Ecological Indicators 158 (2024) 111312

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Spatiotemporal patterns, driving mechanism, and multi-scenario simulation of urban expansion in Min Delta Region, China

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A R T I C L E I N F O

Keywords:
Urban expansion
Spatiotemporal patterns
Driving mechanism
Urban growth simulation
Min Delta Region

A B S T R A C T

Urban agglomerations are important spatial carriers for regional economic development, but sustained urban expansion has triggered a series of issues such as conflicts between "people and land" and "built-up areas and green spaces". However, many studies have rarely incorporated spatiotemporal patterns and driving mechanism into scenario simulation of urban growth, and has also overlooked subsequent discussions on the specific integration of simulation results with spatial planning. Considering the case of Min Delta Region, this study analyzes the spatiotemporal evolution of urban expansion based on multi-source data and explore the influential driving mechanism using Random forest algorithm. A combination of Markov and FLUS models was used to dynamically simulate future urban growth patterns. The results showed that 1) From 1995 to 2015, the urban expansion increased by 2.26 times, showing a trend of first accelerating and then slowing down. It was also discovered that there is an anisotropy toward expansion in the trajectory of urban growth. 2) With marginal increase and enclave increase, general urban expansion was observed to be changing from diffusion to agglomeration, and the urban expansion hotspots mainly located in the southeast coastal area. 3) Humanistic links, geographic position, social and economic considerations all played a role in the development of the Min Delta region, and can be summarized as the "four forces" driving mechanism model. 4) By 2035, the trend of continuous development with the Min Delta built-up area as the main body will be basically formed, and incorporating ecological restrictions can effectively restrain urban growth's encroachment into ecological spaces. Based on the simulation results, Min Delta region gradually showing a spatial structure evolution trend from the single core to the dual core mode, and then to the multi-center and networked mode. This study would serve as a multi-angle decision-making reference for regional spatial and ecological protection planning and urban growth management, and as a scientific foundation for high-quality development planning in the region.

1. Introduction

Globally, urban expansion refers to the development of cities (Schneider & Woodcock, 2008; Yang & Zhao, 2022). Currently, many developing countries are experiencing continuous urbanization. Urbanization in China has increased at an unprecedented rate from 17.90 % in 1978 to 64.72 % in 2021 (Zhou et al., 2019; Wu et al., 2018). Urban expansion is the most direct manifestation of urbanization in physical space. With China's urban built-up area expanding 8-folds in the past 40 years, the rate of land urbanization is far outpacing the rate of population urbanization (Kuang et al., 2016; Ma et al., 2016). Urban expansion is essential for fostering economic growth and quality of life, but it also inevitably causes disturbances in the natural environment and evolution of landscape patterns, resulting in several ecological issues, including heat island effect, water pollution, and biodiversity declination (Yang et al., 2021; Rustiadi et al., 2021; He et al., 2018; Simwanda & Murayama, 2018; Dadashpoor et al., 2019). An urban agglomeration is a highly developed urban form with spatial integration. Urban agglomerations are often economically advanced and densely inhabited, making more pronounced conflicts between the severe limitation of available land resources and the desire for urban expansion (Fang & Yu, 2017; Fang et al., 2020; Ma et al., 2023). Therefore, research on the external morphology and internal mechanisms of the urban growth process is of great importance for improving the planning and

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https://doi.org/10.1016/j.ecolind.2023.111312
Received 4 May 2023; Received in revised form 7 November 2023; Accepted 19 November 2023
Available online 1 December 2023
1470-160X/

management of urban agglomerations, guaranteeing regional ecological security, and promoting sustainable urban development.

The phenomenon of urban sprawl was initially dominated by American cities, where inefficient land use, low-density sprawl, and employment growth occurred on the fringes of cities or metropolitan areas (Garcia-López et al., 2015; Harvey & Clark, 1965; Yudhistira et al., 2019). Urban sprawl has many negative effects, including ecological degradation, reduction in arable land, and traffic congestion (Camagni et al., 2002; He et al., 2019; Catalán et al., 2008; Dinda et al., 2021). Therefore, in recent decades, the United States and other developed nations have partially achieved control on urban sprawl through urban growth boundaries, compact cities, new urbanism, etc. (Laidley, 2016; Brueckner, 2000). International scholars began to pay attention to urban sprawl in the early 1900s, as represented by the Chicago School in the early days, in which the three urban structure models are still considered the classic theory of urban research (Liu et al., 2022a; Gong et al., 2020). With the progress of computer technology, scholars have conducted many pioneering studies on urban expansion based on multi-source remote sensing data at the scales of metropolitan areas, states, and urban agglomerations (Dadashpoor et al., 2019; Gong et al., 2019; Jia et al., 2022; Cao et al., 2022; Yang et al., 2021b), including the characteristics and patterns of urban expansion, influencing factors and dynamic mechanisms, spatial growth simulation and prediction, etc.

Currently, most academics focus on the comparative analysis of urban expansion characteristics in two dimensions: time and space (Liu et al., 2021). In the time dimension, most studies analyze the changes in the expansion area, expansion pattern, and spatial pattern of a single city at different time points. In the spatial dimension, the expansion pattern and spatial distribution of multiple cities or urban agglomerations, as well as the spatial correlation and other characteristics, are revealed (Kantakumar, et al., 2016; Li et al., 2018b; Wang et al., 2021). The quantitative measurement of the characteristics of urban expansion is an important issue in spatiotemporal studies. Frenkel and Ashkenazi (2008) divided the indicators of urban sprawl into five categories: growth rate, density, spatial geometry, accessibility, and symmetry. Schneider & Woodcock (2008) designed four indices of spatial extent, population density, built-up area density, and fragmentation to compare the process of spatial spread in 25 cities. Many scholars in the field of urban ecology have used landscape pattern indices to reflect the spatiotemporal evolution of urban expansion (Jiao, 2015; Qi et al., 2023). Scholars usually divide urban growth patterns into three categories: outlying, infilling, and edge expansions, as well as their derivatives (Dadashpoor et al., 2019). Urban expansion has both global and regional characteristics. For example, it was found that cities in the United States are dominated by in-fill outward expansion patterns, whereas Chinese cities exhibit a concentric circle pattern, spreading from the city center to the urban periphery (Dong et al., 2019; Kuang et al., 2014). He et al. (2019) further explored above pattern and found that the proportion of edge expansion sites in Chinese metropolitan areas is higher than that in the United States and occurs mainly in the core cities of metropolitan areas.

The mechanisms driving urban expansion are also of interest. Natural as well as human (social, economic, and policy) factors are the main drivers of urban expansion (Meng et al, 2020; Jia et al., 2022; Li et al., 2018a; Pratama et al., 2022), and are found to vary by region and spatial scale (Dadashpoor & Ahani, 2021; Li et al., 2018b; Liu et al., 2022b). Li et al. (2022) found that government policies, physical geography, economic growth, industrial structure, and local relationships are key factors in the spatial and temporal evolution of urban expansion. Colsaet et al. (2018) found that population, income growth, transportation infrastructure, and automobile use development are the most frequently identified drivers of urban expansion. Furthermore, some studies have proven that socio-economic factors, such as the number of people and land value, are the main driving forces determining the scale of cities (Poghosyan, 2018). The role of natural geographic factors in influencing urban expansion has gradually diminished (Li et al., 2018b), while the role of government administration and land policies has gradually increased (Jia et al., 2022). Factors influencing urban expansion tend to be complex and diverse (Li et al., 2022; de la Luz Hernández-Flores et al., 2017; Liu et al., 2022c). However, the internal driving mechanism of urban expansion is nonlinear and complex, and the most commonly used methods in existing research such as multiple linear regression, principal component analysis, structural equation modeling, correlation analysis, regression analysis, etc. are unable to solve the problem of factor collinearity (Su et al., 2017). Since Random Forest model, a machine learning algorithm, can explain the complex relationship between nonlinear factors with high simulation accuracy (Zhou et al., 2020; Wu et al., 2021) and measure the relative importance of variables, it has a stronger interpretation ability for the driving mechanism of urban expansion.

