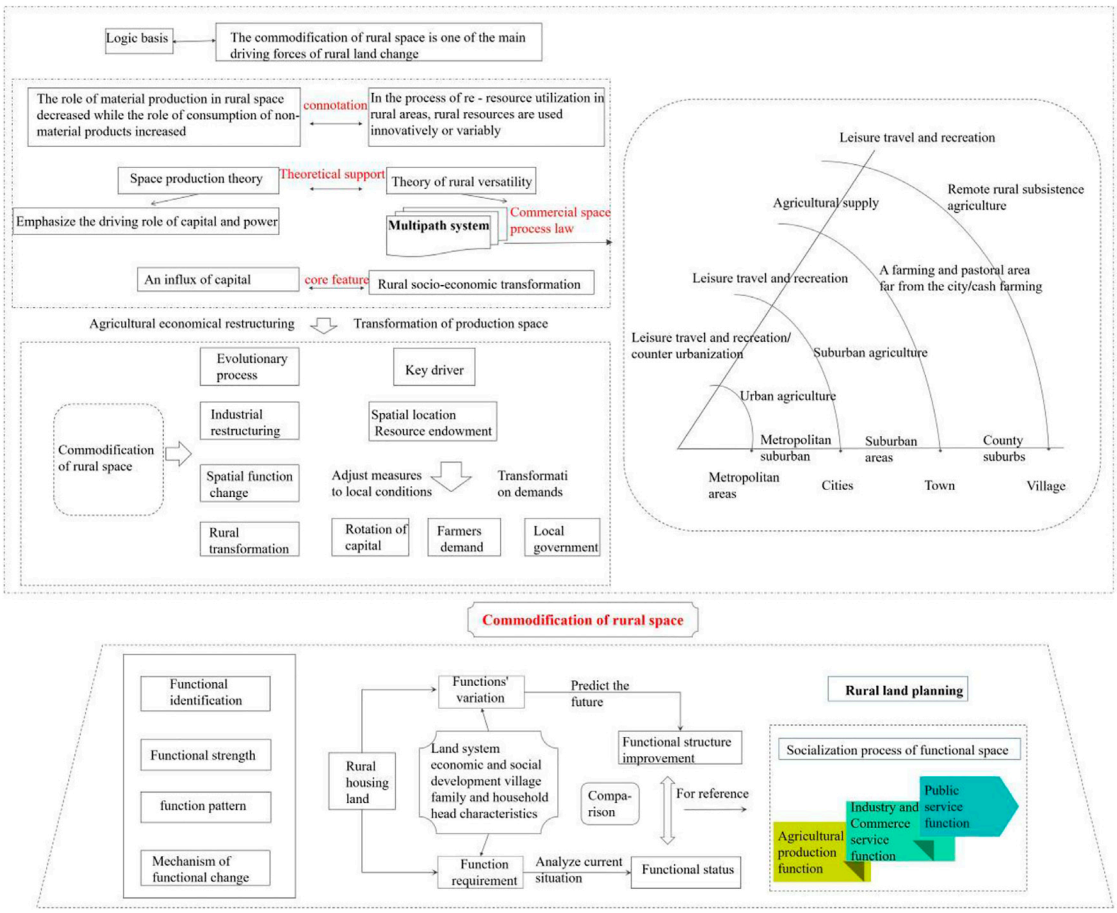

FIGURE 8
The relationship between the production function socialization of rural housing land and rural space commercialization under the background of village planning.

judge of their interests—who are no longer dominated only by the government, not pushing force by mandatory command, and cannot kidnap a few farmers with the will of the many farmers. Government, village collective, and policy researchers and makers need to strengthen two-way communication with farmers, understand the real demand to make sure the farmer rural housing land management system more scientific and democratic. It should make the management accord more with the actual situation and embody the interests of the public demand. In addition, the prescriptive code system for rural housing land management should be improved (Yang et al., 2021).

The income level of farmers and the employment structure should be improved, and the perceived difficulty of the farmers should be weakened. When adjusting the internal land use of rural housing land, the higher the household income, the higher the proportion of non-agricultural land; and the stronger the degree of non-agricultural employment mode, the lower the perceived difficulty of implementation (i.e., the lower the resistance of the change of internal land use of rural housing land). Therefore, we should promote the improvement of rural housing land use, reduce the hindrance of village collective to promote the reform of rural housing land use, and facilitate the advancement of village planning.

5.1.5 Research limitations and prospects

The sample size of this study is limited. Therefore, we recommend that more differentiated data should be collected in the next step. Due to the subjectivity of the survey object, the driving factor index system needs to be further improved. In the new background of urbanization and the request for the integration of urban and rural development, the production function of the rural housing land is taken as the breakthrough point. The index system and quantitative methods should be perfected. In addition, the production functions and space differences of rural housing land should be further studied according to the different kinds of function and farmers' demand to realize the rural housing land standard redesign. Based on this, different scenarios were set up to predict the evolution law of rural housing land function. The potential of rural housing land renovation and the path of function improvement should be urgently studied. Finally, a scientific basis for the reform of rural housing land system and rural land planning should be provided.

6 Conclusion

In this study, Pinggu District and the important channels for the coordinated development of the Beijing-Tianjin-Hebei Urban Agglomeration are taken as an example. Based on the sample data of rural housing land, the theory of planned behavior, and the SEM, the micro-mechanism of rural housing land production function differentiation is analyzed from the perspective of internal land use and its socialization trend is discussed. The main conclusions are as follows:

(1) This study found that the production function of rural housing land in Pinggu District was differentiated and showed significant spatial differentiation. The high-value areas were mainly concentrated in the suburban plain and mid-level mountains. The production function of rural housing land withdrew and socialized in the village, following the rule of socialization of agricultural function—socialization of industrial and commercial service function, and socialization of public service function.
(2) Behavioral attitude, subjective norms, and perceived behavioral control have a significant influence on each other. Among them, the interaction force between behavioral attitude and perceived behavioral control is prominent (the coefficient is 0.71), which was above two and significantly affected the farmers' intentions. The subjective norms and perceived behavioral control significantly affected the production function of rural housing land, reaching 0.41 and 0.79, respectively. The demonstrative norms of family and the commanding norms of the village collective have significant effects on subjective norms (0.93 and 0.83, respectively), while relatives and friends had no significant effects. The perceived behavior control was significantly affected by income scale and structure, family size, and employment type (0.81, 0.71, 0.6, and 0.61, respectively), while the age and educational level of the household head have no significant affected.
(3) To further promote management of rural housing land, it is necessary to improve the institutional reform of rural housing land and optimize its mandatory norms, improve the income level of farmers and the employment structure, and weaken the perceived difficulty of the farmers. The production function socialization of rural housing land is an important prerequisite to realizing the commercialization of rural space. In rural land planning, it is advisable to optimize the layout of land use by zoning and classification according to the different location characteristics and function socialization stages of rural housing land (The Department of Economic and Social Affairs of the United Nations Secretariat, 2018; Zhao et al., 2019).

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics Statement

Ethics review and approval/written informed consent was not required as per the local legislation and institutional requirements.

Author Contributions

QZ: conceptualization, investigation, original draft preparation. GJ: writing-reviewing, editing, funding acquisition, project administration. WM: writing-review, editing, methodology. YY: writing-editing, language polishing. TZ: investigation, editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Spatio-temporal pattern and allocation efficiency of public service land in rural settlements

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The construction of infrastructure and public services is the core of countryside planning. As the carrier of rural public services, the evolutionary pattern and efficiency of rural public service land (RPSL) can directly reflect the development of rural public services. However, existing studies have mainly characterized public service space through the number of public service facilities rather than the area of land occupied. Furthermore, research on public service land in rural settlements is lacking. Taking 273 villages in the Pinggu District of Beijing as an example, this article integrated multi-dimensional data, including geospatial data, big data, and socio-economic data, to analyze the spatio-temporal evolution characteristics of RPSL from 2004 to 2019. The bi-dimensional allocation efficiency index addressing qualitative and quantitative development was introduced to measure the allocation efficiency of RPSL. The results show that the area of RPSL in Pinggu District has increased by 57.28 ha, and the internal land use structure of RPSL has become balanced. The evolution pattern of RPSL was characterized by both agglomeration and dispersion, as well as by a significant tendency to expand along main roads. The uneven distribution of public service facilities and the significant differences in accessibility reflected the non-equalization of public services. The allocation efficiency of RPSL in 79.23% of the villages was at a low level, which is mainly due to the mismatch between the rural public service land area and the population, the non-differentiated allocation of public service facilities, the uneven public service quality, and the low accessibility of RPSL. In the future, policymakers should plan rural public service land rationally from the perspective of the actual situation, such as setting flexible indicators, building a living circle of rural settlements, and so on. This research will not only enrich the research perspective of rural public services but also provide a reference for the study on the utilization and optimization of rural settlements.

