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RESEARCH ARTICLE

The transition characteristics and driving mechanisms of rural residential land in metropolitan areas—a case study of Tianjin, China

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Abstract

Rural revitalization is the core decision for eradicating global poverty and achieving shared prosperity, and one of the most important works is to optimize and manage rural land space. A theoretical framework based on urbanization theory was built to reveal the rural residential land transition in the Tianjin metropolitan area, China from 1990 to 2020. The transition features are identified by computing the land-use conversion matrix and the rural residential land expansion index (RRLEI) and the influencing factors and mechanisms through a multiple linear regression model. The spatial distribution of rural residential land shows that it expands from the inner suburbs to the outer suburbs, then diminishes in the outer suburbs, and extends to the Binhai New Area. Low-level conflicts between rural residential land and urban construction land occurred during the rapid urbanization period, resulting in disorganized and wasteful growth. The inner suburbs have edge-expansion, dispersion, and urban encroachment patterns; the outer suburbs have edge-expansion, infilling, and dispersion patterns, with little urban encroachment; and Binhai New Area has just an edge-expansion pattern. During decelerated urbanization stage, a high-level conflict occurred between rural residential land and arable land, forestland, grassland, water, and urban construction land. Dispersion grew as urban encroachment reduced in the inner suburbs; dispersion increased while urban encroachment declined in the outer suburbs; dispersion, infilling expansion, and urban encroachment increased in the Binhai New Area. During the saturation stage of urbanization, rural residential land evolved in tandem with other forms of land use, with more efficient land use and diverse uses. The main pattern of rural residential land in a suburban region is still edge-expansion, dispersion has expanded in the Binhai New Area, and urban encroachment is the way of urban development in the inner suburbs. Economic factors and economic location strongly impact the dispersion pattern. Edge-expansion and infilling patterns are impacted by comparable variables, including geographical location, topography, population resources, and economic location. Furthermore, the amount of economic growth influences the edge-expansion pattern. It might be influenced by land policy, and the eight elements have no substantial relationship with urban occupancy. Based on resource endowment and pattern features, certain optimization techniques are given.

Keywords Land-use transition · Landscape expansion index · Rural residential land · Driving mechanism · Tianjin

Introduction

Climate change and pandemics pose challenges to global poverty reduction, as do new urban poverty issues caused by urban and rural population movements, such as poor living conditions due to insufficient urban infrastructure supply, health issues caused by overcrowding, exposure to large amounts of concentrated waste, unsustainable resource consumption, and influenced farmers' lifestyles. The global human rush to cities is resulting in the widespread conversion of adjacent lands, such as forestland, cropland, and rural construction land, to urban development with a corresponding decline in rural areas (Estoque et al. 2016; Liu et al. 2018).

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Through sprawl and dispersed growth, urban expansion has taken rural land, fragmented surrounding agricultural and natural regions (Başnou et al. 2013; Salvati et al. 2013), changed the spatial organization of rural areas, and severely impacted environmental and socio-economic systems (Liu et al. 2019a, b; Zang et al. 2020). Rural people are marginalized as a result of urban-oriented land policy (Lu et al. 2007; Su et al. 2015). The stability of rural culture has been undermined by metropolitan values (Zhou et al. 2018). Urban regeneration and growth and industrial construction all boost the economy and living standards, but they also result in unsustainable spatial patterns in rural areas due to the expropriation of rural land (Long et al. 2012; Yu et al. 2018); this phenomenon is particularly visible in urban-rural interfaces along coasts, plains, and metropolitan regions (Kurt 2013; Vaz et al. 2015; Abrantes et al. 2016). From 1953 to 2020, China's urbanization rate increased from 13.26 to 63.89%, making it the largest contributor to global urbanization from 2000 to 2020, with considerable changes in rural land-use patterns (Yao et al. 2014; Zhang et al. 2016). The ratio of rural residential land to urban construction land has dropped from 4:1 to 2:1, indicating that the area of rural areas continued to shrink and the structure and modes of rural residential land are changed in China (RESDC 2021). However, 500 million people still reside in rural regions, accounting for 36.11% of the population (NBSC 2021a). The report of the Communist Party of China's 20th National Congress suggested a thorough promotion of rural regeneration. We must prioritize agricultural and rural development, adhere to integrated urban and rural development, and smooth the flow of urban and rural elements, which is China's response to globalization and an important driving force to promote shared prosperity globally.

Although countries around the world have adopted different measures to change the problems of rural decline (Wilson 2009; Nilsson et al. 2014; Sonn and Gimm 2013), policies that are inappropriate for the stage of development may lead to problems of population polarization and urban stress (Kohler et al. 2015). The rural policy must obey the objective rules of rural development while also meeting the actual demands of rural development; thus, overall spatial planning and suitable interventions are required to address market failures and promote rational rural development. Therefore, it is a basic work to systematically investigate the evolution patterns of rural residential land in different regions and optimize the space of residential land for promoting the efficient use of rural land resources and rural-urban integration. There are relatively many studies on rural settlements land at different levels. Supported by multi-source data and spatial analysis technology, existing studies have focused on the spatial pattern evolution, distribution characteristics, influencing factors and driving mechanism, intensive utilization evaluation, and other aspects of rural settlements land at different scales of the country, province, city, and county. Theories include geoscientific theories on the construction of the new socialist countryside (Liu 2011), theories on rural transformation development (Long 2012), niche theory (Qu et al. 2010), symbiosis theory (Wang et al. 2014), and the landscape ecology theory (Tian et al. 2014). And quality-of-life theory is used to guide the optimization mode of the spatial organization of rural settlements (Xu et al. 2019). Location evaluation and impact factors of rural residential land are explained by natural factors, production factors, and socio-economic factors (Liu et al. 2011; Hai et al. 2013; He et al. 2019a, b; McCarthy 2008). The natural environment forms rural residential land, and the socio-economic environment is a decisive factor in its spatial evolution. There is also considerable interest in the spatial distribution of rural residential land, including its characteristics (Bibby 2009; Yang, et al. 2019; Gorbenkova and Shcherbina 2020), its evolution, and its driving mechanism (Liu et al. 2010a, b; You and Chen 2019; Tan et al. 2021; Shi and Wang 2021), which provide theoretical support for controlling its expansion. Several optimization strategies for rural residential land have been studied, including grade optimization (Zou et al. 2012), merger renovation mode (Xie et al. 2014), farmer-oriented optimization (Qu et al. 2012), function-oriented optimization (Qu et al. 2017a, b; Li et al. 2018), coordinated development of population, and land resources-oriented spatial optimal pattern (Yuliastuli 2014; Kaida and Miah 2015; He et al. 2019a, b). In terms of expansion patterns, the combination of FRAGSTATS landscape pattern analysis and GIS is the most commonly used method to reveal the expansion characteristics of rural residential land (Wen et al. 2020; Chen et al. 2020; Liu et al. 2017). Ma et al. used the Weaver–Tomas composite coefficient (WT) method to quantitatively analyze the spatial structure of rural residential land (Ma et al. 2018a, b). These methods only analyze the area change of rural residential land and the change of overall landscape pattern, and it is difficult to deeply identify the development pattern of new rural residential land. There have been studies made on the different types of urban expansion, including infilling, edge-expansion, spontaneous expansion, and leapfrog pattern (Liu et al. 2010a, b; Chen et al 2010; Liu et al. 2019a, b). Other types of urban growth are recognized, such as linear development, large-scale project, and clustered branches (Wilson et al. 2003). Some studies defined the rural residential expansion patterns based on the urban expansion pattern (Tian et al. 2016; Chen et al. 2020). As the natural resource carrying capacity and urbanization development level of the study area are different, the classification of expansion models cannot be fully applicable to metropolitan areas with tight resources.

Besides, previous studies have not paid enough attention to the expansion patterns and driving mechanisms of rural residential areas in metropolitan areas, especially at the scale of the landscape pattern. In addition, comparative analysis on the dynamic evolution of rural residential areas in multi-period and long term is still rare. There is a paucity of domestic research on explaining the characteristics and driving mechanisms of rural residential land transformation based on the modified S-curve of urbanization and industrialization theory. Therefore, we constructed a theoretical framework based on theories of the industrialization phases and S-shaped curve urbanization. The land-use conversion matrix and the RRLE are used to reveal the transition characteristics of rural residential land, and more extensive index systems are computed using multiple linear regression methods to analyze the driving mechanism. The RRLEI has divided it into four categories, including edge-expansion, infilling, dispersion, and urban encroachment, which is more consistent with the current situation of rural residential land expansion in metropolitan areas. The more detailed spatio-temporal expansion patterns also provide a multi-dimensional analysis basis for the explanation of its expansion driving mechanism, which is helpful to put forward suggestions for spatial optimization of rural residential land in line with the regional characteristics of a metropolis and sustainable development. This study focuses on three questions: What are the dominant and recessive features of rural residential land transitions in Tianjin? What is the mechanism driving the rural residential transition? How can rural residential land be optimized in the context of integrated urban-rural development? It intends to give theoretical support as well as a decision-making basis for rural land planning and management in metropolitan regions. Moreover, evidence from Chinese metropolitan areas contributes to worldwide rural rejuvenation.