Scholars have already conducted a lot of discussions on urban expansion and land use change by using scenario simulation method, and scenario simulation is one of the important works specified in the "Dual Evaluation Guide" of China's national territory spatial planning. Cellular automata (CA) are classical models used in the simulation of urban expansions. Since the 1990 s, research on urban complex spatial modeling and dynamic prediction simulations has advanced markedly. Over the years, many CA-based optimization models have been developed, such as the GeoSOS, SLEUTH, CLUE-S, Logistic CA, CA Markov, FLUS, etc., in combination with remote sensing data, artificial intelligence algorithms, and other multiple technical means, and high-precision simulation results have been verified in some cases. However, these models have certain limitations, for instance, the SLEUTH model ignores socio-economic forces and is inefficient and time-consuming in the simulation (Dadashpoor et al., 2019); Markov model can predict the dynamics of landscape patterns quantitatively but cannot resolve the spatial pattern of landscape change (Saadani et al., 2020); and FLUS model can dynamically simulate the spatial evolution of various land-use types, and if constraints are added to set up scenarios, it can become an effective tool for geospatial simulation and spatial optimization decision-making (Liang et al., 2018; Liu et al., 2022c). As demonstrated by the pertinent studies, the FLUS model is superior to other models for simulating large-scale land-use patterns based on high-resolution data and has certain advantages in terms of computational complexity, working efficiency, and operating flexibility (Liang et al., 2018; Lin et al., 2022; Li et al., 2023).

In summary, existing findings provide a rich theoretical and methodological foundation for the field of urban growth management, but further exploration is needed in the following areas: (1) Most studies have focused on the spatiotemporal characteristics and influencing factors of urban expansion, or directly conduct urban growth scenario simulation based on the parameter settings and impact factor selection in relevant literature, which lack systematic integration. This study adapts a step-by-step technical approach, following the research logic of "spatiotemporal patterns → driving mechanism → scenario simulation"; (2) In terms of the driving mechanism, to avoid the issue of multi-factor spatial covariance, this study adapts the Random Forest Algorithm, which is used to measure the important degree of influencing factors on the urban expansion. (3) The key to the effectiveness of scenario simulation results lies in the setting of model parameters. This study intends to combine the "spatiotemporal pattern" and "driving mechanism" as the input parameters of the main modules of the FLUS model, to improve the validity of the simulation results.

The Min Delta region, located in the southeast coast of Fujian Province, is a significant component of China's urbanization's "two horizontal and three vertical" axis. In 2016, the Chinese government proposed the creation of the first ecological civilization zone in China, the Fujian Pilot Ecological Civilization Zone. In the same year, the Min Delta was included in the National 13th Five-Year Key Research and Development Plan as a special project on ecological safeguard technology for important urban agglomerations. As the strategic hub of Fujian Province's new urbanization and the coastal zone at the junction of sea and land systems, the special natural environment and location not only provide opportunities for Min delta to develop into an active humanistic region, but also lay hidden threats for it to become a highly ecologically sensitive area (Liu et al., 2021b). On the one hand, the region's economy has grown rapidly, triggering problems such as spatial disordered distribution and conflicts between supply and demand of land resources, posing serious security risks to the region's ability to develop sustainably (Liu et al., 2022b; Liang et al., 2023., Liu et al., 2023). On the other hand, under the cross-administrative areas and different levels of development, how to grasp the opportunity of planning reform and scientifically formulate the spatial control path, so as to make it match with the overall development and organically adapt it to each subject, is its unique direction worthy of in-depth exploration. Therefore, by taking the Min Delta as a case study, it is possible to both broaden the study samples for China's urban growth management and to offer specific policy suggestions for the practice of spatial planning in urban agglomerations along the country's southeast coast. Additionally, it can also inspire the planning of urban agglomerations in other developing countries with similar geographic locations, development stages, and development scales.

This study aims to examine the dynamic characteristics of spatio-temporal evolution of the urban expansion in the Min Delta region over time, investigate the underlying mechanisms of a series of influencing factors on urban expansion, and forecast the spatial pattern distribution trends of urban growth by 2035. The following issues are specifically addressed: (1) What were the evolution characteristics of the overall land use pattern of the Min Delta region from 1995 to 2015, as well as the spatial expansion mode of various cities in different periods? (2) What are the relatively important driving factors that influence urban expansion in the Min Delta region? How do these factors affect the urban expansion? and (3) How will the urban spatial pattern of the Min Delta change under different growth scenarios from 2015 to 2035?

By addressing the above issues, we aimed to: (1) provide a thorough analysis of the development pattern of urban expansion in the Min Delta based on long time-series remote sensing imagery and land cover data, using the expansion intensity index, equal sector analysis, and hotspot analysis; (2) measure the significance of social, economic, and natural urban expansion influencing factors and explore their driving mechanism by combining Random Forest algorithms; and (3) simulate the future dynamic changes of the urban spatial pattern using the Markov and FLUS models, to supply references for the optimization of land use and spatial structure patterns and rational allocation of land resources in the Min Delta urban agglomeration. The first two sections lay the cognitive and data foundation for the third section, and the simulation results are useful for proposing spatial planning strategies specifically. We try to combine theoretical research with planning practice, which not only provide decision-making suggestions for the future development planning but also form a set of complete research frameworks and methodologies, which can be used as reference for similar studies of other urban agglomerations.

2. Study area and data sources

2.1. Study area

The Min Delta region (23° 33′ 20″–25° 56′ 45″ N, 116° 53′ 21″–119° 01′ 38″ E), located on the southeast coast of China, includes the cities of Xiamen, Quanzhou, and Zhangzhou, with a total area of approximately 2.54×10^4 km^2 (Fig. 1). The area is dominated by low hills with more than 50 nature reserves, including Daiyun Mountain Nature Reserve, and Qingyuan Mountain Scenic Spot, a well-developed water system with watersheds such as the Jiulong and Jinjiang Rivers. From 1995 to

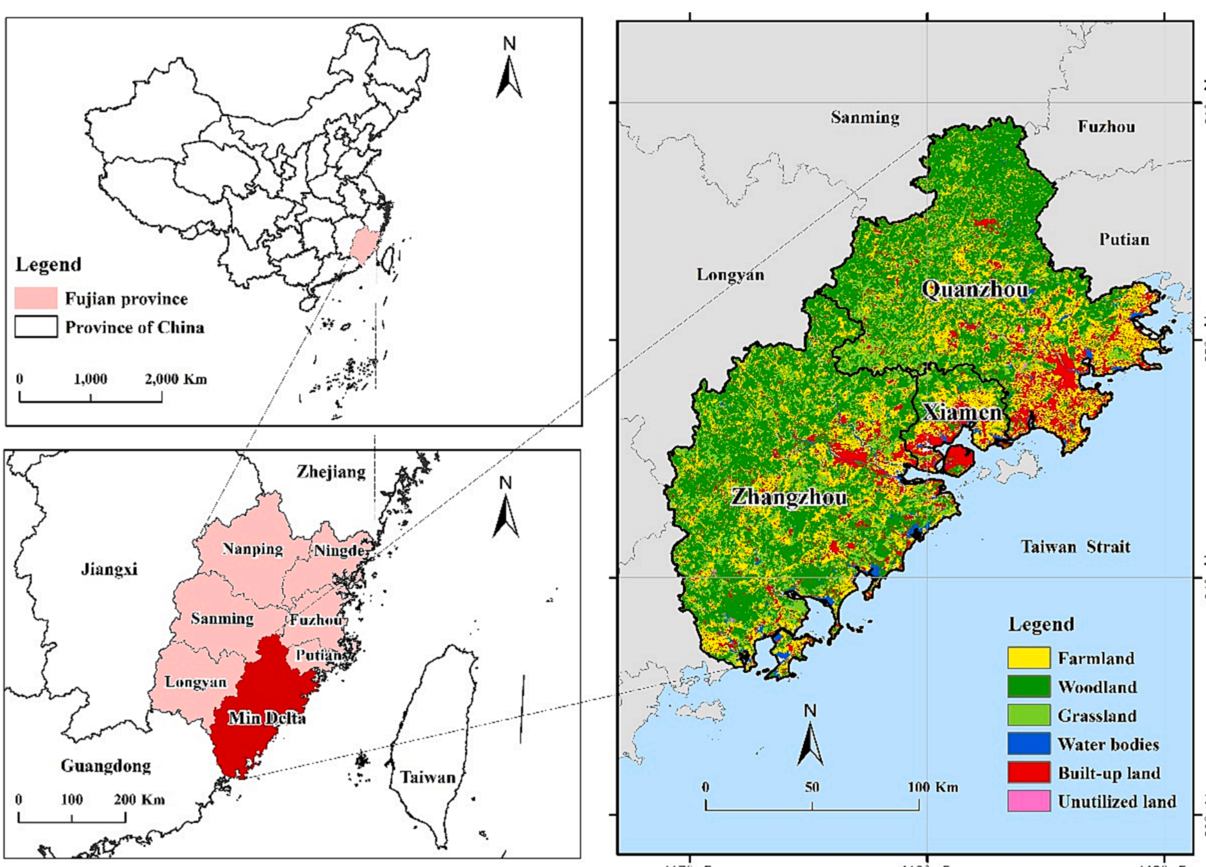

Fig. 1. Location and land use status map.