KEYWORDS

rural public service land, rural settlements, allocation efficiency, metropolitan suburbs, spatio-temporal pattern

1 Introduction

Rural public service land (RPSL) is a land use type of rural construction land and the main part of rural residential areas (Ma et al., 2018). With the new urbanization, the lifestyle of the rural population has gradually changed from rural to urban, and the demand for public services has become stronger (Li et al., 2006). As the carrier of rural public services (Han et al., 2015), the area and structure of RPSL are bound to change significantly (Qu et al., 2018; Qu et al., 2021). It has become an important research field of rural geography and urban–rural planning to grasp the evolutionary patterns of RPSL scientifically.

The definition and scope of public service land vary in countries and regions, but the connotation is similar (Sun and Liang, 2002). Public service land is a unique category of land use in China, which covers a wide range of land with public service functions (for example, education, administration, and healthcare). However, there is no land use type named "public service land" in the land use classification systems of Britain, the United States, Hong Kong, and other countries and regions. Instead, it is split or combined according to public service functions. For instance, in the UK, land for education is classified as non-residential institutions along with land for healthcare, childcare, museums, and libraries, while in Hong Kong, it is classified as a separate category named educational land (Gao and Su, 2010; Marjan et al., 2011). The classification of public service land is usually based on function (Sun and Liang, 2002), profitability (Xu and Li, 2012), resident demand (Xu et al., 2013), spatial distribution (Yang and Zhao, 2002), and availability (Lineberry, 1974).

Due to the different definitions of public service land, the research on the utilization of public service land has gradually shifted to specific and microscopic by focusing on public service facilities (PSFs) (Gao and Zhou, 2009; Robert et al., 2018). Generally, research objects are hospitals, parks, schools, etc. (Meier et al., 1991; Talen, 1997; Aseel and Vincent, 2020). The research content mainly includes PSF's provision (Greenhut and Mai, 1980; Mohammad, 1995; Gao et al., 2010; Zhou and Gao, 2011; Luis et al., 2019), accessibility (Austin, 1974; Orloff, 1977; Tsou et al., 2005; Song et al., 2010), location selection (Teitz, 1968; John, 1981; Liu and Li, 2010), efficiency and fairness (Church and ReVelle, 1976; McAllister, 1976; Bigman and ReVelle, 1978; Zhang and Zhou, 2020), layout (Wolpert, 1976; Rich, 1979; Perl and Ho, 1990; Barbera and Bevia, 2006; Han et al., 2019), effectiveness (Lan et al., 2018; Xu et al., 2022) and so on. In recent years, the equalization of public services has become a hot research topic (Thisse and Wildasin, 1992; Hosseini et al., 2021). The primary research approach is to measure the equality of public services through spatial distribution (Zhu et al., 2010; Song et al., 2012; Sui et al., 2015; Davis et al., 2020; Luo and Sun, 2020; Lee, 2021) or quality (Le Huu et al., 2011; Tervo et al., 2013; Fauster et al., 2017; Liu et al., 2019) of public service facilities and then to propose ways of rationally allocating public service land (Miranda and Tunyavong, 1994; Talen, 1998).

Although the relevant studies have been conducted intensively and achieved rich results, most of them take the urban settlements as the study areas (Meng et al., 2021). In other words, there is a research gap related to public service land in rural settlements. With the introduction of various policies that focus on rural issues, such as the rural revitalization strategy in China, studies on rural settlements have received increasing attention (Ma et al., 2022). Correspondingly, the internal land use structure of rural settlements has been a major focus (Tian et al., 2022). As one land use type of rural residential land, RPSL's area and distribution directly impact the efficiency of rural residential land, as well as the effectiveness and fairness of rural public services (Gao and Tang, 2018) (Luo and Sun, 2020). Therefore, it is necessary to study public service land in rural settlements.

Through literature review, scholars have mainly considered public facilities as a point. The scale of public service facilities is represented through the number of points rather than the area of land occupied (Luo and Wang, 2003; Lv and Yan, 2018; Wei, 2021). As a result, a few studies examine public service spaces by land use data. In addition, most of the existing studies focus on the status of public service facilities in a particular year and lack evolution over a long period (Samuelson, 1954; Demsetz, 1970; Fei and Yao, 2009). From the perspective of geography, this article attempts to study the spatio-temporal evolution of rural public service land by land use data spanning 15 years.

The description of the evolution pattern and utilization characteristics of rural public service land can enrich the research results of rural geography. On the other hand, it can guide the spatial allocation of rural settlements from the equalization of public services. Given this, taking 273 villages in the Pinggu District of Beijing as an example, this article analyzed the spatio-temporal evolution characteristics of RPSL from 2004 to 2019 by integrating multi-dimensional data, including geospatial data, network big data, and socio-economic data. The bi-dimensional allocation efficiency index addressing qualitative and quantitative development was introduced to measure the allocation efficiency of RPSL.

The rest of this article is organized as follows: Section 2 introduces the study area, research methods, and data sources. Section 3 describes the spatio-temporal pattern and the allocation efficiency of RPSL. Section 4 discusses the phenomena involved and suggests an appropriate development direction. Section 5 summarizes the findings by referring to existing literature and the key implications for policymakers and researchers are highlighted.

2 Methodology and data

2.1 Study area

As the capital of China, Beijing is the national center of politics, culture, international intercourse, and technological

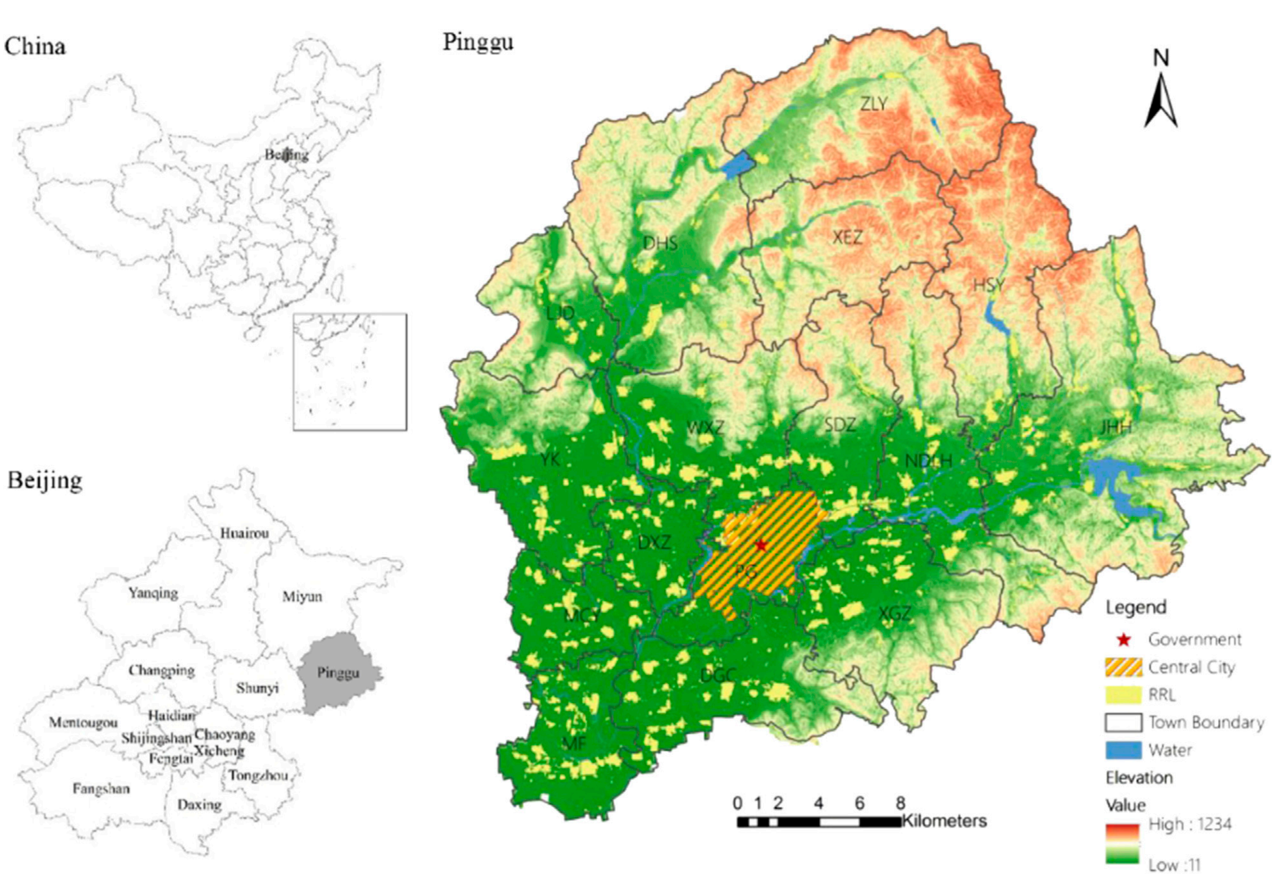

FIGURE 1
The geographical location of Pinggu.