Theoretical framework

Scientific delineation of regional economic development stages is the basis for identifying the stages and characteristics of regional land-use transition. The industrialization stage hypothesis of Chenery uses per capita GDP as an indication of regional economic growth. He proposed the existence of four stages of industrialization development, namely, pre-industrial society, industrialized society, post-industrial society, and modernized society, and determined the composition of the standard industrial structure at different development stages (Chenery 1989). Northam conceptualizes urbanization as an S-shaped curve (Northam 1979); after calibration, Chinese scholars have proposed a four-stage urbanization theory that fits the national context: primary stage of urbanization, mid-stage urbanization, late stage of urbanization, and end-stage urbanization (Fang et al. 2008; Chen and Zhou 2005). The primary stage of urbanization has a population urbanization rate of 1–30%, rural population and agriculture dominate, and rural residential land distribution is far greater than urban. Accelerated urbanization is defined by 30–60% population urbanization rates when urban populations and industrial economies increasingly gain importance. The decelerated urbanization is reached when the population urbanization rate hits 60–80%. While urbanization improves, the rate slows. Despite the urban population and industrial sector dominating the terrain, industrialization is slowing. The 80% saturation stage of urbanization is characterized by slow or stagnant urban population growth, a narrowing of the urban-rural difference, and "counter-urbanization" which has become a development phenomenon. The theory is better suited to explain the transition characteristics of rural residential land in China. The hypothesis of smallholder land-use survival helps explain rural land growth patterns (Angelsen 1999). If land resources are sufficient, peasants use dispersion expansion to achieve subsistence with the least work input, resulting in maximum labor productivity. When land becomes scarce, individuals use the land intensively and bring technology and capital to increase land production efficiency, while labor productivity suffers (Meyfroidt 2018).

Land-use transition refers to the transformation of regional land use from one form to another over a period corresponding to the transformation of economic and social development stages, driven by economic and social changes and innovations, including dominant and recessive features. The dominant features are changes in the quantity and spatial structure of the land use categories throughout time. The recessive features dominate forms such as quality, property rights, functions, management modes, input, and output (Long 2012). The drivers of rural residential land transition can be divided into exogenous and endogenous factors. Therefore, based on the theories of socio-economic development and smallholder land-use survival, we attempted to construct a theoretical framework for analyzing the dominant and recessive characteristics of rural residential land transformation and their driving mechanisms in different periods and proposed strategies and directions for optimizing rural spatial patterns based on different resource endowments and expansion patterns of rural settlements (Fig. 1).

Data source and methodology

Study area

Tianjin is located on the North China Plain, north of Yanshan mountain, on the Bohai Sea. Tianjin's landscape is characterized by "high in the northwest" and "low in the southeast," with 1052 m in the north and 3.5 m in

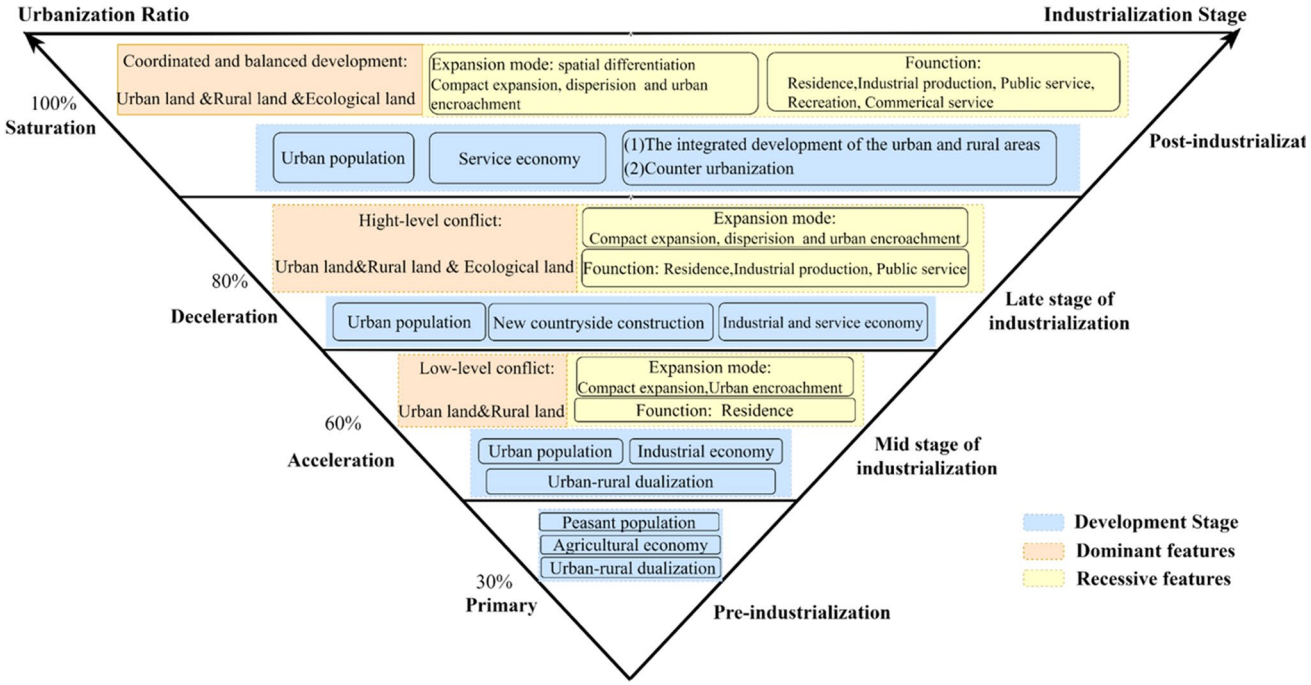

Fig. 1 The theoretical framework for the transition of rural residential land

the south. Tianjin is the Bohai Economic Rim's hub and an R&O zone. Due to its strategic location and plentiful natural resources, it is a leader in new-type urbanization. Urbanization initiatives have been critical in increasing urbanization to 84.70% by 2020 (NBSC 2021a, b). Tianjin's Dongli District has implemented a linked urban-rural construction land policy since 2006. Tianjin's Wuqing District implemented the pilot reform of the land acquisition system in 2011. Tianjin's Jizhou District has been chosen to participate in the national rural land system reform, including rural land acquisition, rural collective operating construction land, and rural homestead land reform in 2015. Land policies have molded Tianjin's rural residential land for a long time. This region has experienced considerable changes in population and construction land; the total rural population decreased by 33%, from 3.93 to 2.12 million, while the area of rural residential land increased by 46.06%, from 826.52 to 1193.97km^2 during 1990–2020 (RESDC 2021). Tianjin's land use will change dramatically in the future, becoming an important part of the Beijing-Tianjin-Hebei metropolitan area with Beijing at its core. Tianjin has jurisdiction over 16 districts, according to the level of economic development and urbanization; it is divided into four circles, including the downtown, inner suburbs, outer suburbs, and Binhai New Area. The downtown includes Hongqiao District, Hebei District, Hedong District, Hexi District, Nankai District, and Dongli District. Inner suburbs include Xiqing District, Wuqing District, and Jinghai District. The outer suburbs include Baodi District, Ninghe District, and Jizhou District (Fig. 2).

Data sources

This analysis uses land-use data from 1990, 1995, 2000, 2005, 2010, 2015, and 2020, which is provided by the Resource and Environment Science and Data Center (RESDC), Institute of Geographic Sciences, and Natural Resources Research (IGSNRR), Chinese Academy of Sciences. The land-use database from 1990 to 2010 is extracted from the remote sensing digital images of the Landsat TM/ETM satellite. The database of the year 2015–2020 with 30 m resolution was updated from Landsat 8 satellite. Primary land-use type is classified into six categories according to the LUCC, namely, arable land, forestland, grassland, water bodies, construction land, and unused land (Liu et al. 2005). The construction land includes urban construction land, rural residential land, and mining and industrial land. Rural residential land is composed of housing land, industrial land, commercial land, infrastructure land, and vacant land.

Image interpretation precision meets the quality control standard for LUCC remote sensing interpretation. Arable land, urban construction land, and rural residential land have data interpretation correctness rates above 95%, while grasslands, forestland, and water bodies have rates over 90%, and unused land has rates exceeding 85% (Ning 2018). DCRES also provides all river networks in China and all sub-basins with an area greater than 100 km^2