2015, the area of land use types transformed into the following order: farmland (819.51 km^2) > woodland (800.82 km^2) > grassland (397.92 km^2) > water bodies (60.11 km^2) > built-up land (18.28 km^2) > unutilized land (0.84 km^2), with the most conversion of farmland, water bodies, and woodland into built-up land, the continuous expansion of built-up land is encroaching on a large amount of ecological space (more details are given in Fig. S1). Therefore, the development of the Min Delta region in recent years has led to a dramatic evolution in land use patterns, it is representative to take the Min Delta Region as a case study to explore the characteristics, mechanism and future growth pattern of urban agglomeration expansion.

2.2. Data sources and pre-processing

The research data mainly included land use, geographic information, remote sensing images, and socio-economic data. Five phases of land use data from 1995, 2000, 2005, 2010, and 2015 with a resolution of 30 m were acquired from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/), which were generated based on manual visual interpretation of Landsat TM/ETM remote sensing images. ASTER GDEM digital elevation data at a resolution of 30 m was obtained from the geospatial data cloud (https://www.gscloud.cn/). Luojia No.1 remote sensing satellite nighttime light data with a resolution of 100 m were obtained from Hubei Data and Application Network Systems (https://www.hbeos.org.cn/). Vector data of traffic arteries, administrative boundaries, river networks, etc. were obtained from the National Geographic Information Resources Catalogue Service System (http://www.webmap.cn). Data on rainfall, temperature, and other meteorological parameters were obtained from the China Meteorological Data Website (https://data.cma.cn/). Geospatial data of hospitals, schools, colleges, nature reserves, etc., were obtained through Python-based Baidu and Gaode maps. It should also be noted that this study uses five periods of data with a five-year interval of one period from 1995 to 2015, which largely matches the planned timing of the major national development strategies. Meanwhile, the 20-year long time series data not only can fully reflect the evolution characteristics of urban expansion, but also satisfy the length requirement of the future simulation period of 2015–2035.

3. Methodology

This study follows the research logic of “spatiotemporal patterns → driving mechanism → scenario simulation” (Fig. 2), in which “spatiotemporal patterns” is the data analysis foundation, “driving mechanism” is the basis for setting simulation conditions, and the results of “scenario simulation ” is the reference for decision-making. Taking the Min Delta region as the empirical case: (1) Identifying the spatiotemporal evolution characteristic of urban expansion in terms of intensity, direction, and hotspots; (2) Quantifying the influencing factors of nature, society, transportation, and location on urban expansion, and summarizing the driving mechanism of urban expansion; (3) Setting the simulation parameters of the FLUS model based on the above two parts results, carrying out the multi-scenario simulation of the future urban expansion, and putting forward the spatial planning suggestions.

3.1. Analysis of urban expansion pattern

Urban expansion intensity (UEI), urban expansion anisotropy (UEA) and hotspot analysis were chosen to quantitatively measure the evolution of spatiotemporal patterns. On the one hand, the above indicators were chosen to analyze the evolutionary characteristics in three dimensions: scale structure, development direction, and spatial distribution; on the other hand, these three indicators can provide data basement for setting model parameters and summarizing the mechanism in the subsequent study.

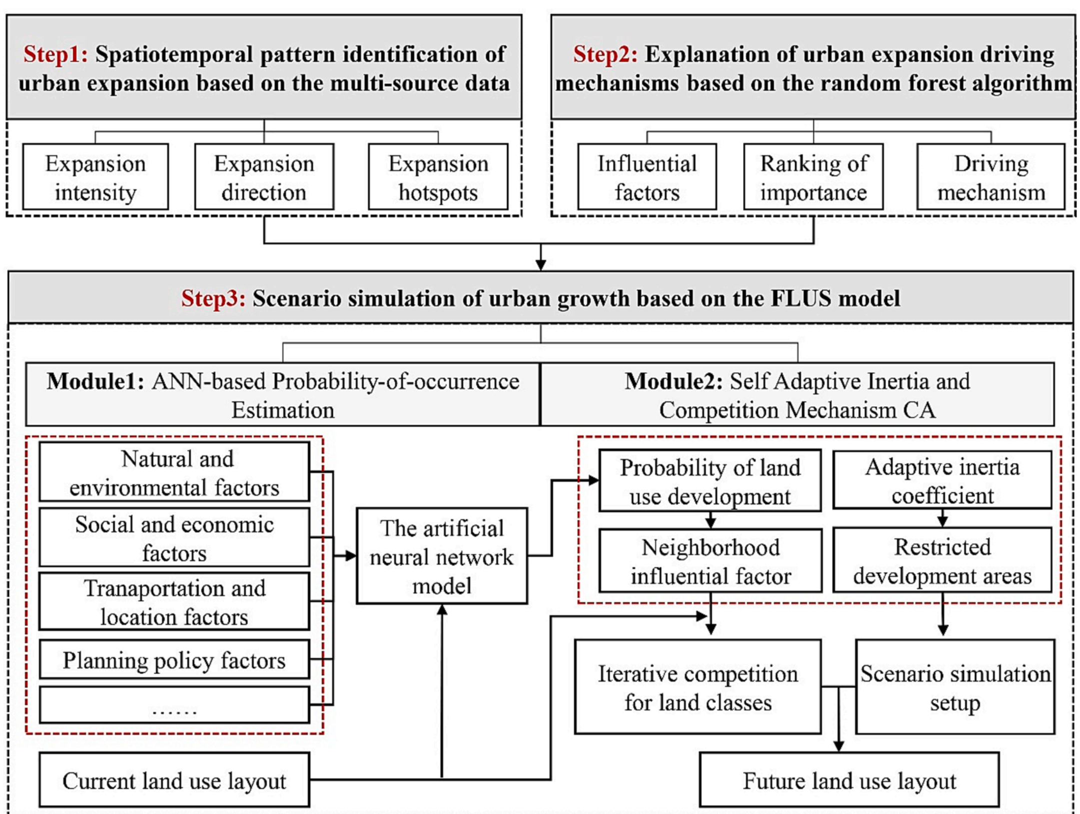

Fig. 2. The framework of the study.

3.1.1. Urban expansion intensity (UEI)

The UEI index is the percentage of the expansion area of built-up land in a specific geographical unit compared to the total land area of its unit during the study period. The strength, speed, and trend of the expansion of built-up land area in different periods, units, and directions can be compared using UEI, calculated as follows:

$$C_t^{t\sim t+n} = \frac{[(A_i^{t+n} - A_i^t)/n]}{S_i} \times 100 \quad (1)$$

where $C_t^{t\sim t+n}$ is the UEI index of the spatial unit i;A_i^t and A_i^{t+n} are the built-up land area of unit i in t and $t+n$, respectively; and S_i is the total land area of unit i.

3.1.2. Urban expansion anisotropy (UEA)

The spatial divergence of urban expansion in various directions can be described using equal-sector analysis. The study area was equally divided into 16 sectors on average, starting 11.25° east of the north (N), and the growth area of built-up land in each sector in different cycles was calculated (Fig. 3), to visually depict the spatial heterogeneity and dominant directions of the spatial expansion.

3.1.3. Hot spot analysis

The hot spot analysis reflects the spatial clustering of new growth land. The $Getis-OrdGi^*$ spatial correlation index was used to identify the distribution of high-value clusters (hotspot areas) and low-value clusters (cold spot areas) of the spatial growth of built-up land, calculated as follows:

$$Getis-OrdGi^* = \frac{\sum_j^n w_{ij}(d)x_j}{\sum_j^n x_j} \quad (2)$$

where d is the distance to each spatial raster cell;$w_{ij}(d)$ is the spatial weight defined by the distance rule; and x_j is the annual average expansion intensity index of the j raster cell.

The analysis results of the Getis-Ord Gi* statistical model include three fields: GiZScore, GiPValue, and Gi_Bin. The higher the GiZscore score, the closer the aggregation of high values (hotspots), indicating that the attribute values around the cell are relatively high. A lower score indicates a denser aggregate of low values (cold spots) and that the attribute values around the unit are relatively low. A Gi_Bin score of 1, 2 and 3 corresponds to a high value concentration area with a confidence level of 90 %, 95 %, and 99 %, respectively, while − 1, − 2, and − 3 correspond to a low value dispersion area with a confidence level of 90 %, 95 %, and 99 % (Liu et al., 2023).