innovation, as well as a modern international metropolis. Pinggu District is one of the suburbs of Beijing. Driven by the radiation of the central area of Beijing, Pinggu District has seen rapid urbanization and non-agriculturalization. The rising living standards of inhabitants have placed higher demands on public services such as hospitals and schools. Therefore, Pinggu District can be used as a typical case to study the rural public service land in metropolitan suburbs.

Pinggu (40°02′–40°22′N, 116°55′21″–117°24′07″E) lies in the northeast of Beijing (Figure 1). The widest distance from east to west is 40.25 km, and the longest distance from north to south is 38.5 km. It locates at the junction of Beijing, Tianjin, and Hebei provinces, with an advantaged location and traffic conditions. In terms of topography, Pinggu District is low in the southwest and high in the northeast. Pinggu District is surrounded by mountains on three sides, showing topographic features of 1:1:1, with mountains of 1/3 (in the north), shallow mountains of 1/3 (in the southeast), and plains of 1/3 (in the southwest). Pinggu District consists of 16 towns and 273 administrative villages. According to the 2019 Pinggu Statistical Bureau, the population was approximately 456 thousand, of which the rural population was about 192 thousand.

2.2 Research methods

2.2.1 Characterizing the spatial differentiation of rural public service land

Kernel density analysis takes a certain regular area around any point in space as the calculation range. It analyzes the spatial distribution trend of the observed objects by calculating the density of the observed data in the area. The data points close to the center point are given a higher weight, otherwise a lower weight. The estimated density of each point is the weighted average density of all points in the region. We used the kernel density analysis tool in ArcGIS 10.2 to analyze the kernel density of rural public service land in Pinggu District and visualize its spatial clustering.

$$P_i = \frac{1}{n\pi} \times \frac{1}{R^2}\sum_{j=1}^{n} K_j\left(1 - \frac{D_{ij}^2}{R^2}\right)^2. \quad (1)$$

TABLE 1 Evaluation index system of basic public service capacity.

Evaluation target	First-level indicators	Second-level indicators (unit)	Indicator attribute	Weight
Baisc public service capacity	Guaranteed Service Capacity (1/3)	The construction cost of public facilities (ten thousand yuan)	+	0.13
		Concentrated water supply rate (%)	+	0.15
		Number of lighting facilities (pcs)	+	0.12
		The satisfaction rate of public security (%)	+	0.13
		Number of medical institutions (pcs)	+	0.25
		Number of medical beds per 10,000 people (pcs)	+	0.22
	Essential Service Capacity (1/3)	Number of secondary schools, primary schools, and kindergartens (pcs)	+	0.22
		Average educated time (years)	+	0.18
		Number of technical training lectures (times per year)	+	0.10
		the shortest distance from the village to the bus stop (km)	-	0.19
		Garbage disposal rate (%)	+	0.16
		Sewage treatment capacity (tons)	+	0.15
	Developmental Service Capacity (1/3)	Green area (m^2)	+	0.20
		Number of parks (pcs)	+	0.24
		Recreation room area (m^2)	+	0.26
		Library collections (volumes)	+	0.18
		Number of cultural activities (times)	+	0.12

In formula (1), P_i is the kernel density of any rural public service land. K_j is the weight of the object j. D_{ij} is the distance between point i and object j. R is the bandwidth of the selected regular area ($D_{ij} < R$). n is the number of objects within the range of bandwidth R.

2.2.2 Evaluating the basic public service capacity

Basic public service capacity (BPSC) represents the quality of public services provided by the local government through finance and other ways. It is also a vital indicator to reflect the utilization efficiency of public service land. We construct an evaluation system consisting of 15 indicators (Table 1) to evaluate the BPSC of 273 villages in Pinggu District in 2019. The evaluation index system covers three dimensions of BPSC: guaranteed service capacity, essential service capacity, and developmental service capacity.

The guaranteed service capacity refers to the ability to ensure the residents' survival and security, mainly reflected in infrastructures and medical resources. The construction cost of public facilities represents the government's financial investment in public services and is selected as a positive indicator. Water, electricity, and security are critical to modern life. Three indicators were selected to characterize: concentrated water supply rate, the number of lighting facilities, and the satisfaction rate of public security, with higher values indicating greater guaranteed service capacity. The supply of medical resources is reflected by the number of medical institutions and the number of medical beds per 10,000 people, both of which are positive indicators.

The essential service capacity refers to the ability to meet the residents' living and production needs, including four aspects: education, convenient transportation, employment security, and sanitation. In terms of education, this article selected two indicators. Specifically, the number of educational institutions (secondary schools, primary schools, and kindergartens) was selected to represent the government's investment in public education. Moreover, the average educated time characterized the educational attainment of the population. Both of them are positive indicators. The higher the value, the better the public education services. Travel convenience is measured by the shortest distance from the village to the bus stop. It is a negative indicator. The greater the value, the longer the distance, and the lower the ease of access. Technical training seminars are one method of enhancing employment, so this article selected the number of technical training lectures as a positive indicator. In terms of sanitation, waste disposal and sewage treatment are particularly important, so the garbage disposal rate and the sewage treatment capacity were chosen as positive indicators.

With the improvement of material living standards, people are gradually focusing on the enjoyment of the spiritual world. The developmental service capacity refers to the ability to meet the residents' entertainment and social needs (Xu et al., 2013). We chose five indicators: green area, number of parks, recreation room area, library collections, and the number of cultural activities, respectively. All five indicators are positive, with the first two reflecting the space of residents' activities and the last three representing the diversity of their recreational choices.

Regardless of the dimension of basic public service capacity, it is closely related to people's life and social development, and there is no difference in importance. Therefore, the three dimensions in the above index system are given the same weight, i.e., 1/3. The entropy method was used to determine the weight of each second-level indicator. The formula for calculating the basic public service capacity is given as follows:

$$M_i = \sum \left(X'_{ij} \times W_j \right), \tag{2}$$

where M_i is the basic public service capacity of *i* village, W_j is the weight of *j* indicators, and X'_{ij} is the standardized value of *j* indicators.

2.2.3 Constructing the accessibility model of rural public service land

Generally, accessibility can be divided into geospatial accessibility and traffic accessibility (Penchansky and Thomas, 1981). Geospatial accessibility is measured by calculating the spatial distance between the demand point and the supply point. Traffic accessibility refers to calculating the shortest distance between traffic networks based on the impedance and capacity of each class of road. In this research, Voronoi was used to measure the geospatial accessibility of rural public service land in Pinggu District and the gravity model was used to measure traffic accessibility.

2.2.3.1 Geospatial accessibility based on Voronoi

Voronoi (Thiessen polygon) can break the boundary of administrative division and truly reflect the spatial accessibility of rural public service land. Only one generator exists in a Thiessen polygon, and the distance from any point in the polygon to the generator is closer than its distance to a generator in another polygon. In this research, the generator refers to the rural public service land parcels. People will prioritize the nearest public service land to obtain public services. Therefore, the area of the Thiessen polygon can be used as an indicator to measure geospatial accessibility. The smaller the area of the Thiessen polygon, the higher the level of geospatial accessibility.