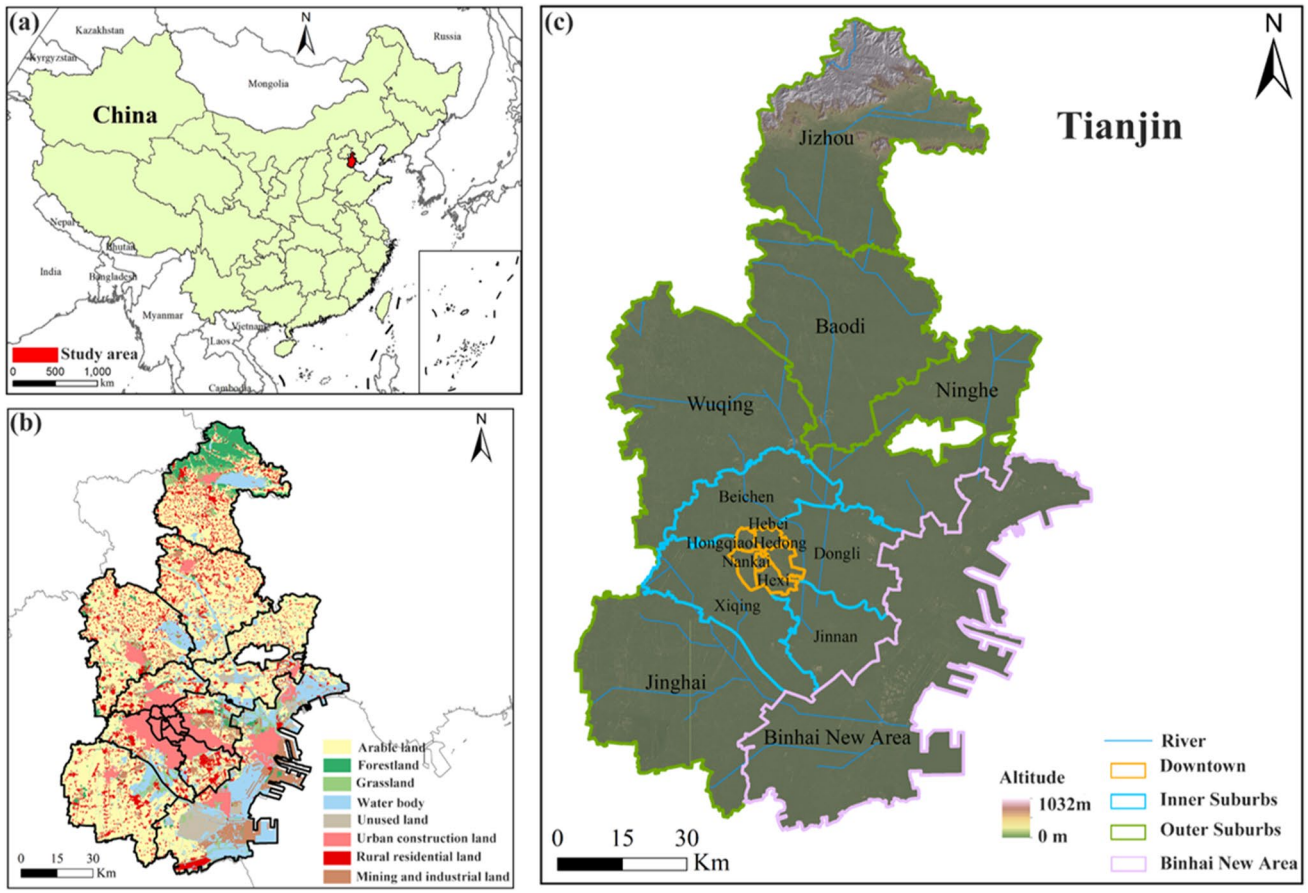

Fig. 2 Map of Tianjin in the year 2020 (**a** the location of Tianjin in China, **b** LUCC of Tianjin, **c** altitude and administrative districts of Tianjin)

extracted based on the digital elevation model (DEM) and the spatial distribution data of national GDP and national population density in each period with a spatial resolution of 1 km × 1 km. The DEM data was SRTM data with a 90 m resolution (CNIC 2020). Mountain slopes and mountain shadows were extracted based on DEM data. Vector data including roads and railway stations in 2015 were acquired from OpenStreetMap (OSM 2020). The other statistics were obtained from the Tianjin Statistical Yearbooks (TSB, 1991-2021).

Methodology

Land-use conversion matrix

The study analyzed conversion matrices in every two adjacent datasets from 1990 to 2020 using the raster calculator function of ArcGIS software to determine changes in land use. The property value in pixels revealed changes to each land-use type. Land use changes of rural residential land include source and usage. An index of land-use conversion rate (LCR) can represent the dominant process of land-use change in rural residential land. The calculation formula is shown in formula (1) (Tian et al. 2003).

$$\mathrm{LCR}_{ij} = \frac{A_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n}A_{ij}} \quad (1)$$

where LCR_{ij} is the probability of land-use category i transformed into j; A_{ij} is an area of land-use category i transformed into j; and n is the sum of land-use categories.

Rural residential land expansion index (RRLEI)

Landscape pattern is the spatial distribution and combination rule of landscape spatial patches with different sizes, shapes, and attributes (Li 1989; Franklin and Forman 1987). Landscape patterns analysis attempts to grasp the complicated relationships between abiotic and biotic components of the landscape to foresee the outcomes of landscape change

in terms of species protection, biodiversity, and ecosystem function (Schröder and Seppelt 2006).

Landscape indices can be used to uncover landscape structures and spatial heterogeneity. Different algorithms of landscape indices can be used to quantitatively analyze the spatial characteristics of patches, classes of patches, or entire landscape mosaics (O'Neill et al. 1988; Turner and Gardner 1990; Matsushita et al. 2006). The landscape expansion index is a method for describing the spatio-temporal dynamics of land use in fast-growing regions better than the landscape index (Liu et al. 2010a, b). Using the landscape expansion index, this paper defines the rural residential land expansion index (RRLEI) to classify the expansion of rural residential land into four modes. RRLEI was defined using the buffer analysis, which is one of the most important spatial analysis functions of ArcGIS10.5. The buffers are the zones within specified distances around any new patch of rural residential land (Fig. 3). The buffer distance may affect the RRLEI value. Generally, the buffer distance should be set roughly equal to or smaller than the spatial resolution of remotely sensed data (Liu et al. 2010a, b). According to the image resolution of 30 m and the area of Tianjin, the buffer distance is set equal to 30 m, and the equation of RRLEI is as follows (Tian et al. 2014):

$$\mathrm{RRLEI} = \frac{A_0}{A_0 + A_C} \times 100 \tag{2}$$

where RRLEI is the rural residential land expansion index;A_0 is the intersection between the buffer zone and the occupied land category; and A_C is the intersection between the buffer zone and the vacant land.

When $0 < \mathrm{RRLEI} \leq 50$, the newly grown patch is defined as the edge-expansion pattern, which means the rural residential land expanded in parallel along the edges of the old ones (Fig. 3a). When $50 < \mathrm{RRLEI} \leq 100$, the new patch is defined as the infilling pattern, which means the new patch fills the gaps between the two old patches or fills the holes within the old patch (Fig. 3b). When $\mathrm{RRLEI} = 0$, the new patch is defined as a dispersion pattern, the new patches are isolated from the old one and there is no old patch in the buffer zone (Fig. 3c). The urban encroachment pattern is extracted from the increased urban construction land (Fig. 3d). Edge-expansion is the most compact pattern, dispersion is the diffusion pattern, and infilling is the coalescence pattern. Highly intensive use of land includes edge-expansion and infilling expansion, while dispersion is an inefficient pattern of land use. Urban encroachment is the seizure of rural residential land by urban-gro.

The multi-variate statistical modeling

Natural factors define the macro-level direction of land use/cover change (LUCC) owing to its stability and cumulative impact on the regional environment (Kraaij and Milton 2006), whereas human activities are the key driving factors (Shao et al. 2006). Topography and vegetation are key determinants on the landscape scale (Roy et al. 2005). Long term, both natural and human forces, influences landscape modes (Tittonell et al. 2005). Existing research indicated that topography and resource endowment were the main endogenous driving factors that affected the change of rural residential land (Ariti et al. 2015), given the effect of light, temperature, precipitation, technology, and population on residential land changes is mainly reflected on the macro-scale (Tian et al. 2016; Tian et al. 2014; Ma et al. 2018a, b). Therefore, the geographical location, topography, and population resources were selected as endogenous driving factors of rural residential land expansion. In a similar vein, urbanization, economic development level, and policy implication

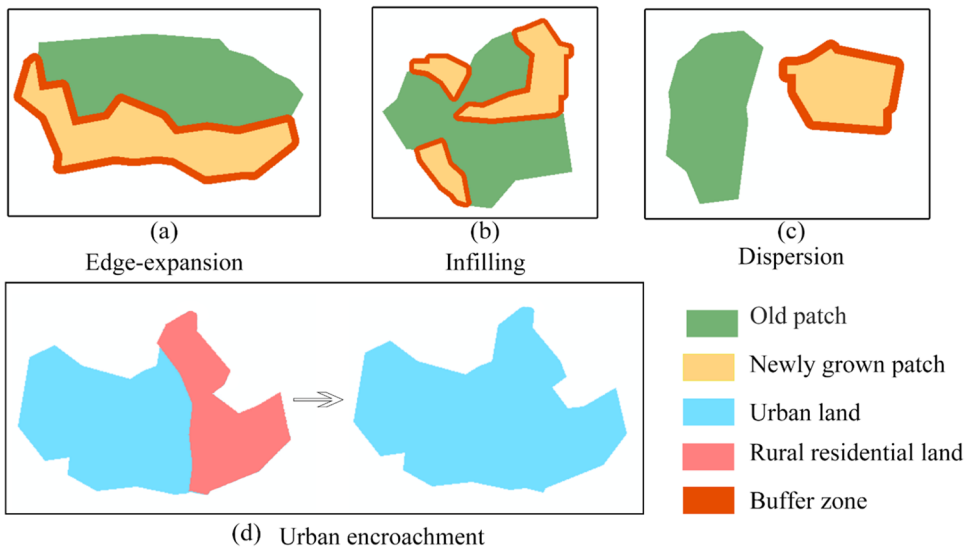

Fig. 3 Four expansion patterns of rural residential land

were the main exogenous factors that affect the evolution of rural residential land (Tan et al. 2013), such as household income influences farmers' subjective willingness to build houses, which will change the structure and function of rural residential land (McCarthy 2008). We selected economic locations and economic development level as exogenous factors of rural residential land expansion (Zhou et al. 2020; Ma et al. 2018a, b). The driving factors are listed in Table 1, and Fig. 4 shows the spatial distribution of the eight drivers (using 2005 as an example), the distance to the town, road, rail station, and water body is counted using the Euclidean distance algorithm.