3.2. Measuring the driving factors of urban expansion

3.2.1. Selection of influencing factors

In this study, 27 variables including social, natural, environmental, and economic aspects, were chosen as influential factors (Fig. 4, more details are given in Text S1 and Table S1). Factors such as distance to roads at all levels were uniformly calculated according to the Euclidean distance method. GDP per capita, population density, and urbanization rate were calculated according to the administrative units of districts and counties. Nighttime light data reflect the dynamic spatial distribution of human activities and the level of social and economic

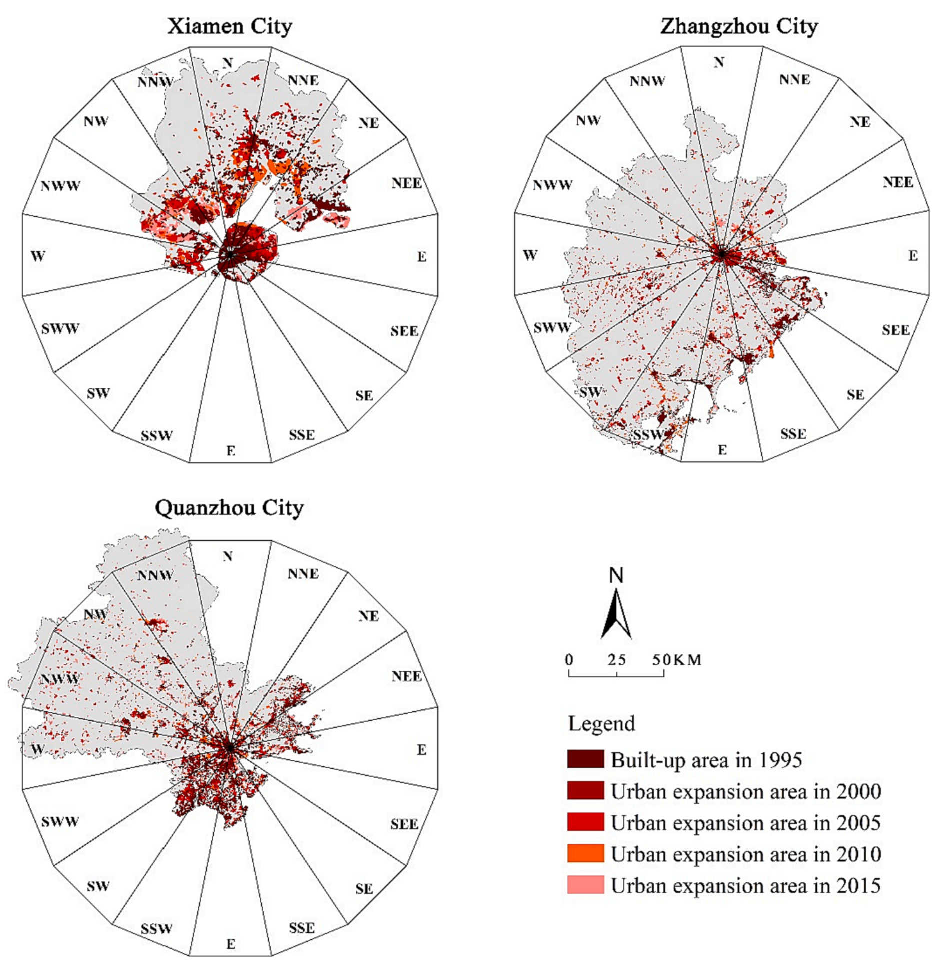

Fig. 3. Overlay of urban expansion in each direction in three cities from 1995 to 2015.

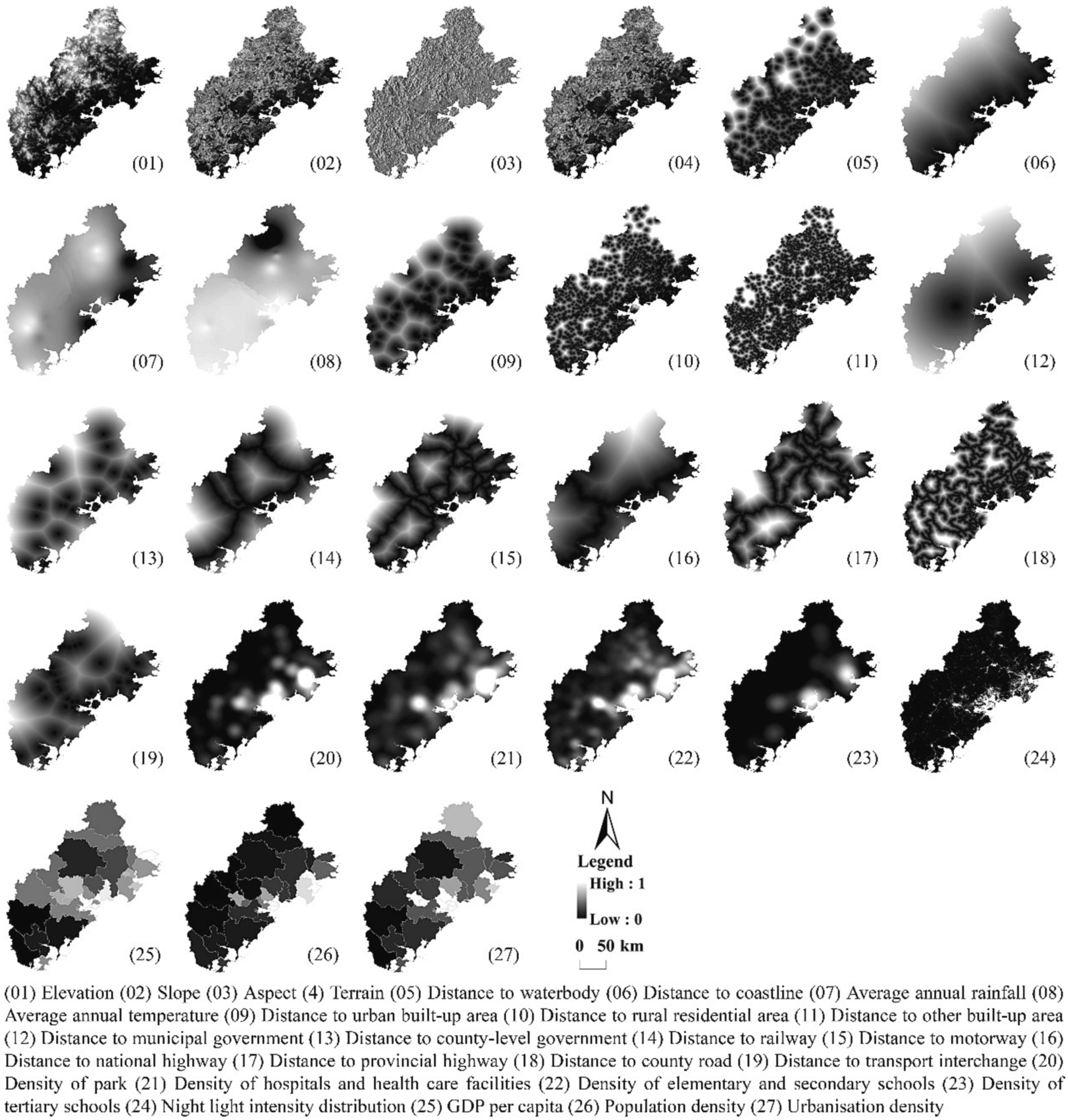

Fig. 4. Factors influencing urban expansion in the Min Delta region.

development (Feng et al., 2020; Jean et al., 2016; Yang et al., 2021a).