2.2.3.2 Traffic accessibility based on the gravity model

The improved gravity model will be introduced to calculate the traffic accessibility of rural public service land (Yang and Xu, 2015), which consists of three elements: origin, destination, and connectivity, as illustrated in the following formula:

$$\mathrm{S_i} = \sum_{j=1}^{n} \frac{\mathrm{M_j}}{\mathrm{d_{ij}^{\beta} V_j}}, \qquad \mathrm{V_j} = \sum_{k=1}^{m} \frac{\mathrm{P_k}}{\mathrm{d_{kj}^{\beta}}}, \tag{3}$$

TABLE 2 Evaluation index system of allocation efficiency of RPSL.

Target layer	Evaluation index (unit)
Input index	Rural public service land area per capita (m^2 per person)
Output index	Number of rural public service facilities (pcs)
	Accessibility of rural public service land
	Basic public services capacity

where S_i indicates the gravitational accessibility from village *i* to RPSL, and the larger the *Si*, the better; *n* and *m* are the number of RPSL and village centroids in the study area, respectively; M_j indicates the attractiveness of RPSL *j*, which is expressed by the area of RPSL; D_{ij} indicates the shortest path distance from village *i* to RPSL *j*; V_j is the influencing factor of population size; P_k indicates the resident population of the village; It is generally believed that the value of β changes according to the changes of various influencing factors. By referring to previous studies, it can be found that the value of β is generally concentrated in the range of 0.90–2.29, and when the value of β is between 1.5 and 2, the influence on the research results is weak. Therefore, the value of β is 2 in this article.

2.2.4 Measuring the allocation efficiency of rural public service land

Rural public service land is a kind of non-profit land type. The efficiency of rural public service land is not marked by maximizing economic output but rather by the values of rural public service. Hence, this study considers the allocation efficiency of RPSL as the public service value produced per unit area of RPSL. Furthermore, this study created a model for allocation efficiency of rural public service land, which takes the area of RPSL per capita as an input factor and the public service values of RPSL as an output factor. The public service values of RPSL are mainly reflected in both quantity and quality. The former is represented by the number of rural public service facilities, while the latter is mainly reflected in two aspects, namely the accessibility of rural public service land and the level of basic public services capacity. A system of indicators for evaluating the allocation efficiency of rural public service land is detailed in Table 2.

The model for measuring the allocation efficiency of rural public service land is shown as follows:

$$E_i = \frac{S'_i \times M'_i \times F'_i}{L'_i}, \tag{4}$$

where E_i is the allocation efficiency of RPSL of village *i*, S'_i is the accessibility of RPSL of village *i* after normalization, M'_i is the basic public service capacity of village *i* after normalization, F'_i is the number of public service facilities of village *i* after normalization, L'_i is the per capita area of RPSL in village *i* after normalization.

TABLE 3 Dataset.

Data type	Data	Year of data	Data source
Land use change data	The second national land survey data	2004	The Beijing Municipal Commission of Planning and Natural Resources
	Land use change survey data	2019	
Socio-economic data	population	2004/2019	The socio-economic statistical yearbooks
	The construction cost of public facilities	2004/2019	
	Number of secondary schools	2019	Economic management stations of Pinggu District
	Number of primary schools		
	Number of kindergartens		
	Average educated time		
	Number of technical training lectures		
	Garbage disposal rate		
	Sewage treatment capacity		
	The concentrated water supply rate		
	Number of lighting facilities		
	The satisfaction rate of public security		
	Number of medical institutions		
	Number of medical beds per 10,000 people		
	Recreation room area		
	Number of cultural activities		
	Library collections		
Network data	POI data	2019	Google Maps

2.3 Data

2.3.1 Data source

Land use change data of Pinggu in 2004 and 2019 were obtained from the Beijing Municipal Commission of Planning and Natural Resources, with the accuracy of 1:10000. The socio-economic data of Pinggu in 2004 and 2019 were obtained from the socio-economic statistical yearbooks and economic management stations of Pinggu District. The POI data in 2019 was crawled from Google Maps by data crawler technology, including six attributes: longitude, latitude, name, address, type, and administrative region (Table 3).

2.3.2 Data processing

This research defined rural public service land (RPSL) as independent rural settlements' land used for healthcare, public facilities, public education, administration, sports entertainment, parks, and green space. From the attributes perspective, rural public service land belongs to rural residential areas. Therefore, the spatial data of RPSL can be extracted from land use change survey data. First, we used ArcGIS to extract rural settlements in Pinggu District in 2004 and 2019 (the field is CZCSXM and the code is 203). And then, we extract the public service land from the rural settlements (the field is DLDM and the code is 08). Thus, the database of rural public service land in Pinggu District is established, including public facilities land, park and green space, organization land, science and education land, sports and recreation land, health and charity land, and scenic land.

3 Results and analysis

3.1 Spatio-temporal evolution characteristics of rural public service land

3.1.1 Time series change of rural public service land

During the study period, the area of rural settlements in the Pinggu District expanded (from 5,536.09 ha to 6,075.97 ha). Meanwhile, the area of rural public service land also increased, expanding from 329.24 ha in 2004 to 386.53 ha in 2019. The increase in RPSL was 57.28 ha, accounting for 10.61% of the total expansion of rural settlements. The proportion of RPSL in rural residential areas has also increased, from 5.95% to 6.36%. Among the 273 villages in Pinggu District, 193 villages have increased the rural public service land area. The rural public service land area per capita decreased from 10.22 m^2 per person

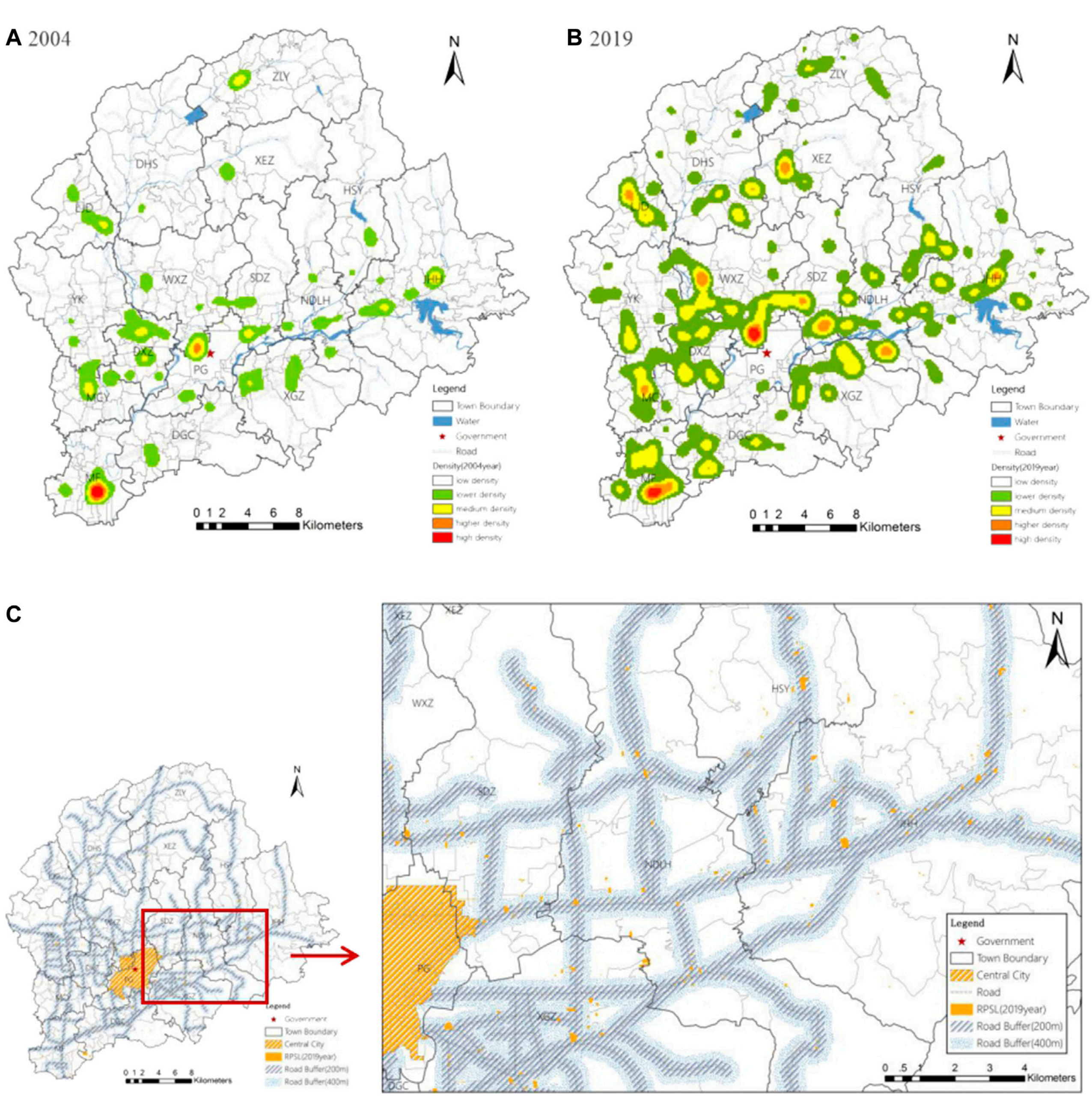

FIGURE 2
The spatial distribution of RPSL in Pinggu.

in 2004 to 9.57 m^2 per person in 2019, but it is still higher than the maximum of 7.6 m^2 per person in CECS354:2013 (Standardization Corporate Average Fuel Economy, 2013). In 2019, 153 villages had more than 7.6 m^2 per person of the rural public service land area per capita, representing 58.85% of the total number of villages.