Multiple linear regression is used to explore the proximate cause of certain expansion modes of rural residential land. We employed STATA 15.0 to conduct a bivariate correlation analysis between RRLEI and its potential

Table 1 Index system of driving factors

Category		Indicators	Code	Source
Endogenous factors	Geographic location	Distance to water body (km)	x_1	(Tian et al. 2016; Tian et al. 2014)
	Topography	Mountain slopes (°)	x_2	(Zhou et al. 2020)
		Mountain shade	x_3	(Ma et al. 2018a, b)
	Population resources	Population density (persons/km^2)	x_4	(Tian et al. 2016)
Exogenous factors	Economy	GDP density (million yuan/km^2)	x_5	(Zhou et al. 2020)
	Economic position	Distance to the city center (km)	x_6	(Tian et al. 2016; Tian et al. 2014)
		Distance to railway (km)	x_7	(Zhou et al. 2020)
		Distance to the main road (km)	x_8	(Ma et al. 2018a, b; Su et al. 2019)

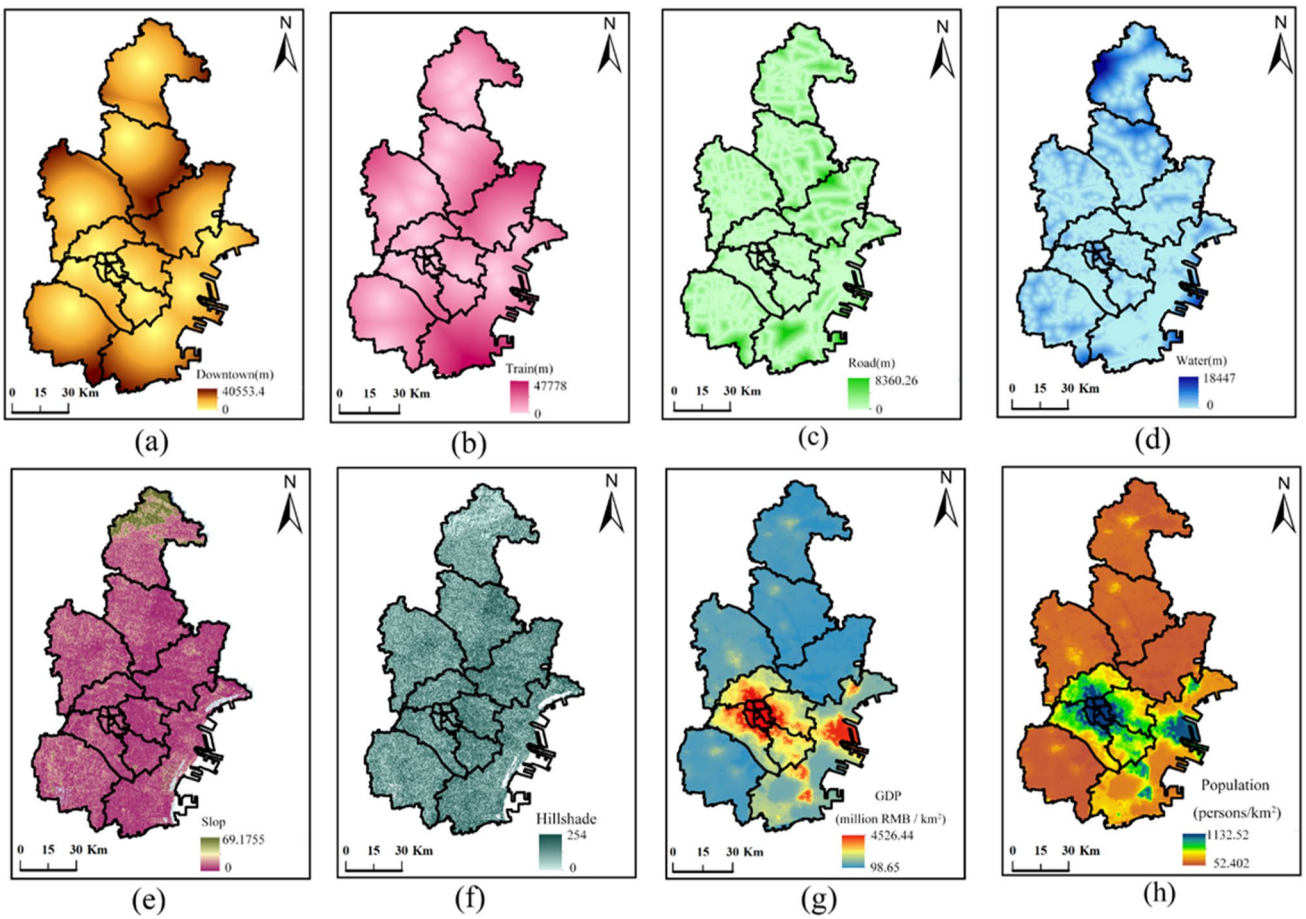

Fig. 4 The spatial distribution of the eight drivers in 2005, **a** the distance to the downtown, **b** the distance to the train station, **c** the distance to the road, **d** the distance to the water body, **e** the mountain slope, **f** the hillshade, **g** the GDP per capita, **h** population density

influencing factors. The stepwise selection method was used to incorporate the independent variables into the model in the specific operation (Li et al. 2012). The idea of stepwise regression is to introduce the independent variables into the model one by one, and then perform *F*-tests on the model and *t*-tests on the already introduced independent variables to ensure the overall validity of the model and the significance of each independent variable ($p < 0.1$). R^2 is used to describe the goodness of fit of the model (Draper and John 1981). The formula is as follows:

$$\text{Area} = \sum_{i=1}^{n} \partial_i x_i + \partial_0 + \varepsilon_0 \quad (3)$$

where Area is the expanded area of a certain rural residential land expansion pattern, x_i is the driving factor, ∂_i is the coefficient of the driving factor of i-th, ∂_0 is the constant, ε_0 is a random error, and i is the number of non-collinear driving factors, n =8.

Result analysis

Land-use conversion characteristics of rural residential land

The conversion paths of rural residential land and other categories of land use from 1990 to 2020 (Fig. 5) in Tianjin demonstrate that rural residential lands are sourced from the agricultural, forest, grassland, water bodies, and construction land; rural residential lands are utilized in urban, other construction, arable, forest, and water bodies. The area of rural residential land was 862.52 km^2 in 1990, and the net increase area (NIA) of rural residential land was 367.45 km^2 in 2020. The net increase rate (NIR) of rural residential lands was 46.06% from 1990 to 2020. The sums of rural residential land transformed into other categories of land use were 3590.28 km^2, including urban construction land, other construction land, arable land, forestland, grassland, water bodies, and unused land. The sums of other categories of land use transformed to rural residential land were 730.29 km^2, and the increased rural residential land is mainly sourced from arable land, other construction land, water bodies, forestland, and grassland. Between 1990 and 2020, urban construction land expanded due to the increased area transformed from rural residential land, while rural residential land expanded due to the increased area transformed from arable land. Rural residential land's NIA is −8.38% during 1990–1995 and then decreased steadily from 1995 to 2010, is 31.19%, 30.21%, and 24.92%, respectively. The NIA reached the highest value of 76.34% in 2015, and then rural residential land declined to 23.89%. Rural residential land increased at the quickest pace during 2010–2015 because the area of rural residential land converted to other types of land is small, while the area of other types of land converted to rural residential areas is large, leading to a large net increase rate. The net increase of arable land converted into rural residential lands was 98%, while rural residential land is mainly transferred out to arable land and urban construction land. Unlike this stage, the source of rural residential land is mainly arable land, other construction land, and urban construction land during 2015–2020, where the net area transferred from rural residential land to forestland, grassland, water body, and unused area increased, increasing to 14.26 km^2 in the green area.

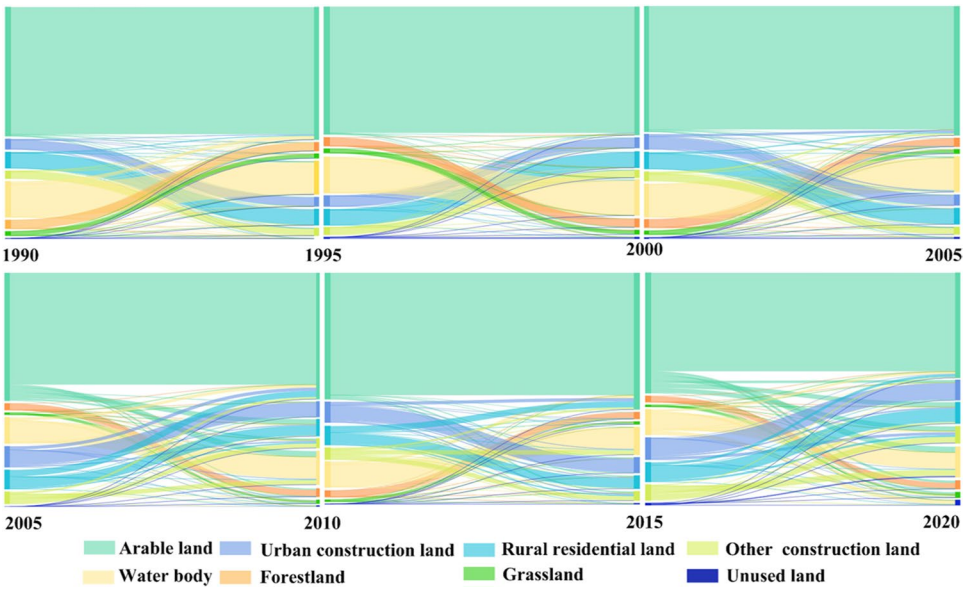

Fig. 5 The conversion paths of rural residential land and other categories of land use from 1990 to 2020. The width of the flow line represents the area of different categories of land use (km^2)

As far as rural residential land transformed into other categories of land use from 1990 to 1995, the rural residential land transformed into arable land was about 64.66%, transformed into urban construction land was about 23.18%, and transformed into other types of land use was about 12.16%, showing that agricultural and urban expansion competed for rural residential land. Approximately 88.13% of the area was transformed from rural residential to arable land, 2.23% of the area was transformed from rural residential to forestland,

1.50% of the area was transformed from rural residential to other construction land, and 1.37% of the area was transformed from rural residential to grassland between 1995 and 2000. From 2000 to 2020, the percentage of area transformed from rural residential land to arable land decreased year by year, with a minimum value of 46.62% in 2005, while more rural residential land was transformed into urban land and other construction land. From 1990 to 2020, the proportion of rural residential land transformed into forests, grassland, and water bodies has been small, fluctuating slightly over time.