3.2.2. Random forest algorithm (RFA)

The Random forest algorithm is used to solve the issue of spatial linear correlation of influencing factors, while quantifying factor weights and selecting dominant ones. An RFA is a natural nonlinear modeling tool that integrates numerous decision trees for intelligent combination prediction (Shafizadeh-Moghadam et al., 2021; Zhou et al., 2020; Li et al., 2021). The "RRF" package in the R studio was used to run the Random Forest model. First, the 27 influential factors were used as spatially independent variables, and the change in built-up land in 2010–2015 was used as the spatially dependent variable. Next, classification and regression tree operations were carried out to generate the out-of-bag (OOB) data, based on which the Random Forest model can calculate the importance of the input variables, which is represented by the mean decrease in accuracy (MDA). The larger the value, the more significant is the variable (Lv et al., 2021; Shafizadeh-Moghadam et al., 2021). MDA was calculated as follows:

$$MDA(v) = \frac{1}{nTrees}\sum_{t=1}^{nTrees}\left(errOOB_t - errOOB_t^{'}\right) \tag{3}$$

where *MDA(v)* represents the reduced value of the average accuracy of variable *v; nTrees'* denotes the number of decision trees; $errOOB_t$ denotes the out-of-bag error of decision tree *t*; and $errOOB_t$ *'* denotes the out-of-bag error of decision tree *t* after the random disruption of sample data outside the bag. The classification accuracy validation can be judged using a confusion matrix (Liu et al., 2022b; Chen, 2022). The results not only provide analysis basis for exploring the driving mechanism, but also serve as important input data for the "ANN-based probability-ofoccurrence estimation" module of the FLUS model. It should be pointed out that drawing on the land use change between 2010 and 2015, the 27 variables covering both physical environment and sociodemographic background are based on the circumstances in 2010, and when simulating the future urban growth, the selected driving forces are 2015-based.

3.3. Construction of urban growth simulation model

3.3.1. FLUS model

The FLUS model can be used to simulate land-use changes and future land-use scenarios under the combined influence of ecosystem and human social systems (Liang et al., 2018). The model is based on the CA model and an artificial neural network (ANN) algorithm, which combines Markov chains to predict land use demand under various growth scenarios. It can be divided into two modules: 1) first, the historical land use data and driving factors are integrated to obtain the suitability development probability of various land use types; 2) and then, the overall conversion probability of cells is calculated, and the interactive competition of different land use types is solved through a roulette mechanism for spatial allocation. Among them, the selection of dominant influencing factors and their weights are the important input data of Module 1; the characteristic indicators such as UEI index are the important input data of Module 2, including the neighborhood influential factors and the conversion cost matrix. In addition, national nature reserves, forest parks, and wetland parks are regarded as prohibited development areas (Liu et al., 2021), which were inputted into the FLUS model as space constraints (More details are given in Text S2).

3.3.2. Urban growth scenarios design

The following possible scenarios may exist in the future development of the Min Delta: (1) 1995–2005 was a period of rapid growth, and the rate of urban expansion slowed down in 2005–2015, which growth trend is likely to continue; (2) With the ongoing promotion of China's ecological civilization construction and new urbanization strategy, the Min Delta needs to realize the integrated development of the region in the future under the principle of coordinating ecological protection and economic development; (3) The Min Delta will likely continue to experience rapid socioeconomic development for some time to come under the guidance of policies like being included in the core-driven area of the Southwest Fujian Cooperative Development Zone in 2019. Therefore, three scenarios were designed: natural development, ecological protection, and economic development. In addition, the land-use scale projections are based on 2010–2015 data combined with Markov modeling (Xu et al., 2020; Liu et al., 2022b).

The natural development scenario assumes that the historical growth mode will continue and excludes the use of artificial urban planning and control strategies. The second scenario emphasizes ecological and environmental priorities. Based on the historical land use conversion matrix from 2010 to 2015, reducing the probability of converting farmland, woodland, water bodies, and grassland to built-up land by 50 %, 40 %, 40 %, and 30 %, respectively, and increasing the probability of converting unutilized land to farmland, woodland, and grassland by 30 %. The third scenario emphasizes economic development as a priority. Based on the historical land-use conversion matrix from 2010 to 2015, increasing the probability of converting farmland, woodland, water bodies, grassland, and unutilized land to built-up land by 40 %, 30 %, 30 %, 20 %, and 20 %, respectively.

4. Results and analysis

4.1. Spatiotemporal patterns of urban expansion

4.1.1. Intensity of urban expansion

In the Min Delta region, the built-up land area increased by 2.26 times from 1995 to 2015. The overall expansion intensity index in the four periods was 0.05, 0.68, 0.21, and 0.30, respectively, showing a development tendency of "low-speed growth, high speed growth, and medium speed growth." From the perspective of city, Xiamen, Quanzhou, and Zhangzhou had ascending orders of built-up land growth speed. Xiamen began to develop rapidly in 2000, and gradually slowed down in the later period. The built-up land expansion areas of Zhangzhou and Quanzhou were comparable, but Zhangzhou's development momentum was slightly slower than that of Quanzhou. In general, the Min Delta saw a medium-speed development stage during 1995–2015, with an increase of 1581.01 km^2 in built-up land area, comprising 254.86 km^2 in Xiamen, 647.89 km^2 in Zhangzhou, and 678.24 km^2 in Quanzhou (Fig. 5).

4.1.2. Direction of urban expansion

Xiamen showed the following trend of sector expansion: from 1995 to 2000, the direction of urban expansion was anisotropic, with rapid growth in the North-west-west (NWW) and North-east-east (NEE) directions; from 2000 to 2005, N and NNE directions of urban expansion were dominant; from 2005 to 2010, the trend of the previous period continued, supplemented by N and North-east (NE) directions; from 2010 to 2015, there was a symmetrical situation of two wings in the NNE and NWW directions. Zhangzhou was dominated by circular sector expansion as follows: from 1995 to 2000, South-east (SE) expansion was dominant; from 2000 to 2005, semi-circular expansion trend was southwards; from 2005 to 2010, South-south-west (SSW) was the dominant direction; from 2010 to 2015, expansion gradually demonstrated a northward development trend. Quanzhou City's urban development was primarily in the NE direction, with support from the North-west (NW) and SSW as follows: from 2000 to 2005, urban development became more balanced; from 2005 to 2010, the development was primarily in N; from 2010 to 2015, the expansion was primarily in NW, South-west (SW), and NE, showing a dwindling trend demonstrating a tendency towards diverse expansions (More details are given in Fig. S3). Generally, Xiamen expanded markedly to N, Zhangzhou was mainly in the South, supplemented by the East, and Quanzhou focused on development in the NW and SW (Fig. 6).

4.1.3. Hot spots of urban expansion

According to Fig. 7, from 1995 to 2000, the urban expansion was dominated by edge growth patterns, with hot spots of expansion located in the districts of Xiamen's Huli, Siming, and Haicang; Zhangzhou's Longwen and Zhangpu; and Quanzhou's Licheng, Fengze, Jinjiang, and Quangang. In 2000–2005, all five districts outside Xiamen Island displayed spatial expansion clustering. Zhangzhou's Longwen and Longhai, as well as Quanzhou's Licheng and Fengze, were also hotspots for spatial expansion. The overall trend during this period was "pie-spreading," with edge growth and in-fill growth patterns. Urban expansion in 2005–2010 was restricted to a certain extent, and the hot spots of Xiamen's expansion were located in the bay area outside the island. Whereas, the hotspots of Zhangzhou's spatial expansion were concentrated in Xiangcheng and Longhai with some inland mountainous areas and the growth pattern for Quanzhou was not only growing at edge but also to a new center growth. During 2010–2015, Xiamen's urban expansion was mainly concentrated in Haicang, Jimei, and Xiang'an; Zhangzhou's was concentrated in the downtown area, where Zhangpu and Nanjing were new expansion hotspots; and the central urban area of Quanzhou showed edge growth, and new center growth was scattered throughout other districts. In general, the built-up land of the Min Delta expanded outward along the central urban area throughout the study period, and the urban expansion pattern was dominated by edge growth, accompanied by in-fill and new center growths.