In terms of internal structural changes, in 2004, the rural public service land in Pinggu District was dominated by land for science, education, culture, and health, with a high proportion of 54.00%, and its share declined to 43.8% in 2019. Accordingly, the proportion of public facilities land and administration land increased from 4.33% to 20.01%–30.60% and 22.71%, respectively. It indicates that the structure of rural public service land is becoming more balanced and diversified. In the early years, rural residents' demand for public services mainly revolved around basic public services such as medical treatment and education. In 2004, China launched the construction of a new socialist countryside with the main focus on the cleanliness of villages and the improvement of facilities. Basic public service facilities such as water, roads, electricity, gas, and networks have been continuously improved, and the land for public facilities has significantly increased. In addition, Pinggu, as a suburb of the metropolis, has seen a continuous rise in social and economic development and the material living standards of its people. Rural residents have also developed higher demands for the residential environment, public safety, culture, and recreation, as evidenced by the increased area of administration land.

Over the 15 years, the rural public service land in Pinggu District has expanded by about 17.40%. Comparing the changes in different towns, we can find that the expansion of rural public service land in towns located in remote mountainous areas is significantly higher than that in other towns. For instance, XEZ increased by 83.99% and DHS by 66.65%, while the growth rate of DXZ, which is located around the central city, is relatively low at 10.08%. To some extent, this significant regional difference can reflect the local government's support for the construction of public services in remote areas. The villages located in the central area benefit from the radiating effect of the central city and already have a good foundation for public services construction. The rural public service land is no longer obsessed with the expansion of area but is developing in the direction of improving quality and efficiency.

3.1.2 Spatial pattern of rural public service land

This study analyzed the spatial distribution characteristics of rural public service land in the Pinggu District. As shown in Figure 2A, the rural public service land in Pinggu District shows a clear pole-nucleus distribution, with a spatial pattern of dense in the southwest and sparse in the northeast, which is consistent with the low topography in the southwest and high in the northeast of Pinggu District. The high-density poles concentrate in the PG urban fringe, the MF industrial zone, and the center of townships. These areas have obvious commonalities, that is, excellent location, convenient transportation, and a high level of socio-economic development, which can provide material conditions for the construction of rural public services and guarantee the development of public services. In contrast, the low-density poles are distributed in the mountainous areas of the northeast, where the transport network is irregular, and the rural settlements are scattered due to the mountainous terrain. As a result, rural public service land is also relatively scattered and fails to show some agglomeration.

According to Figure 2B, the density of high-density poles has increased continuously over 15 years. It formed a large medium-density area with the surrounding areas, showing a trend of concentrated contiguity. It means that the public service centers in Pinggu District are being improved, and their functions are being upgraded during the study period. At the same time, the diffusion pattern of rural public service land is reflected in the formation of many new agglomerations in the northern mountainous areas. It can be seen that the planning and development of rural public service land in the Pinggu District have gradually shifted to the periphery areas of the central city, which is constantly filling up the shortage of rural public service land in the northern mountain areas. In general, the spatial distribution of public service land in Pinggu District has become increasingly balanced over the study period under agglomeration and diffusion. The agglomeration evolutionary pattern is formed by the fact that the central town has an absolute advantage in terms of gathering the best public services. Conversely, the pattern of diffuse evolution is shaped by the forced marginalization of remote rural areas, which constrain the development of public services.

By extracting the rural public service land within 200m and 400 m of the main roads (Figure 2C), we found that more than 85% of the rural public service land in the Pinggu district distribute along major transport routes. The proportion of rural public service land within 200 m along the main roads is as high as 50%, which is getting larger during the study period, reaching more than 62.56% in 2019. This result implies a significant trend in expanding rural public service land along major roads. As for the reasons, topography and accessibility are factors that are taken into account when planning and developing rural public service land. Rural public service land is often planned in areas that are easily accessible in order to cover a larger area, such as on both sides of main roads and at village entrances on flat terrain.

According to Figure 3A, there are significant regional differences in rural public service land area per capita in Pinggu District. There are two high-value areas, one of which is located in the northern mountainous, such as DW village, whose RPSL area per capita was as high as 124.56 m^2 per person in 2019. DW village has a small population of only 146 people, which is one of the reasons for its high rural public service land area per capita. Another high-value area is the edge of the central city, such as XSQ village, with a rural public service land area per capita of 51.94 m^2 per person, which is close to the central city and has an adequate supply of rural public service land. Accordingly, rural public service land area per capita is at a high level in XSW village. It is urgent to strengthen intensive utilization.

3.2 Public service values of rural public service land

3.2.1 Construction of rural public service facilities

According to statistics, in 2019, the number of public service facilities built within rural settlements in Pinggu District totaled 3,721, including nine types of public facilities, parks and green spaces, healthcare, welfare charity, education services, organization, entertainment, press and publication, and living