Other categories of land use transformed into rural residential land over six time periods show that arable land was the main source of rural land expansion, though the proportion of arable land transformed into rural land declined over time; in 2020, the proportion of arable land transformed into rural residential land fell to 57.89%, while from 1990 to 2020, the sum area of construction land transformed into rural residential land gradually increased, the proportion of construction land transformed into rural residential land highly rose to 18.94% during 2015–2020. The total sum of forestland, grassland, and water bodies transformed into rural residential land was below 20% during 1990–2020.

In the past 40 years, the transformation of rural residential land to arable land and urban construction land in Tianjin has become more and more frequent, and the transformation area has been expanding. New rural residential land usually occupies a small amount of arable land first, then occupies a large amount of arable land, and finally recovers a large amount of arable land. This shows that China's policies on farmland protection have been strengthened. The transformation from rural residential land to urban construction land reflects the trend of small growth, growth, and big growth. This reflects the changing trend of urban expansion in different stages of Tianjin's urbanization development.

Spatio-temporal patterns of rural residential land expansion

From 1990 to 2020, rural residential land expansion modes show spatial heterogeneity (Fig. 6). In general, the edge-expansion mode has the largest proportion, and the infilling mode has the smallest. The urban encroachment and infilling modes have decreased, while the proportion of dispersion patterns has slowly increased over time. Different development stages and policy directions in the region resulted in varying degrees of competition for rural and urban land. A negative link exists between edge-expansion and urban encroachment mode, the former expands rural residential land, while the latter expands urban construction land.

From 1990 to 2000, Tianjin was in the stage of accelerated development (Fig. 7). During 1990–1995, edge-expansion and urban encroachment patterns accounted for 49.63% and 38.40% of the total expanded area, respectively, and dispersion and infilling patterns total 11.86% (Fig. 6a). From 1995 to 2000, the proactive expansion modes including edge-expansion, infilling, and dispersion accounted for 87.49%, 8.31%, and 3.55% of the total area, respectively, with almost no urban construction land expansion (Fig. 6b). Between 2000 and 2010, Tianjin was in the stage of decelerating development (Fig. 7). The tertiary industry became the primary driver of urbanization throughout the latter stages of industrialization. Total of 2.6 million rural people transferred to cities, resulting in a considerable increase in the urbanization rate (75.1%), which reduces the proportion of edge-expansion to 53.59% while increasing the proportion of urban encroachment to 21.82.4 % (Fig. 6c), and the dispersion expansion rose to 21.22%. Between 2005 and 2010, the urbanization rate climbed to 79.6%. Edge-expansion and dispersion became the dominating patterns, rising to 50.59% and 36.04%, respectively, while urban encroachment fell to 9.84% (Fig. 6d). The period from 2010 to 2020 was the saturation stage with the urbanization rate exceeding 80% (Fig. 7). This corresponds to post-industrialization and top economic development, meaning that urban expansion was slow or even stagnant. In addition to decreasing land demand to expropriating rural regions, the service industry became the driving factor behind urbanization. From 2010 to 2015, dispersion and urban encroachment all decreased steadily (Fig. 6e), while edge-expansion and infilling increased to 63.40 % and 20.83%, respectively. From 2015 to 2020, the proportion of edge-expansion remained stable at 64.01%, that of dispersion increased to 26.39%, and that of urban encroachment decreased to 0.02% (Fig. 6f). The proportion of the urban encroachment scale fell as the pace of urbanization grew, which matched the discovery that the rate of urban growth was inversely connected to city size (Sun and Zhao 2018). In the new-type urbanization phase, the public and decision-makers have paid more attention to rural development, and several policies have promoted diversified rural residential land expansion patterns, including in situ urbanization, new-type villages, and distinctive towns. At the same time, some rural residential land became hollow villages.

Spatial metrics analysis provided further insight into the different expansion patterns. The percentage of rural residential land expansion modes (PREM) can be used to reveal

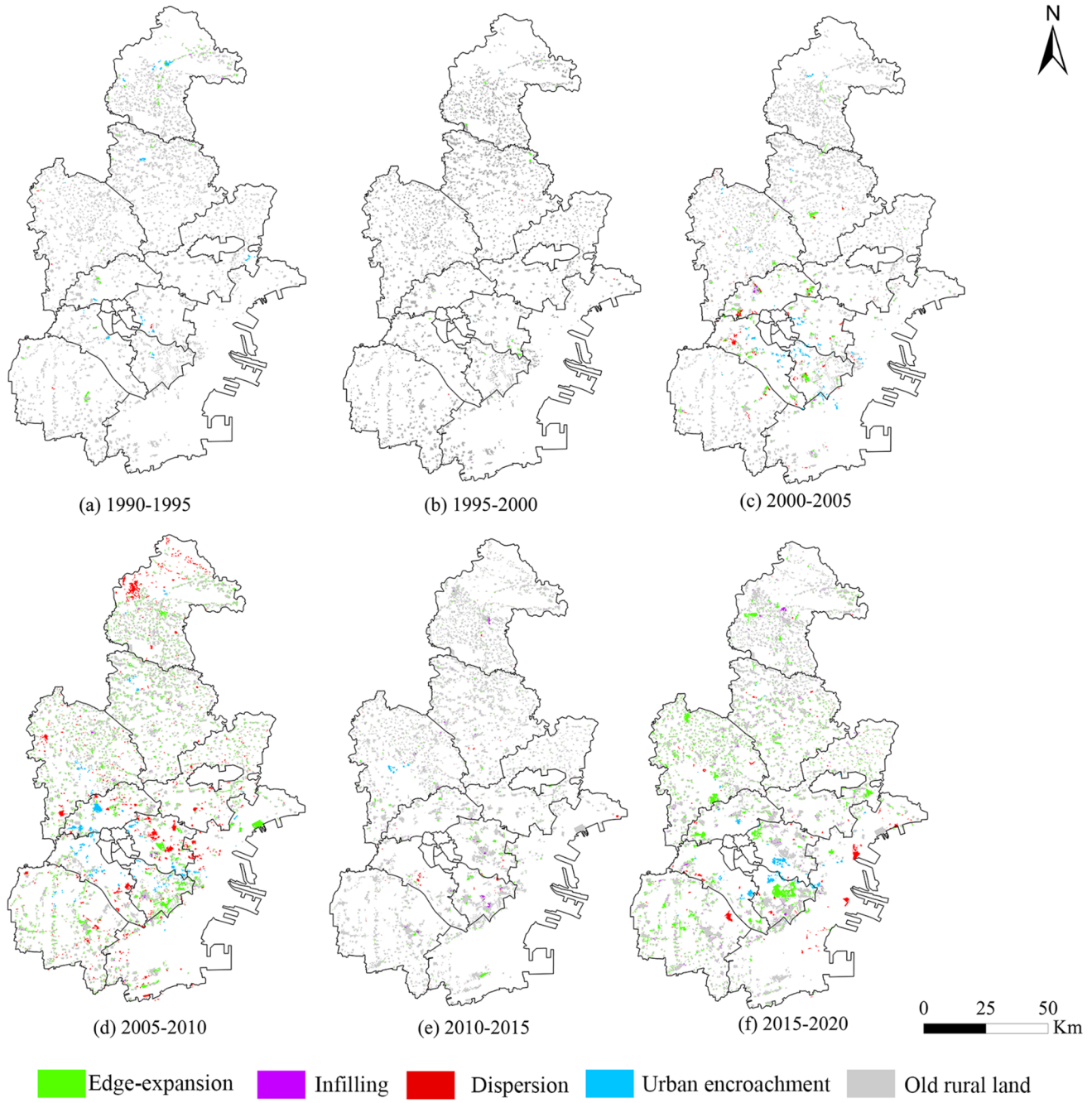

Fig. 6 The spatio-temporal expansion patterns of rural residential land

how modes are heterogeneous across regions (Fig. 8). The outer suburbs have more idle land than the inner suburbs, and the edge-expansion mode is higher in the outer suburbs than it is in the inner suburbs, and the urban encroachment mode is higher in the inner suburbs than it is in the outer suburbs. In contrast to the rural residential land levied by the government to support urban expansion, the rural residential land developed with a dispersion mode in areas not included in the planning, which helps farmers to improve labor productivity based on the theory of land use for petty farmers' survival. When land resources are scarce, petty farmers will choose compact expansion to increase land productivity through specific production methods, but labor productivity will fall. Based on the original rural residential land, the outer suburbs expanded mainly through edge-expansion and infilling mode. Furthermore, the mode of rural residential land expansion demonstrates the characteristics of regional differentiation.