4.2. Analysis of driving factors of urban expansion

According to the results of the confusion matrix of the Random Forest classifier, the accuracy was 97.38 %, which can be used for the next

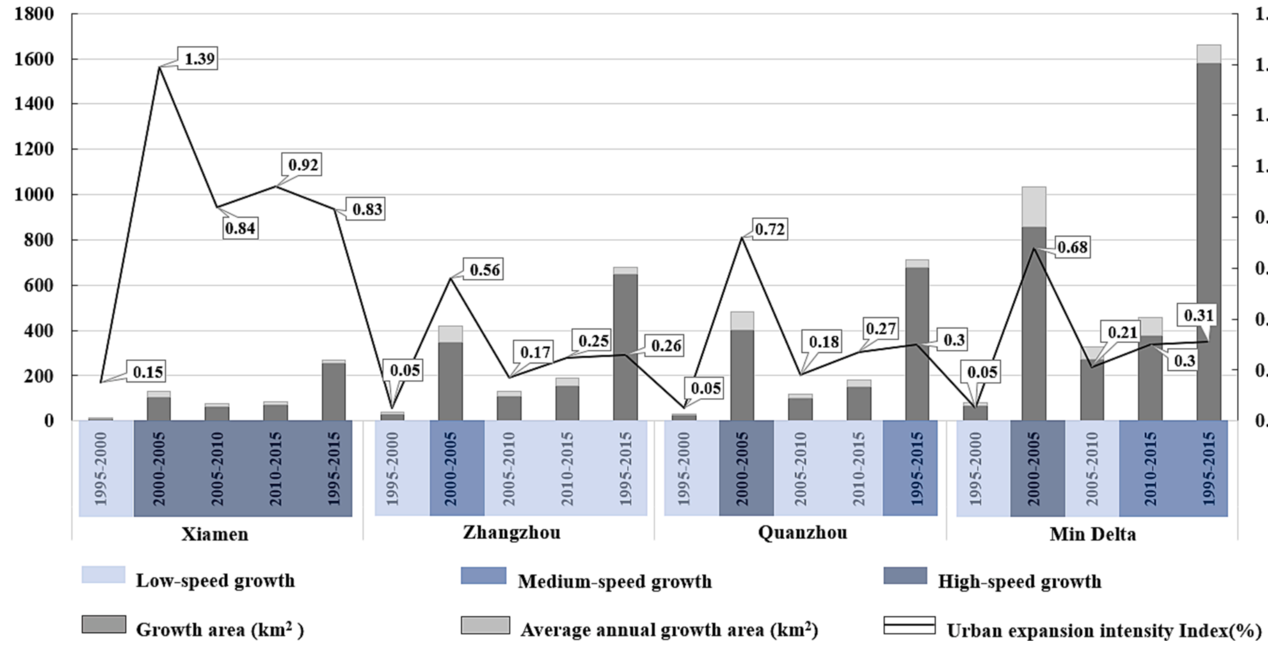

Fig. 5. Urban expansion intensity in Min Delta Region.

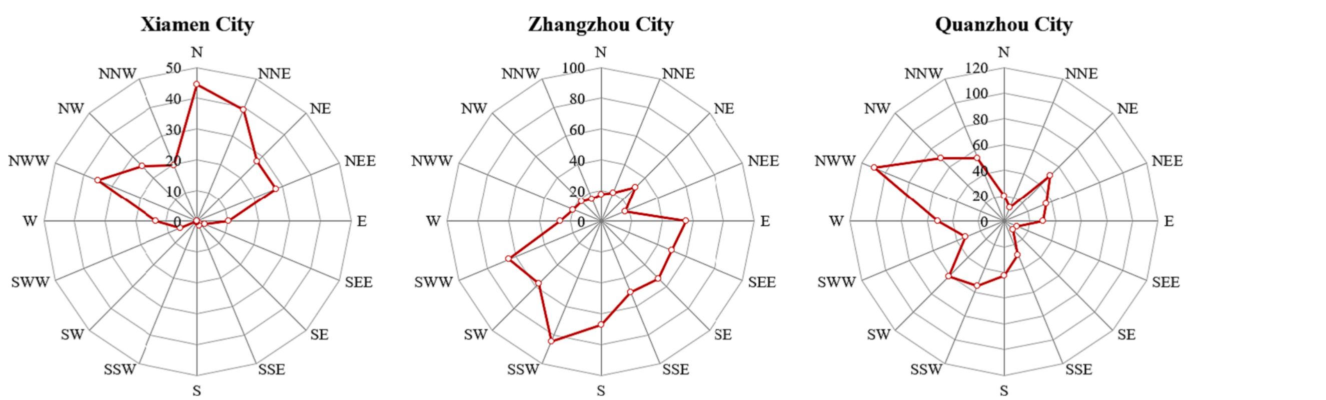

Fig. 6. Radar map of the urban expansions (km^2) of Xiamen, Zhangzhou, and Quanzhou from 1995 to 2015.

analysis (more details are given in Text S3 and Table S2). The two natural climatic factors, average annual rainfall and temperature, had the greatest influence on the urban expansion of the Min Delta, followed by the transport conditions and location factors. Simultaneously, educational and medical resources such as hospitals and elementary and secondary schools also contributed significantly to the model. However, topographic and geomorphological conditions, such as slope, aspect, and terrain, were less important because they have been in a stable state for a long time. It should be noted that the factor of distance to the coastline ranked fifth, which perfectly illustrated the spatial characteristics of coastal urban development. GDP per capita, urbanization rate, and population density were the last three socioeconomic drivers that are not discussed in this study because the units of these three factors were too large to be suitable for fine-grained modeling. Additionally, the nighttime data representing socio-economic development ranked seventh, indicating that socio-economic development has a considerable positive effect on urban expansion (Fig. 8).

4.3. Multi-scenario simulation of urban expansion

To simulate the land use pattern of the Min Delta in 2015 using the FLUS model, which could further simulate future land use changes, the Kappa coefficient was 0.93, with an overall accuracy of 95.97 % (More details are given in Text S4 and Fig. S2). The simulation results based on the design of the three urban growth scenarios are displayed in Fig. 9. By 2035, the built-up areas of Xiamen, Zhangzhou, and Quanzhou will form a continuous development trend, showing a pattern of expansion from the SE coast to the NW inland. Furthermore, most land use changes will occur in areas with relatively gentle terrain, and the expansion of built-up land will cause the transformation of a large amount of farmland, woodland, and grassland around it. In particular, hotspot analysis of the three development scenarios demonstrates that the phenomenon of "pie-spreading" urban expansion can be effectively contained after regulating the growth rate of built-up land (Fig. 10). Under the natural development scenario, the area of built-up land would grow to 3383.75 km^2, the rate of urban expansion would continue its historical trend, and the land increment would be mainly distributed around the previous built-up land. Under the ecological protection scenario, the area of built-up land would increase to 3102.94 km^2, compared with a moderate urban expansion trend, and the growth of land was concentrated. The area of built-up land would increase to 3567.82 km^2 under the economic development scenario, with a clear tendency toward urban expansion. Built-up land will be dispersed in clusters, separating and occupying part of the ecological space.