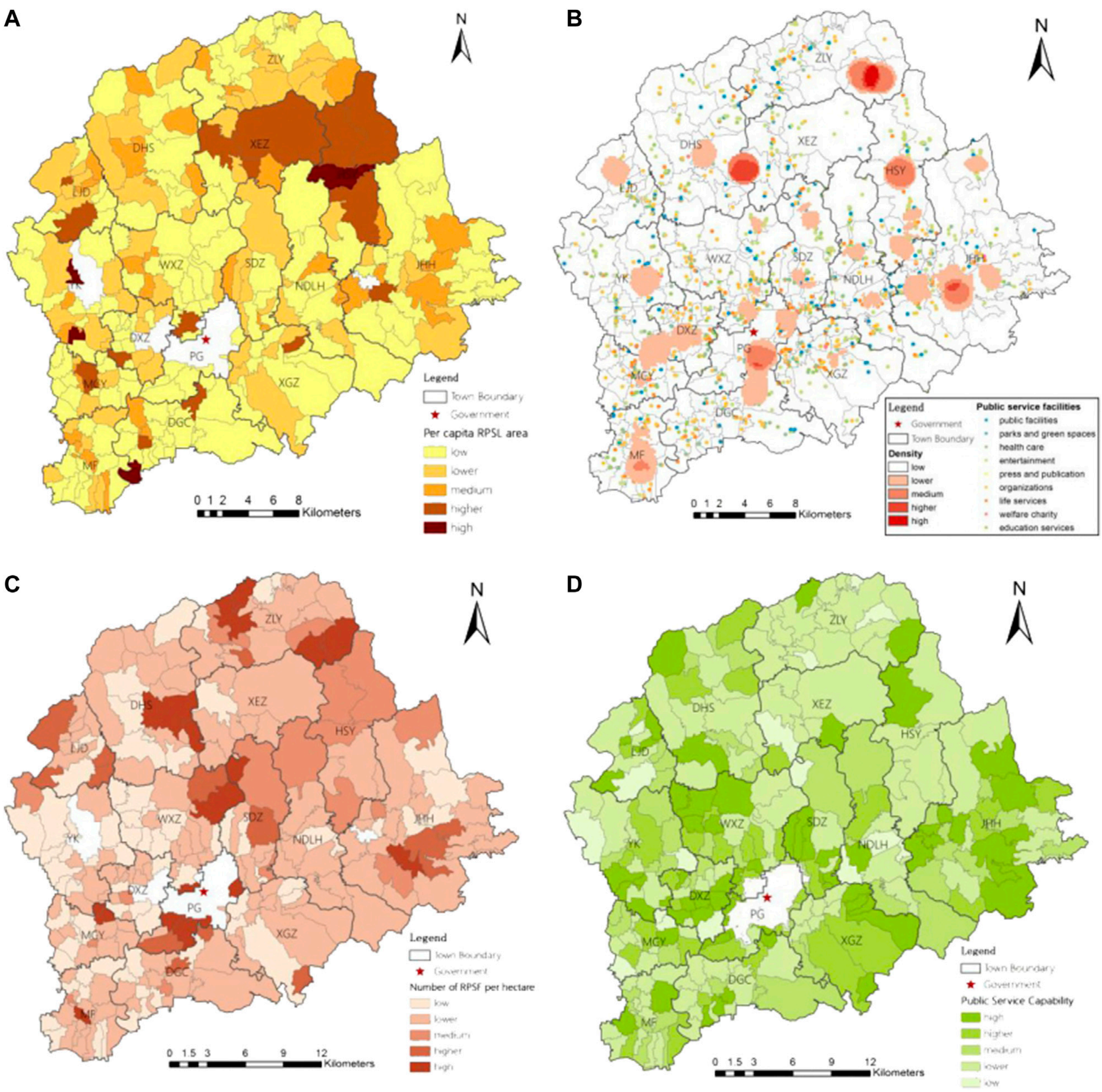

FIGURE 3
The public service values of RPSL in Pinggu.

services. The spatial distribution of rural public service facilities in Pinggu District is closely related to the village system, with a number of clusters (Figure 3B). In other words, the rural public service facilities are clustered around the town centers, and the aggregation is weakened with the reduction of the village system level.

In 2019, the number of rural public service facilities in the Pinggu District was 3.27 pcs per hectare. According to Figure 3C, there is a significant spatial difference in the number of rural public service facilities per hectare, showing a spatial pattern of high in the north and low in the south. On the one hand, for the northern mountainous areas, due to the topography and socio-economic level, it is difficult to develop and utilize the land, and the construction of rural public service facilities can only be concentrated on the limited land. On the other hand, the central and southern regions have a larger area of rural public service

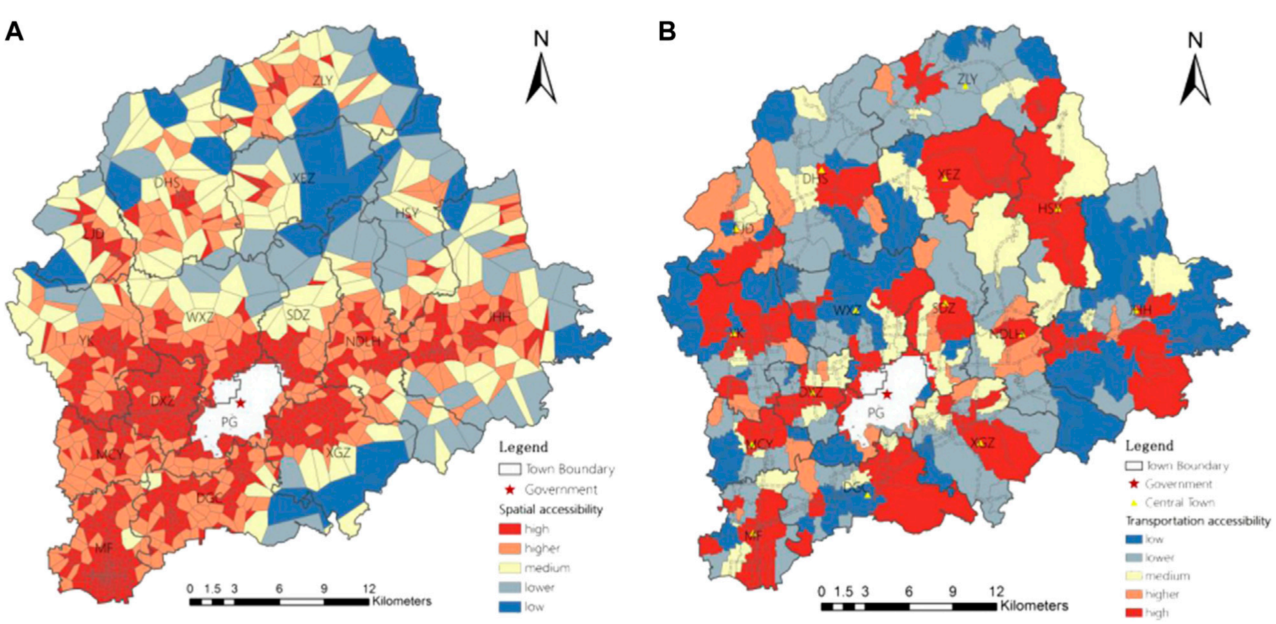

FIGURE 4
The accessibility of RPSL in Pinggu.

land and well-equipped rural public service facilities. However, the rural public service facilities are scattered, which reduces the number of rural public service facilities per hectare to a certain extent. With limited rural public service land, the Pinggu district is relatively well served by public service facilities, but there are also significant differences between villages.

3.2.2 Level of the basic public service capacity

Basic public service capacity represents the quality of public services provided by the local government through finance and other ways (Wang, 2010). In this study, it is regarded as one of the indicators reflecting the public service values of RPSL in the Pinggu District. The basic public service capacity level is measured according to the index system (Table 1) shown in Figure 3D.

The evaluation score for basic rural public service capacity in Pinggu District is about 2.027. There are great differences between villages, the village with the highest evaluation score is located in WJZ village at 3.272, while the lowest score is only 0.620, which is LHS village in JHH township. The gap in scores between the two villages reached more than five times. According to Figure 3D, basic public service capacity is higher in peri-urban villages than in remote villages and higher in plain villages than in mountainous villages. To summarize, basic public service capacity in the Pinggu District is characterized by "towns > villages" and "central villages > peripheral villages." Under China's dualistic urban-rural structure, advantageous resources tend to tile towards the central cities and towns. In the case of Pinggu, the central towns have absolute regional advantages in providing public services such as education and healthcare. In addition, most of the road networks in the central towns arrange in a grid, which contributes to even distribution and high overall coverage of public service facilities. Accordingly, the basic public service capacity is high.

3.2.3 Accessibility of rural public service land

With the help of the Voronoi model, this study measures the accessibility of rural public service land in Pinggu District under ideal conditions. The results show that the geographical accessibility of rural public service land in the Pinggu District is seriously polarized. Specifically, the smallest Tyson polygon is only 90 m^2 in YGZ village around the urban area of Pinggu, which means that people can access public services within a 90 m^2 area. However, in HY village, the nearest public services available to residents are up to $10^6 m^2$. The gap in geographical accessibility between the two villages is great. According to Figure 4A, geographical accessibility shows a circled expansion that gradually decays outwards from the central town. Specifically, the Tyson polygons in Pinggu town and MF town are small in area but large in number, while the Tyson polygons in the northern areas are much larger than the former but smaller in number. It indicates that the closer to the center area of Pinggu, the greater the accessibility of residents to public services.

TABLE 4 The allocation efficiency of rural public service land in Pinggu.

Level of allocation efficiency	Number of villages (pcs)	Proportion in the total number of villages (%)
High	11	4.23%
Higher	9	3.46%
Medium	34	13.08%
Lower	162	62.31%
Low	44	16.92%

The above is the ideal accessibility of rural public service land. In fact, the accessibility of rural public service land will not be ideal due to the influence of the traffic road network and the slope of the terrain. Therefore, this study further describes the traffic accessibility of RPSL in the Pinggu District by analyzing the shortest distance between traffic networks. The visualization results are shown in Figure 4B. The results show that the average traffic accessibility of RPSL in Pinggu District is about 52.69. The highest value of 345.28 is located in LY village of MF town, and the lowest value is in DYS village of ZLY town at only 2.32, a difference of nearly 150 times. There is a large gap in traffic accessibility of RPSL between villages. It also reflects, to a certain extent, the uneven distribution of rural public service land in the Pinggu District.