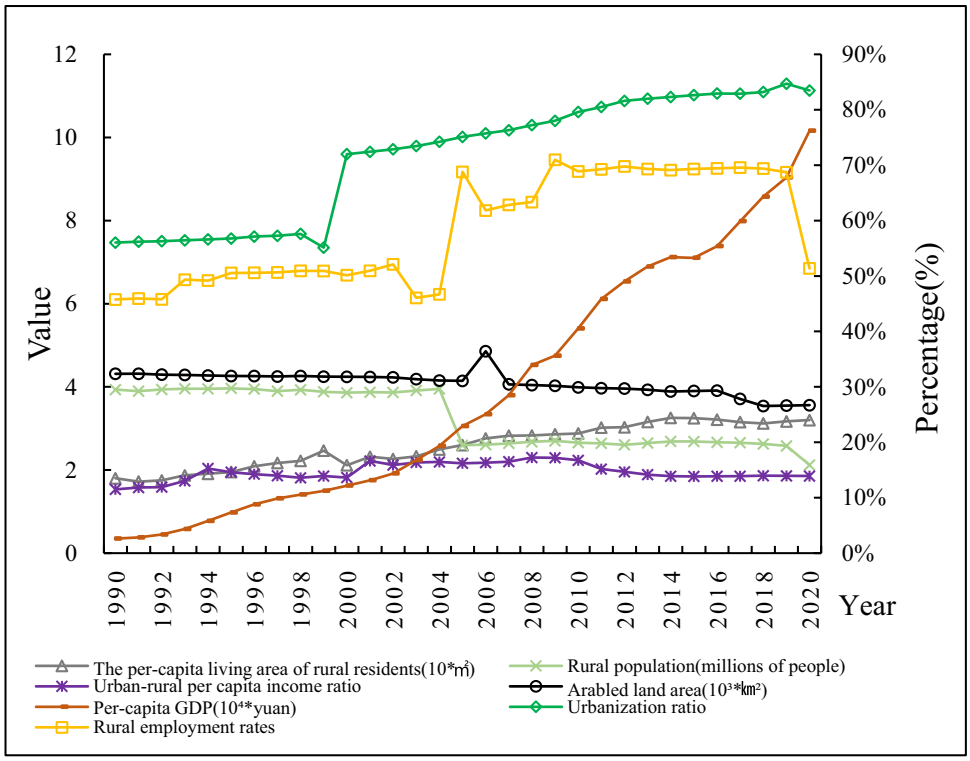

Fig. 7 Economic and social development indicators of Tianjin during 1990–2020

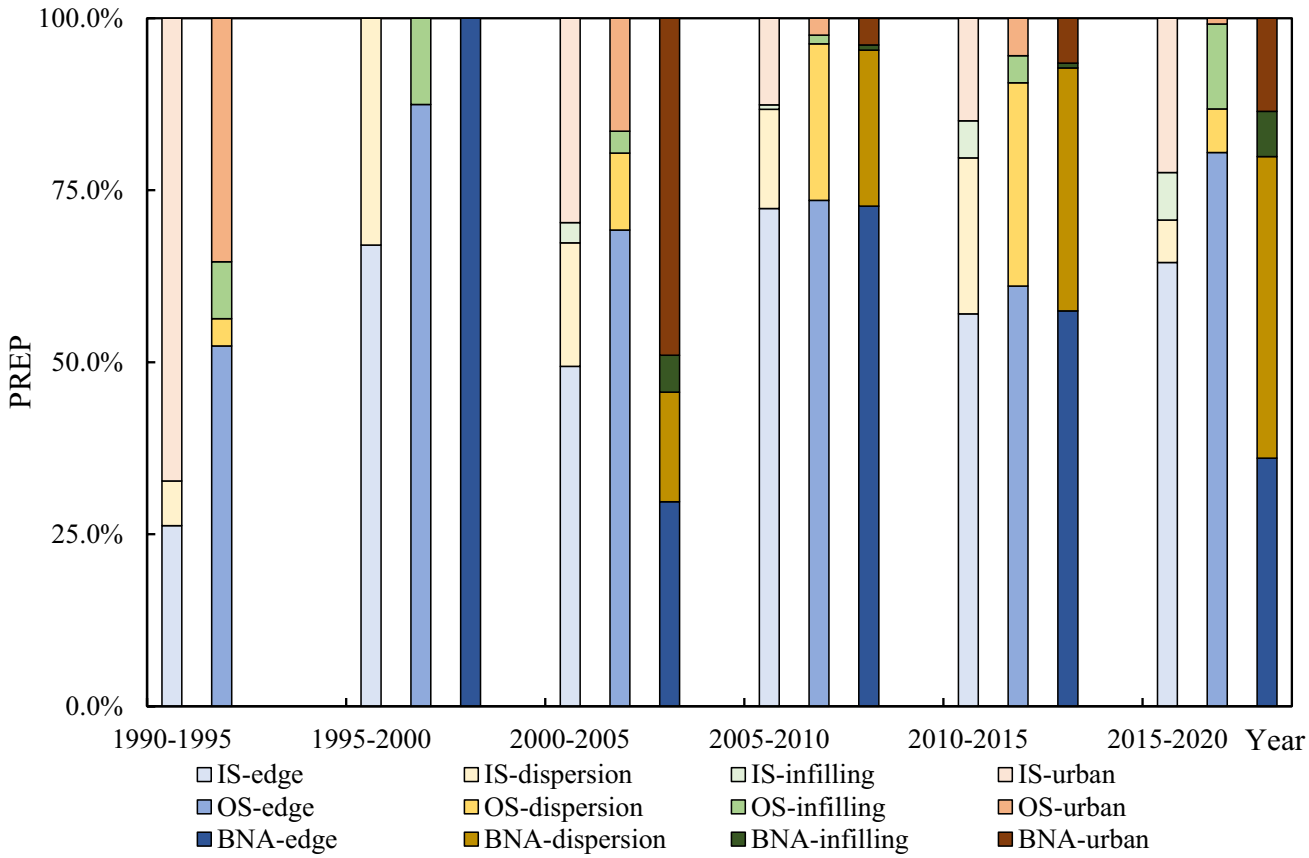

Fig. 8 The percentage of rural residential land expansion patterns in the inner suburbs, the outer suburbs, and the Binhai New Area during 1990–2020. (IS the inner suburbs, OS the outer suburbs, BNA Binhai New Area)

Rural residential land expanded toward the downtown in the inner suburbs, while expansion in mountainous regions slowed, and even stagnated during 1990–2020. Furthermore, the expansion mode is gradually diversified, and the degree of land-intensive use has been improved. In the accelerated urbanization stage, rural residential land is slowly expanding with edge-expansion and dispersion patterns, and a large number of rural residential land in the inner suburbs is occupied by urban construction land. In the outer suburbs, rural residential land expands in the form of edge-expansion, infilling, and dispersion, while urban encroachment is relatively small. The rural residential areas in Binhai New Area have hardly expanded.

During the decelerated development period, rural residential land expanded significantly in the inner suburbs and outer suburbs and began to expand slowly in the Binhai New Area. The infilling patterns in the inner suburbs increased, while the dispersion and urban encroachment decreased. The edge-expansion dispersion and infilling of rural residential land in outer suburbs are mainly patterns, but the proportion of dispersion pattern has increased, and the proportion of urban encroachment has decreased. The dispersion, edge-expansion, and urban encroachment increased in Binhai New Area. In the saturation stage of urbanization, the proportion of edge-expansion, dispersion, and infilling patterns is stable; the urban encroachment pattern in the inner suburbs is significantly reduced, while the urban encroachment pattern in the outer suburbs is improved, including edge-marginal expansion and dispersion which are the main expansion patterns in the outer suburbs. Binhai New Area is dominated by edge-expansion and dispersion, and a small number of rural settlements are occupied by urban construction land.

Driving factors of rural residential land expansion

The factors influencing the different expansion patterns and their significance are shown in Table 2. Economic factors and economic location have a significant influence on the dispersion pattern, while topographic factors have less influence on it. After controlling for other factors, the area with dispersion pattern is significantly negatively correlated with road distance, the closer the distance to the road, the larger the expansion area; significantly negatively correlated with hillshade, the lower the hillshade, the larger the expansion area; and significantly positively correlated with GDP per capita, the higher the GDP per capita, the larger the expansion area of rural residential land. The geographical position, terrain factors, population resources, economic factors, and economic position have a significant impact on the edge-expansion pattern. Its development relies on original rural residential land with sophisticated infrastructures, convenient transportation,

Table 2 The multiple linear regression of the RRLEI

	Dispersion area	Edge-expansion area	Infilling area	Urban encroachment area
x_1	0.0052	−0.0028**	−0.0284***	−0.0154
	(0.5645)	(−2.0462)	(−3.4269)	(−1.1122)
x_2	0.0132	−0.0147**	−0.0445	−0.0205
	(0.7723)	(−2.1769)	(−1.5344)	(−0.4761)
x_3	−0.0132*	0.0011	0.0175*	0.0146
	(−1.6609)	(0.7715)	(1.7232)	(1.0880)
x_4	0.0371	0.0478***	0.0788***	−0.0299
	(0.8172)	(8.3341)	(6.0787)	(−0.9126)
x_5	0.0912***	0.0118***	−0.0071	0.0110
	(4.6685)	(5.3632)	(−0.7353)	(0.4505)
x_6	−0.0090	−0.0000	−0.0388***	0.0006
	(−0.9368)	(−0.0222)	(−4.4867)	(0.0263)
x_7	−0.0024	0.0009	0.1434***	−0.0142
	(−0.2565)	(0.6218)	(8.6539)	(−0.9809)
x_8	−0.0519***	−0.0100***	0.0037	−0.0287
	(−4.1707)	(−4.3392)	(0.3060)	(−0.4628)
_cons	0.0320***	0.0009	−0.0130	0.0338**
	(4.2246)	(0.7157)	(−1.3713)	(2.2085)
N	1552	6842	933	591
R-squared	0.0402	0.0284	0.1388	0.0092

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, and values in parentheses are *t*-statistics

and rich resources. Specifically, after controlling for other factors, the expansion area with edge-expansion was significantly and negatively correlated with the distance from the road, the closer the distance from the road, the larger the expansion area; it was negatively correlated with the distance from the water body, the closer the distance from the water, the larger expansion area; it is negatively correlated with the slope of the mountain, the lower the slope of the mountain, the larger the expansion area; it is positively correlated with GDP per capita, the larger the GDP per capita, the larger the expansion area; and it is positively correlated with population density, the larger the population density the larger the expansion area of the rural residential land. Infilling mode is influenced by geographical position, terrain factors population resources, and economic position. After controlling for other factors, the infilling pattern's area is negatively correlated with distance from downtown, the closer to downtown, the larger the expansion area; significantly positively correlated with distance from the railroad station, the closer to the railroad station, the larger the expansion area; and negatively correlated with distance from water body, the closer to water, the larger the expansion area.