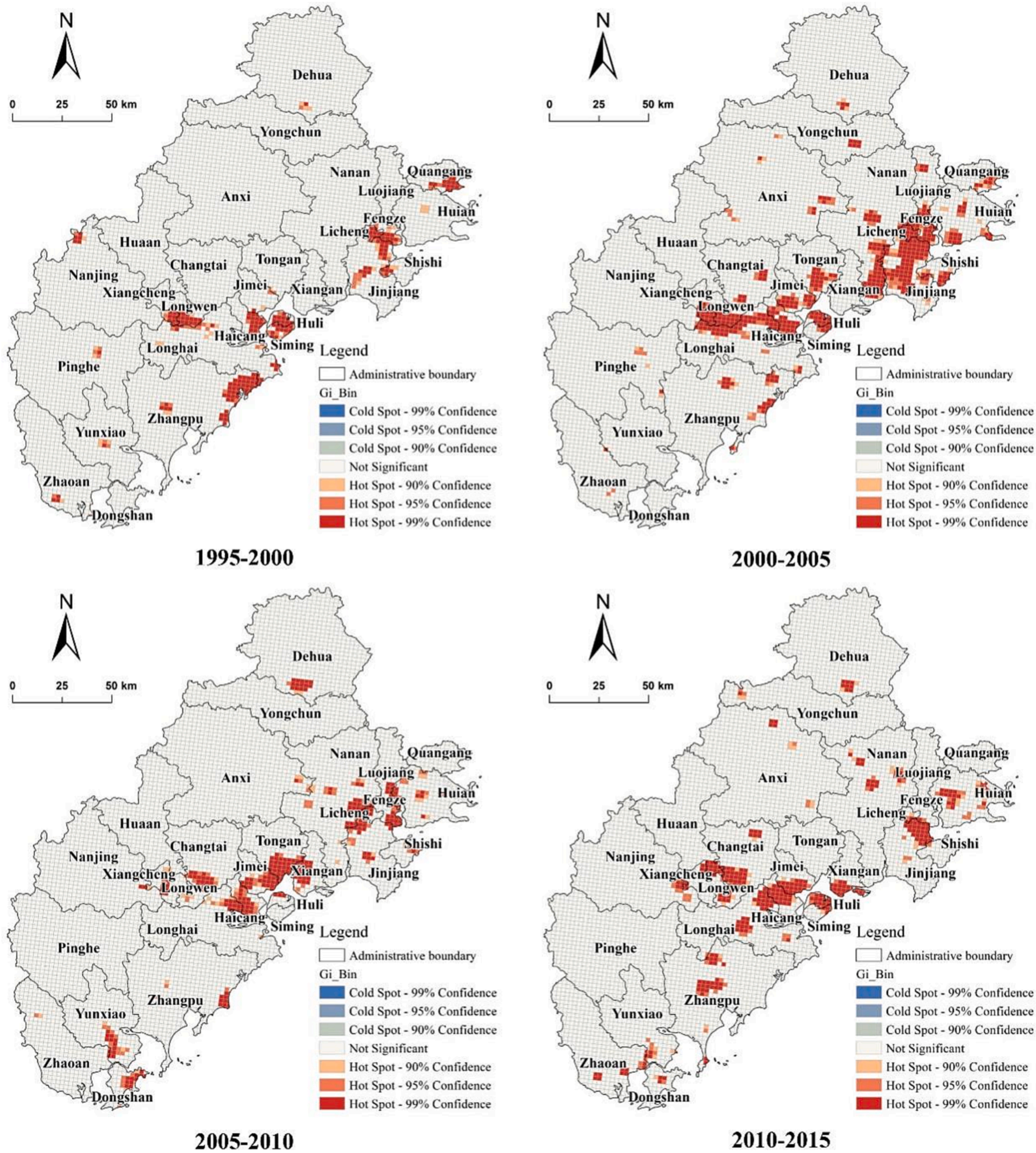

Fig. 7. Distribution of urban expansion hotspots in the Min Delta over the four five-year cycles.

5. Discussion

5.1. Growth pattern of urban expansion in the Min Delta

(1) **Urban expansion happened in stages.** Urban construction was underway between 1995 and 2000, motivated by reform and opening up, but pertinent policies were not yet developed. Thus, urban development mostly relied on the gradual rise of a few areas along the SE coast, including Xiamen Island. Due to the nation's rapid socioeconomic development between 2000 and 2005, the Min Delta has experienced its most intense urban expansion. Between 2005 and 2010, the urbanization bottleneck era dramatically restricted the rate of urban development. The Min Delta once again displayed accelerated expansion between 2010 and 2015, along with the implementation of the Xiamen-Zhangzhou-Quanzhou Metropolitan Area Master Plan. However, under the mandate of ecological civilization construction, urban development was dominated by the medium-low expansion mode. In general, the Min Delta's urban expansion process exhibited periodic fluctuations, gradually shifting from rapid to stable expansion.

(2) **The direction of urban expansion demonstrated diversification.** The rate of urban growth in the three cities varied considerably over time, as did the major growth directions. The

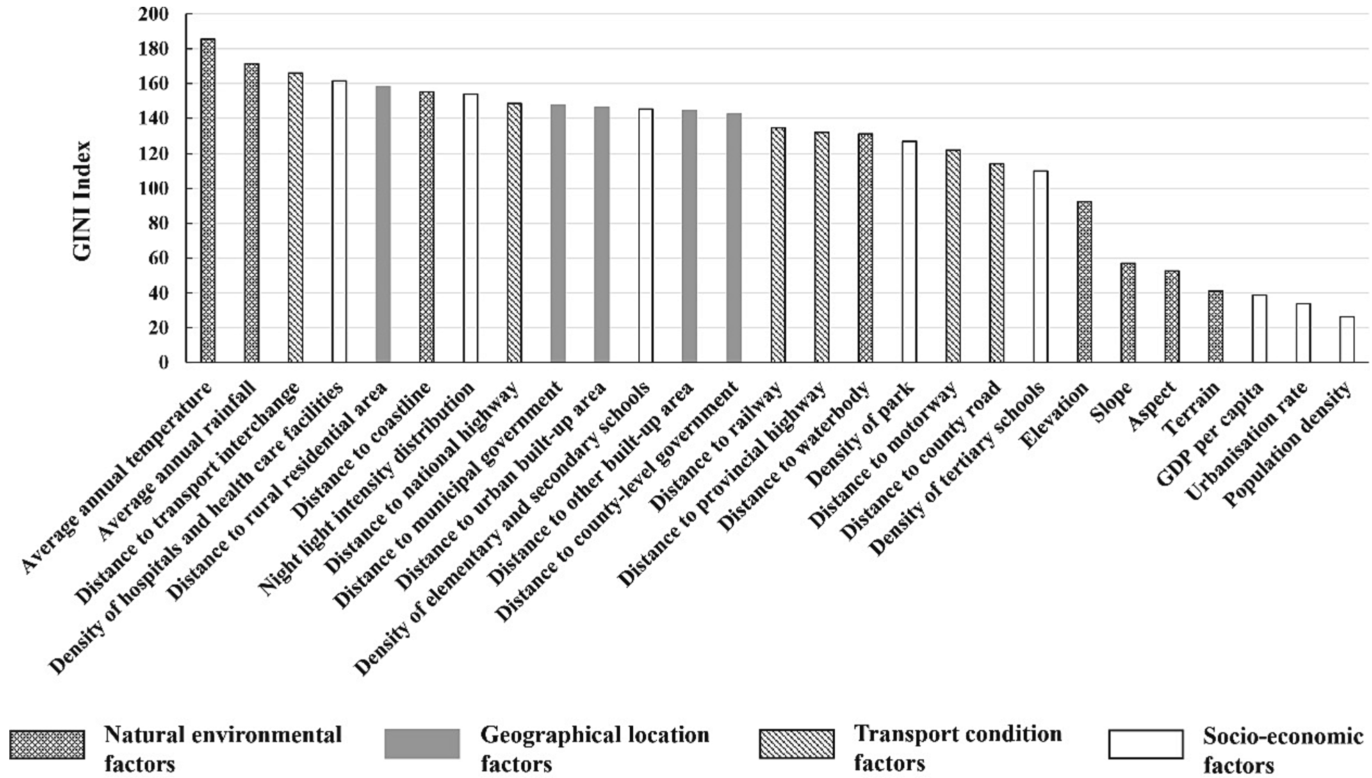

Fig. 8. Ranking the importance of urban expansion drivers in the Min Delta, 2010–2015.

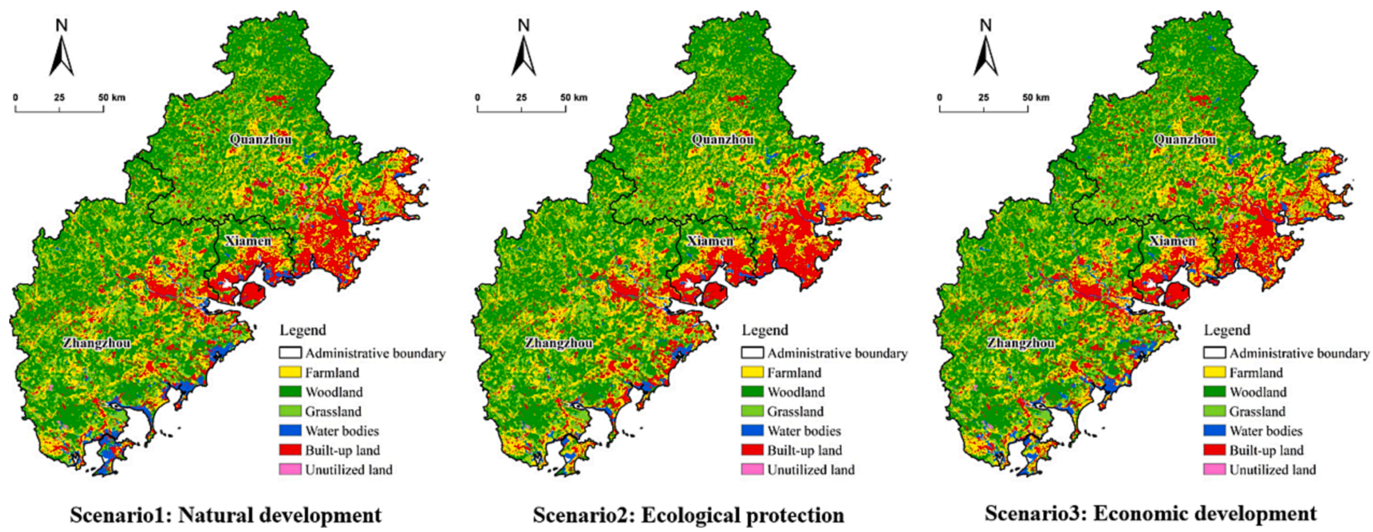

Fig. 9. Simulation of the 2035 land use pattern of the Min Delta under scenarios planning.

topographical layout of Xiamen City, which pushed it to actively develop built-up land outside of its island, caused it to spread northward throughout the entire research period. Zhangzhou City's dominant expansion directions were southward to the coast and eastward to connect with Xiamen City. The directional expansion of Quanzhou City was diverse and dominated by the NW and SW. The urban expansion of Zhangzhou and Quanzhou was driven by the need for urban center expansion and the planning of the integrated development of the Min Delta urban agglomeration.