According to Figure 4B, there is a consistency between the areas with high traffic accessibility of RPSL and the township centers. In other words, the spatial pattern of traffic accessibility of RPSL in Pinggu is centered on the central town. In addition, it is not difficult to see that the areas with high traffic accessibility are obviously distributed along the main traffic routes, and their levels are closely related to the density of the road network. On the one hand, the well-developed transport infrastructure and transport road network in the central towns bring convenience in accessing public services, thus enabling the public services in the central towns to serve both the local area and the surrounding area. On the other hand, villages with poor economic development lack public services, as well as the roads can only be built according to the terrain, making the road network within the village irregular, which has a significant impact on the accessibility of public services.

3.3 Allocation efficiency of rural public service land

According to the model for allocation efficiency of rural public service land, the allocation efficiency of RPSL in Pinggu District is measured, and we divided it into five levels: high level, higher level, medium level, lower level, and low level. The number and proportion of villages at different levels are shown in Table 4.

In 2019, the allocation efficiency index of rural public service land in Pinggu District was 0.690. Only 54 villages reached the medium level and above (with an allocation efficiency index of 0.690 or above), accounting for 20.77% of the total number of villages. Only 4.23% of the villages had high allocation efficiency, while 79.23% were below the lower level. Clearly, the rural public service land has not been fully and rationally utilized, and there is a waste of resources with a mismatch between inputs and outputs. Significant differences are found when comparing the allocation efficiency of rural public service land in different villages. For example, there is a large disparity in the allocation efficiency index between the XNJY village and TZY village, also located in the DHS town, with the former being as high as 7.181, while the latter is only 0.015. This regional difference is also visually reflected in space. According to Figure 5, the areas with low allocation efficiency occupy most of the Pinggu District, while the high-level areas show a circled distribution centered on the central town.

Obviously, the use of rural public service land in the Pinggu District is inefficient. In recent years, China has increased investment in rural public services in the context of building a new socialist countryside. Moreover, rural public service land has been planned and developed, which has contributed to an effective improvement of public services in the suburbs of metropolitan areas such as Pinggu. However, excessive development, extensive utilization, and poor quality of public services will make the low allocation efficiency of rural public service land. These three scenarios are explained in detail below.

First, there may be a mismatch between the planned rural public service land and the actual situation. Although the government has planned a large area of land to construct public service facilities, only a small proportion of the land area is actually utilized, or even a large area of land is idle. Alternatively, undifferentiated planning between villages has resulted in the land area not matching the actual population, resulting in the crude and inefficient use of rural public service land. Second, in some areas, even though there is a suitable area of RPSL, there may be problems with public service facilities, such as a small number of facilities, poor equipment, low coverage, and substandard quality. In addition, the undifferentiated scale and content of the facilities may lead to homogenization and a lack of personalized services. Rural residents prefer to spend time and money to enjoy quality public services in the central town rather than settle for less. This results in an inefficient situation where facilities are available but not used. Third, Pinggu has a large mountainous and semi-mountainous area with relatively complex topographical conditions, which limit the development of rural public service land in villages in mountainous areas. The rural public service land is often concentrated on the sides of main roads or at the entrances to villages with flat terrain. Moreover, the accessibility of rural public service land in remote villages is low.

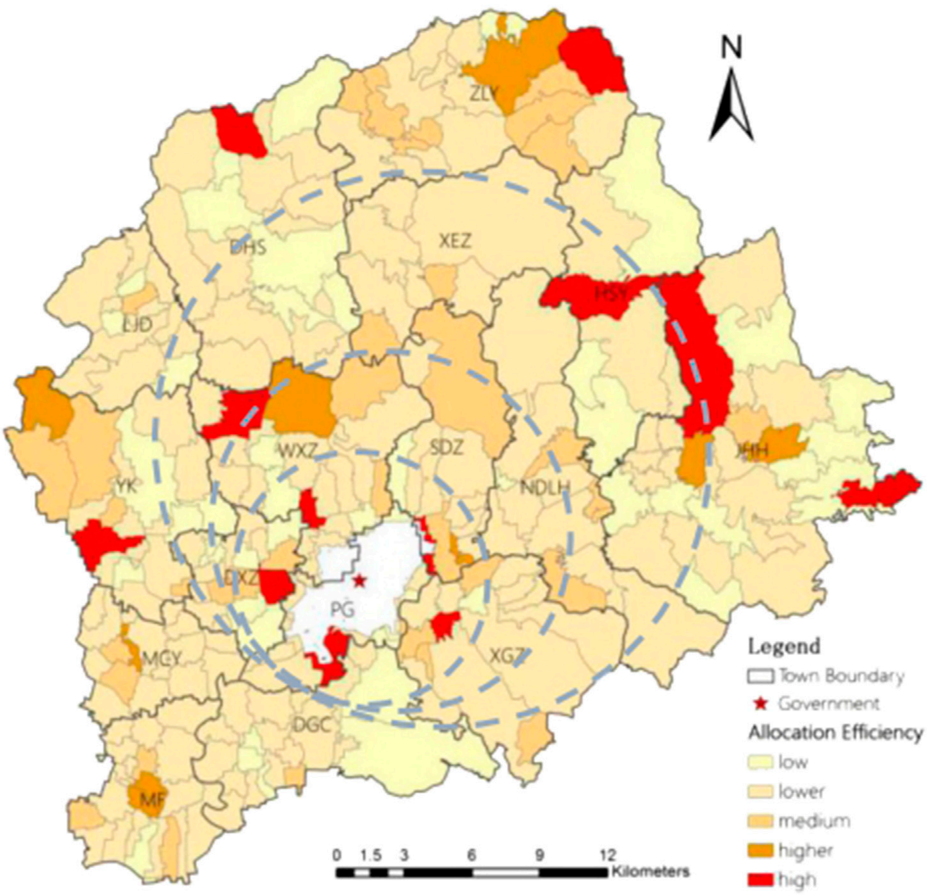

FIGURE 5
The allocation efficiency of RPSL in Pinggu.

It would somewhat impact the efficiency of rural public service land use.

4 Discussion

4.1 Growing and diversified demand for rural public service land

During the study period, the increase in rural public service land in Pinggu District accounted for 10.61% of the total increase in rural residential areas. In fact, the expansion of rural public service land has become a common phenomenon in the metropolitan suburbs with rapid urbanization represented by Pinggu. Since the 21st century, China has started to follow the development path of promoting agricultural development through industry and rural development through urban development. To realize it, China has begun to pay attention to the issues relating to agriculture, rural areas, and farmers. The government has provided policy preference to the development of agriculture, rural areas, and farmers, including increased public financial support for agriculture. Since 2004, China launched a new socialist countryside construction and has taken a series of measures to strengthen the public services, including strengthening the construction of rural infrastructures such as irrigation and water conservancy and rural roads and increasing financial investment in compulsory education and medical conditions in rural areas, etc. These measures aim to allow public services to reach more rural areas and benefit farmers. Public financial support for rural public services has directly contributed to expanding and restructuring rural public service land as a spatial carrier of various public facilities.

Although the national supply of public services is increasing, there is still a great demand for public service land in most rural areas. Villages located in the suburbs of metropolitan areas are more likely to be driven by the radiation of the metropolis than other remote areas. As a result, these villages tend to have a more pressing need for road network improvements, infrastructure construction, and improved educational and medical resources.

It also requires the government to plan more rural public service land to ensure the physical basis for constructing public service systems. However, in Pinggu District, a metropolis suburb with a population of over 400,000, the proportion of rural public service land in rural residential areas has increased from 5.95% to 6.36% but still falls short of the standard line (10%) (Standardization Corporate Average Fuel Economy, 2013). The supply of rural public service land in remote areas is still critical, given the inadequate area of rural public service land in the metropolis suburb.

In the future, the relevant government departments should dynamically adjust the supply of rural public service land to adapt to the increasingly diversified demand for public services. In the early years, people's demand for public services was elementary, mainly for basic public services such as medical treatment and education for children. Rural public service land was mainly used for rural infrastructure construction, such as road hardening, installation of street lights, conversion of toilets and kitchens, and construction of rubbish disposal stations. In recent years, with the development of humanism, the connotation of farmers has begun to change substantially. Farmers are no longer passive identities traditionally bound to the land but modern individuals with an independent spirit. Especially in the rural areas of well-developed regions such as metropolitan suburbs, the non-agriculturalization and the rise in material living standards have prompted a significant shift in the farmers' demand for public services. Not only do farmers have a strong demand for basic public services, but they also have more diversified needs in terms of spiritual and emotional experiences such as the living environment, public safety, and recreation. Moreover, they even put forward higher requirements for the quality of public services. Therefore, policymakers and planners should plan rural public service land rationally from the perspective of rural residents in the future. It can be done by setting flexible indicators for rural public service land to adapt to the changing public service needs of residents dynamically.