The comparative analysis of the driving factors of the different expansion patterns of rural residential land shows that the factors affecting the edge-expansion and infilling patterns are roughly the same, both of which are affected by the geographical location, terrain, population resources, and economic location. In addition, the edge-expansion pattern is also significantly affected by the level of economic development. As far as the economic location is concerned, the edge-expansion pattern is more likely to expand in the location where the traffic is developed and gentle, while the infilling pattern will expand near the downtown and in the location where the traffic is developed. Fewer driving factors are limiting the dispersion pattern, which is mainly affected by household income and distance from the main road. It is easier to develop near the new economic development zone and is not easy to be restricted by land and population sources. The correlations between urban encroachment patterns and all eight influencing factors were not significant, most likely because the conversion of rural residential land to urban construction land is more influenced by land policies and human factors, but these factors were not included as drivers due to their more complex quantification.

Discussion

The comprehensive feature of the rural residential land transition

The period from 1990 to 2000 was the accelerated urbanization phase when the demand for land was high due to the outward expansion of towns and cities as a result of economic and industrial growth. Because rural land resources were more available and rural residential land was occupied as urban construction land, the primary characteristic of land use transition was a low-level conflict between rural land and urban construction land. However, the forced intervention of land policies can change the conversion of land use, so it is necessary to analyze expansion patterns in the context of land policies of different periods. From 1990 to 1995, rural residential land is mainly developed through edge-expansion pattern, and very few through dispersion expansion, while a large number of rural residential land is occupied by urban construction land. This is because rural areas are still rich in resources, farmers have stable agricultural production activities, and there is still a demand for rural homestead and agricultural facility land. The rise of small and small-scale township companies in the process of rural industrialization reorganized rural resources, promoted farmers' non-agricultural income, and strengthened their willingness to improve the residential environment, ultimately promoting the expansion of rural residential land. Rural residential land close to downtown is converted to urban construction land. From 1995 to 2000, the land system reform strengthened the protection of arable land and the approval of urban construction land resulting in a large reduction in urban encroachment expansion. Rural residential land developed slowly in the pattern of edge-expansion, which can reduce the cost of agricultural production.

The period from 2000 to 2010 was decelerated urbanization phase. The increase in the level of economic development and the awareness of environmental protection led to an increase in the conversion of rural residential land to arable land, forestland, and grassland waters, resulting in a high degree of conflict between rural residential land and other types of land use, and a complex competition between urban land, rural land, and ecological land. From 2000 to 2005, the expansion of rural residential land accelerated, showing a variety of expansion patterns in the outer suburbs, including edge-expansion, dispersion, and infilling. More rural residential land near downtown has been converted to urban construction land. From 2005 to 2010, rural residential land shows a larger expansion. Four expansion patterns have emerged in both the inner and outer suburbs, the edge-expansion is the main expansion pattern, while urban encroachment still mainly occurs in the inner suburbs. But there is a large number of dispersion patterns in Jizhou District, Wuqing District, Ninghe District, Beichen District, Dongli District, and Xiqing District. In 2006, the new rural construction advocated for maintaining and enhancing the "family contract system," eliminating agricultural levies to enhance farmers' income. The income level and willingness of farmers to build houses have improved, and a large amount of rural

land has been developed and constructed. However, due to incorrect planning, the phenomenon of disorderly and scattered expansion of rural settlements is prominent, and the utilization efficiency is low. It was possible to use land compactly and protect the red line of arable land by edge-expansion pattern. There was a dramatic decline in the rural population as farmers relocated to cities and towns in pursuit of better opportunities (Fig. 8). As a result, the paradox of scarcity of urban land resources, the abandonment of rural arable land, and the increase of "hollow villages" have intensified.

The urbanization saturation stage occurred from 2010 to 2020. Integrated urban-rural development emphasizes the protection of food security and ecological safety, and rural residential land and other types of land use are developed in a coordinated manner under the policies of "cultivated land balance" and ecological protection. The phenomenon of disorderly expansion of rural residential land, new construction, and occupation of arable land privatively has caused widespread concern in society. The effective implementation of laws and regulations such as "one house per household" and the red line of arable land protection have curbed the disorderly expansion of rural residential land. From 2010 to 2015, the expansion of rural residential land decreased rapidly, and the dispersion and urban encroachment pattern decreased significantly, mainly edge-expansion and infilling, which promoted the spatial pattern of rural residential land order. From 2015 to 2020, rural residential land experienced large-scale expansion with edge-expansion pattern, while the proportion of urban encroachment decreased significantly, only in the four inner suburbs. The rural revitalization strategy introduced in 2017 promoted rural prosperity and development. The government has issued effective measures to strengthen the flow of urban capital, technology, and human resources into the countryside, promote the flow of urban and rural production factors, and provide a realistic demand for rural land expansion. The expansion of rural residential areas is characterized by more intensive and orderly development, and their functions are upgraded to commercial services, tourism services, and residential services, improving the intensification of land use.

In the Baota District of loess plateau, where the ecology is relatively fragile, the expansion of rural residential land has changed from a diversified pattern to a single pattern. Overall, the expansion of rural residential land was mainly concentrated around the city and in the river valley, and there was very little expansion of residents in deep gullies (Chen et al. 2021). However, our results show that in recent five years, the rural residential land in the outer suburbs of Tianjin is still dominated by large-scale edge-expansion, which may be due to the good ecological environment and high level of economic development in the outer suburbs, which is conducive to the implementation of the rural revitalization policy and promote rural development. This result is supported by other studies of rural residential land in metropolitan areas; a study on the evolution of rural residential land in Tongzhou District, Beijing also demonstrates the differences in the functions and structures of rural residential land in different periods of economic and social development (Li and Song 2020).

Driving factors and optimization strategy

Because the dispersion pattern is often remote from the urban center and independent of the old rural regions, the closer to the main road and the greater the degree of economic growth, the more farmers will be attracted. The convenience of transportation and higher economic level imply better industrial growth, which can lead to more non-agricultural job opportunities for farmers, as well as an increase in income and quality of life. Simultaneously, due to the relatively sufficient land resources, more arable land, forestland, and grassland are occupied to construct the rural new house. The plot area in the edge-expansion pattern is modest, but the dispersed scope is extremely large. It is attached to the old rural residential land, which means that there are high requirements for rural production environments, and the majority of farmers are still involved in agricultural production. As a result, access to water, a low slope, and a high population density are important elements in promoting its spread, as they are more suited to food cropping and cooperative production. Similarly, the closer the old rural residential land is to the transportation trunk line and the higher the economic level, the greater the mobility and selling price of agricultural goods, which is beneficial to raising farmers' income and stimulating the scale growth of the old site. The edge-expansion pattern has been the dominant pattern over the last 40 years, with an increased area of 1212.88 km^2, while the rural population has decreased by 1.81 million and farmers' per capita living area has increased by 14 m^2, indicating that many rural in remote mountainous areas have become hollow villages. The expansion area and scale of the infilling pattern are small. It also belongs to the in situ expansion of rural residential land, which with good agricultural production conditions attracts more farmers. Therefore, close-to-water areas and sufficient human resources are indispensable agricultural conditions. The infilling pattern, on the other hand, is typically found in rural locations surrounding urban centers with big shadows and poor lighting conditions. This may be due to limited land resources, but it is also beneficial to boosting land resource usage efficiency. Furthermore, the greater the distance from the train station, the more favorable its growth. The railway may occupy rural residential land, causing farmers to relocate to other rural regions, but there will be many urban encroachments near the railway.

As a result of the rapid urbanization and industrialization progress, more farmers are expected to migrate to cities and townships in the Tianjin metropolitan region. The rapid urbanization and industrialization process have transformed the economic and social systems of rural regions. Some farmers can continue to work in the primary sector, while others can relocate to adjacent cities and work in the secondary and tertiary industries. Although new settlements were obtained through three expansion methods, the old houses in remote rural areas were still retained, resulting in the contradiction between the waste of rural land resources and the tension of land resources in the urban area. Therefore, the spatial pattern of the urban and rural areas should be designed holistically. In particular, the development and usage of land resources at the urban-rural junction should take into consideration farmer living needs as well as urban development demands and implement a spatial pattern beneficial to carrying out integrated urban and rural development. In recent years, the transition in China's metropolitan areas has begun a trend of "counter-urbanization," with urban capital trying to embed itself in rural areas in new ways. It is demonstrated not only by the spatial changes of rural residential land but also by policies, such as the implementation of the "Comprehensive Land Reclamation of the Whole Area" project under the "Rural Revitalization" strategy. Therefore, the rural areas in the late urbanization period are not only a living space for farmers but also a key place to realize the economic inner circle, which depends on a more liberal land use policy and good cooperation between all levels of government, farmers, and enterprises.