4.2 Spatial imbalance in the allocation of rural public service land

The rural public service land in Pinggu District presents a clear pole-nucleus distribution, with a spatial pattern of dense in the southwest and sparse in the northeast. The rural public service land area per capita is obviously polarized. In addition, the public service values of RPSL in Pinggu District show significant regional differences, which are inflected in three aspects: the rural public service facilities are clustered around the town centers, and the aggregation weakened with the reduction of the village system level; basic public service capacity in the Pinggu District is characterized by "towns > villages" and "central villages > peripheral villages"; the high-level traffic accessibility of RPSL in Pinggu centers on the central town. It is not difficult to find that these high-value areas are all areas with good location, transportation, and socio-economic development. To some extent, it also reflects the uneven spatial allocation of rural public service land due to differences in the socio-economic development of the countryside.

The uneven spatial allocation of rural public service land reveals the reality of the non-equalization of public services. Under China's dualistic urban-rural structure, advantageous resources tend to tile towards the central cities and towns, which has also brought about the non-equalization of public services (Gao and Tang, 2018). In general, as the forerunner areas of urbanization, the central towns have an absolute advantage in supplying rural public service land. It also can gather the best educational, cultural, and medical resources in the region. Also, with the advantages of a dense road network, a wide range of public service facilities, and a high overall coverage rate, it can naturally radiate to the surrounding villages and drive basic public service capacity. However, remote rural areas are forced to be marginalized due to the limited radiation range. The backwardness of economic development affects the supply of social resources, which in turn makes the high-quality resources scarce, as evidenced by the lack of rural public service land, the low standard of public service facilities, and the low quality of public services. Furthermore, the low level of economic development has led to a massive outflow of the population in rural areas, which has restricted the development of public services. Rural areas are trapped in a situation where the quality of public services is low and difficult to improve. For example, a village is well-equipped for medical care, but there are no doctors or doctors with no specialist skills. In this way, the gap is gradually widened.

The equalization of public services is a critical path to realizing the integrated development of urban and rural areas. The rational allocation of rural public service land is the cornerstone for realizing the equalization of public services. In the future, it is proposed to build a living circle of rural settlements based on the public service needs of residents and to optimize the allocation of rural public service land based on the living circle. Second, it is suggested that the government should improve the planning for the construction of public service systems to build a public service system with a clear hierarchy and complete content, thereby promoting an even spatial distribution of public service facilities. Last but not least, the urban-rural disparity is inevitable to a certain extent, so it is recommended that policymakers appropriately shift their focus from the urban-rural disparity to the rural-rural disparity. To achieve the goal of equalization of public services by giving preferential policies to remote and backward villages.

4.3 Inefficient utilization of rural public service land

In Pinggu District, 79.23% of the villages have a low allocation efficiency of rural public service land. It indicates that the rural public service land has not been fully and rationally utilized and that there is a waste of resources with a mismatch between inputs and outputs. Specifically, it is evident in four aspects. First, there is a mismatch between the area of rural public service land and the population. Second, there is no differentiated way of allocating public service facilities. Third, the quality of public services varies. Fourth, the accessibility of rural public service land is low. It means that the allocation of rural public service land in Pinggu District is not reasonable, and its growth and imbalance coexist.

In recent years, the Chinese government has been planning and developing rural public service land to ensure infrastructure construction, thereby strengthening the public service system. In fact, the function of rural public service land and the type of public service facilities are also essential parts of the public service system construction, directly affecting the allocation efficiency of rural public service land (Zhan et al., 2015). Driven by the goal of equalization of public services, rural areas tend to refer to cities in the construction of public services in order to reduce the difference between them and cities as soon as possible. It can result in a negative outcome, namely, that the public service system is constructed exactly according to the standards of the cities, ignoring the actual situation in rural areas and the actual needs of residents. Such an undifferentiated approach to the construction of public service systems often results in a mismatch between supply and demand for resources, leading to idle and inefficient use of rural public service land.

In order to maximize the efficiency of rural public service land use, the government should plan rural public service land reasonably according to the actual situation of village development to avoid the source problem of mismatch between supply and demand. For villages with poor natural background conditions, issues such as population outflow and demographic imbalance should be properly considered in land use planning and development, and the area of rural public service land should not be expanded blindly. Meanwhile, it is also possible to supply on demand by surveying the individual needs of residents regarding public services. On the other hand, for the rural areas of the metropolitan suburbs, it is necessary to allocate various public service facilities reasonably, given the limited rural public service land, so that it can serve the local population on a larger scale and at a higher quality. In addition, the quality of public services can be strengthened by improving existing public service facilities, thereby increasing the efficiency of rural public service land utilization. For instance, renovating and reusing old public service facilities that are structurally intact and of good quality.

5 Conclusion

Rural public service land is the carrier of rural public services. Understanding the spatio-temporal pattern and allocation efficiency of rural public service land is the basis for promoting the efficiency of rural residential land and the equalization of rural public services. Taking 273 villages in the Pinggu District of Beijing as an example, this article integrated multi-dimensional data, including geospatial data, network big data, and socio-economic data, to analyze the spatio-temporal evolution characteristics of RPMSL from 2004 to 2019. The bi-dimensional allocation efficiency index addressing qualitative and quantitative development was introduced to measure the allocation efficiency of RPSL. The conclusion is as follows:

The demand for public services in rural areas is increasing and diversifying. During the study period, the area of rural public service land in Pinggu increased by 57.28 ha, accounting for 10.61% of the total expansion of rural settlements, and the expansion rate of the northern mountainous areas was higher than that in other areas. The proportion of rural public services land in rural residential areas has increased from 5.95% to 6.36%. The rural public service land area per capita decreased from 10.22 m^2 per person in 2004 to 9.57 m^2 per person in 2019, and the intensive utilization needs strength. The rural public service land in Pinggu District was dominated by land for science, education, culture, and health, and the structure of rural public service land is becoming more balanced and diversified. The rural public service land in Pinggu District presents a clear pole-nucleus distribution, with a spatial pattern of dense in the southwest and sparse in the northeast. Rural public service land is characterized by both agglomeration and dispersion, as well as by a significant tendency to expand along main roads.

The number of public service facilities built within rural settlements in Pinggu District totaled 3,721 and is 3.27 pcs per hectare. The spatial distribution of rural public service facilities in the Pinggu District is closely related to the village system. The rural public service facilities are clustered around the town centers, and the aggregation is weakened with the reduction of the village system level. The level of basic public service capacity and the public service accessibility vary considerably between villages, with the former reaching a high of 3.272 and the lowest 0.620, and the latter reaching a high of 345.28 and a low of 2.32. Significant regional differences exist in the public service values of rural public service land, and the spatial distribution of high-value areas is closely related to the urban system. It shows the uneven spatial allocation of rural public service land. Furthermore, the uneven spatial allocation of rural public service land reveals the reality of the non-equalization of public services.

The mismatch between supply and demand could lead to inefficient rural public service land use. The overall allocation efficiency index of rural public service land in Pinggu District is 0.690.79.23% of the villages are below the lower level, which indicates that the rural public service land has not been fully and rationally utilized and that there is a waste of resources with a mismatch between inputs and outputs. It is mainly reflected in the mismatch between the rural public service land area and the population, the non-differentiated allocation of public service facilities, the uneven public service quality, and the low accessibility of rural public service land.

In the future, policymakers should plan rural public service land rationally from the perspective of the actual situation in the future. First, it is possible to dynamically adapt to changes in residents' public service needs by setting flexible indicators for rural public service land. Second, it is proposed to build a living circle of rural settlements to optimize the allocation of rural public service land. Third, the mismatch between supply and demand can be avoided by surveying residents' individual needs for public services. Finally, the allocation efficiency of rural public service land can be improved by improving existing public service facilities.

The contribution of this study is not only to enrich the research perspective of rural public services but also to provide a reference for the study on the utilization and optimization of rural settlements. The scientific originalities of the article are to understand the development of rural public services by exploring the evolution pattern and allocation efficiency of RPSL using land use data.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

QZ: conceptualization, methodology, investigation, writing—original draft, and writing—review and editing. GJ: writing—review and editing, supervision, and funding acquisition. YT: investigation, formal analysis, and data curation. LM: investigation and formal analysis. LY: visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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