Rural resource endowments are heterogeneous, and each expansion pattern has its advantages; thus, it is critical to have a diverse approach for optimizing rural residential land development (Fig. 9). To avoid disorderly expansion of rural land, the dispersion pattern should be limited. The newly developed rural resettlement sites to fulfill farmer relocation demands should be scaled strategically, with non-ecological regions given precedence. Binhai New Area may suitably

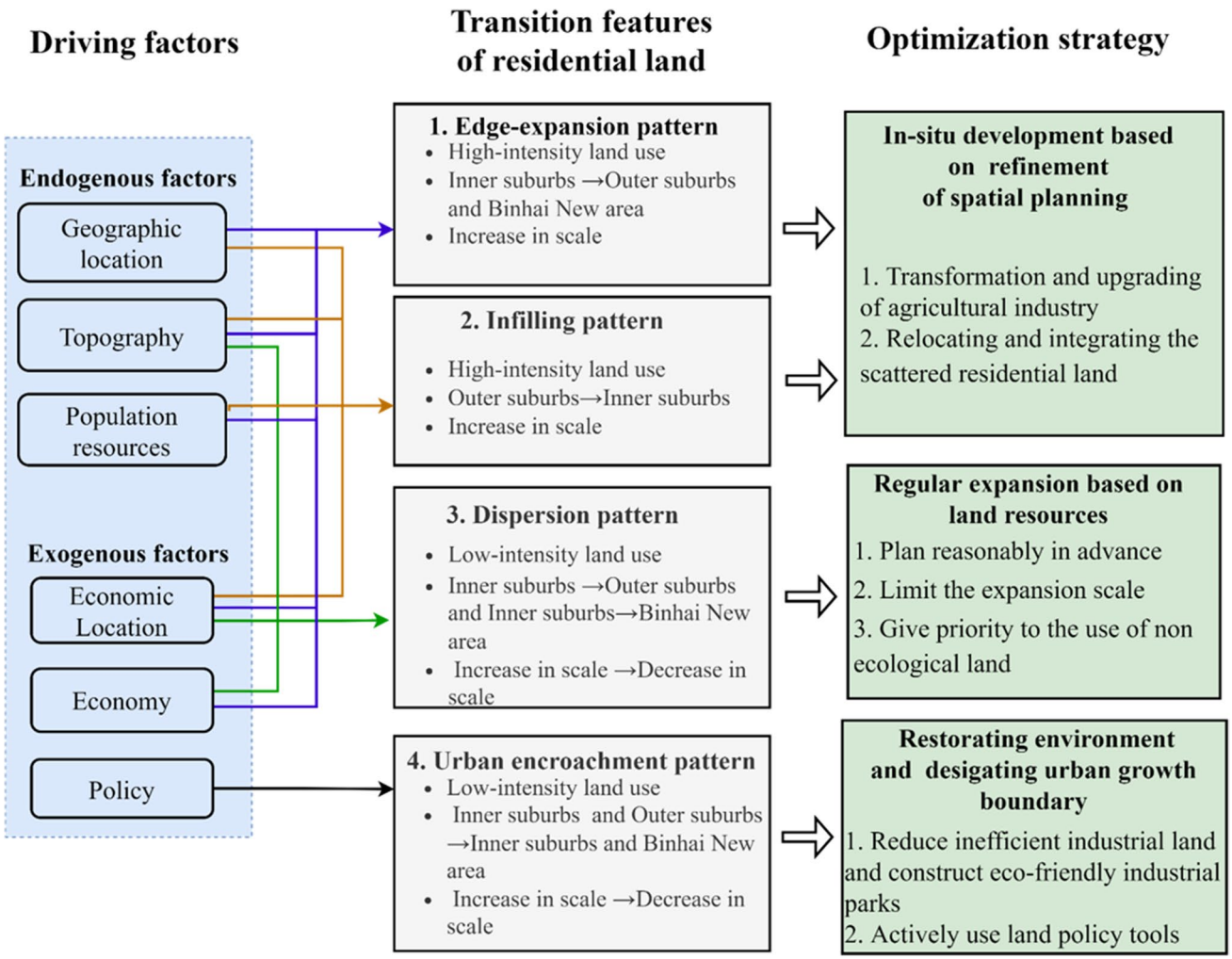

Fig. 9 The space differentiation characteristics, driving mechanism, and optimization strategy of rural residential land transition

carry out a dispersion expansion pattern. The edge-expansion is still the main trend in a rural area with good natural resource endowments near cities and towns. To favorably integrate with contemporary agricultural industrialization, policymakers should design development plans for rural residential land with good resource endowment. First, the rural production space, living space, and ecological space should be carefully planned, and resources may be restructured in the appropriate space. Revitalize rural culture by excavating ancient villages and giving traditional culture new significance. Transforming resource advantages into economic development advantages in rural areas, and the natural environment is also protected by building leisure farms, recreational communities, special ancient towns, country parks, other ecological payment projects, and traffic facilities to meet urban residents' demand for ecosystem services. The infilling pattern is most prevalent in the outer suburbs where urbanization is sluggish, such as Jizhou District. It has the potential to increase efficiency and reduce environmental impact. Farmers' productivity and living conditions can be improved in "hollow villages" through relocation, living environment management, and poverty alleviation schemes. To develop bigger size center communities, integrate scattered land and merge it with the central village in an infilling pattern. Although the pattern of urban encroachment is gradually decreasing, it remains the primary method of urbanization, particularly in the outwardly growing downtown. The scope of urban building land should be thoroughly investigated and approved, and urban limits should not encroach on agricultural or ecological land. Managers can use the policy tool of "reduction of inefficient industrial land" to sort out more ecological land indicators and give subsidies to farmers through the "ecological compensation" policy to alleviate the scarcity of urban ecosystem services. Land policy tools such as "the hook of urban construction land increase and rural residential land decrease" and "the marketization of rural collective-owned land market" are encouraged to be used, which can reasonably develop rural land to meet the land demand of urban expansion, but also ensure that rural residents are given reasonable land appreciation benefits.

Conclusion

The land use transition is the result of conflicting interests and balancing them in different sectors at different stages of economic and social development. The land use flow matrix can quantify the main sources and uses of rural residential land and reveal the dominant characteristics of its transition, while the identification of rural residential land expansion patterns can reveal its spatial evolution patterns, land use intensity and functions, and other implicit characteristics, providing a theoretical basis for rural residential land regulation. The dominant features of the rural residential transition include a diversified usage direction and a more complicated land-use competition involving rural land, urban land, and ecological land. In terms of spatial distribution, because of the siphoning effect of the large cities and downtowns, rural settlements are gradually expanding to the inner suburbs and Binhai New Area, while gradually declining in the outer suburbs. The recessive features are the change in utilization intensity and function of rural residential land.

The accelerated urbanization phase leads to low-level conflicts between rural residential land and other types of land use, with rural residential land competing mainly with urban construction land. The expansion pattern is mainly based on edge-expansion and urban encroachment modes; rural residential land is expanding on a smaller scale. During the deceleration stage of urbanization, there are more conflicts between rural residential land and other types of land use, and rural residential land is interchanged with construction land and ecological land, forming a more complex land use structure. The expansion patterns become diverse, including edge-expansion, dispersion, infilling, and urban encroachment patterns. The layout is relatively scattered, and rural residential land mainly plays the function of agricultural production and residential development. In the saturation of the urbanization phase, rural residential land developed in coordination with other types of land use. The expansion of rural settlements is mainly edge-expansion and dispersion with diversified functions, such as industrial production, public services, and commercial services, improving the intensive use of land.

Economic factors and economic location have a significant influence on the dispersion pattern, while topographic factors have less influence on it. The geographical position, terrain factors, population resources, economic factors, and economic position have a significant impact on the edge-expansion pattern. Its development relies on original rural residential land with sophisticated infrastructures, convenient transportation, and rich resources. Infilling mode is influenced by geographical position, terrain factors population resources, and economic position. Urban encroachment is more influenced by land policies and human factors. To avoid the disorderly expansion of rural land, the dispersion pattern should be limited. The edge-expansion is still the main trend in a rural area with good natural resource endowments near cities and towns. The infilling pattern maximizes land use efficiency and can safeguard the environment. Through this pattern, the abandoned rural residences in the "hollow village" may be reformed. Both edge-expansion and infilling patterns are examples of in situ expansion and should be encouraged. Special consideration should be given to the environmental impact of urban growth. It can not only appropriately develop rural land but also fulfill the

land demand of urban growth and ensure that rural inhabitants can earn acceptable land value-added income by adopting suitable land system instruments to relieve the tension between urbanization and ecological protection. There are some ways to improve our study. Further research is required to quantify the influence of land policy on the transition of rural residential land and provide more appropriate policy recommendations for future land-use plans.

Author contributions Lan Yang and Guangjin Tian contributed to the conception of the study; Lan Yang performed the experiment; Lan Yang and Jinlong Duan contributed significantly to analysis and manuscript preparation; Lan Yang performed the data analyses and wrote the manuscript; and Li Li helped perform the analysis with constructive discussions.

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Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publish Not applicable.

Conflicts of Interest The authors declare no competing interests.

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