(3) **The spatial form of urban expansion had continuity.** Urban expansion in the Min Delta was primarily characterized by edge growth, while the built-up areas of the three cities gradually established an integrated development trend. Additionally, the connection between the low mountainous hilly areas in the NW and the plain areas in the SE has gradually improved as a result of the economic development of the Jiulong and Jinjiang River Basins, and the spatial form of urban expansion in the SE coastal area was influenced by the integrated development policy, which essentially follows a continuous growth pattern from scattered to concentrated.

5.2. Driving mechanism of urban expansion in the Min Delta

The physical qualities of different land-use types, as well as social, economic, and natural driving forces, work together to cause urban

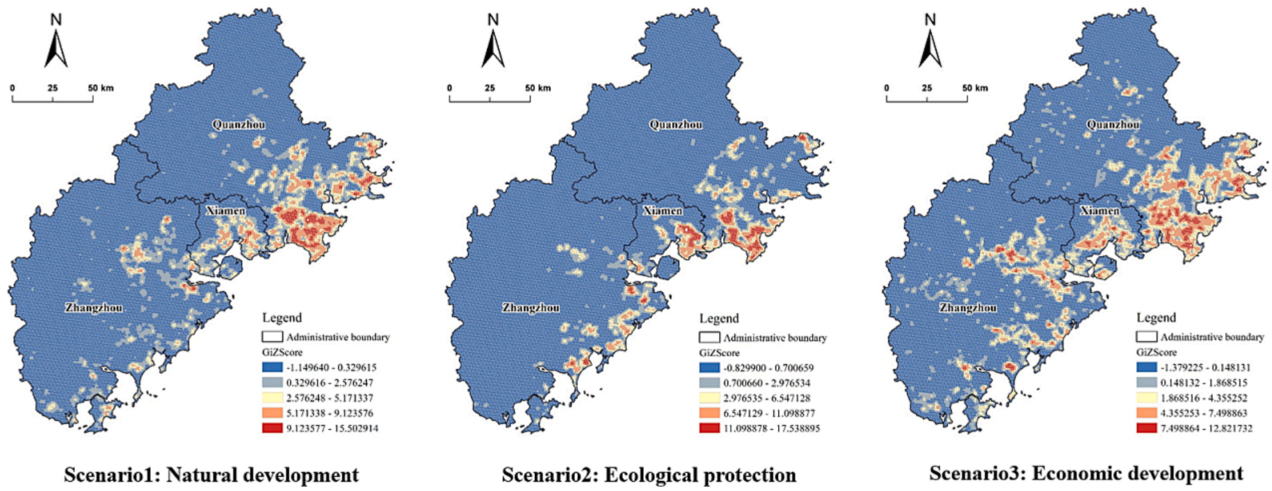

Fig. 10. Urban expansion hotspots under scenarios planning.

expansion. Natural environmental factors determine the overall spatial pattern and have a stable and long-lasting impact on urban expansion. Location and transportation factors provide the gravitational force that pulls urban growth around the built-up land. Socioeconomic factors are direct drivers of urban expansion and can directly affect the intensity and direction of urban development. Therefore, on this basis, this study proposes a "four-forces" driving mechanism framework for urban expansion (Fig. 11).

(1) **Natural environmental factors are the self-resistance of urban expansion.** The material basis of urban patterns is provided by the topographic and geomorphic elements. The Min Delta has high topography in the NW and low topography in the SE. The areas suitable for living and production are mainly concentrated along the SE coast. In the future, with the gradual development of flat lands, the constrictive effects of topography and geomorphology on urban expansion will become more evident. Trade exchanges along the coastline are frequent, and spatial development also demonstrates a considerable dependency on hydrological resources. In addition, due to the influence of the Pacific temperature difference, the Min Delta has long been plagued by severe weather events, such as typhoons and torrential downpours, which also have a certain resistance to urban expansion. Therefore, it is also suggested that future research should focus on the impact of extreme climate disasters on the development of study area.

(2) **Socio-economic factors are the driving force of urban expansion.** Urban expansion has been significantly and positively accelerated by socioeconomic progress. On one hand, economic development directly influences change in industrial

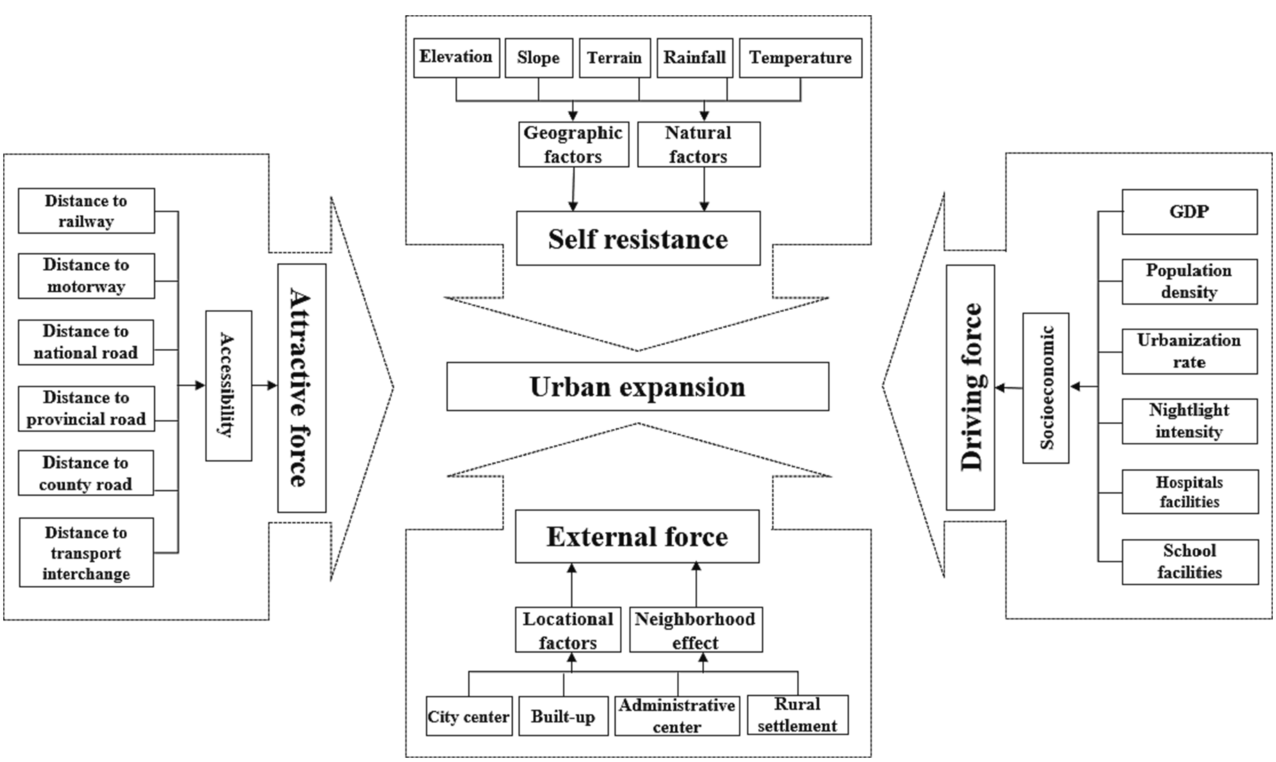

Fig. 11. "four forces" driving mechanism of urban expansion in the Min Delta.

structure, which in turn promotes the transformation of the structure of production, living, and ecological land use. On the other hand, economic development is an important driving force of urbanization, encouraging population gathering from rural to urban areas, leading to the transformation of non-construction land to construction land. Furthermore, the gradual increase in residents' demand for education, medical care, and other service facilities has a direct role in promoting the growth of urban built-up land.

(3) **(3) The transportation condition factor is the attraction of urban expansion.** The closer to the transit arteries and the better the accessibility, the greater the probability of urban-land expansion. Transportation hub facilities (such as ports, light rail stations, and airports) also play an important role in urban expansion. As an illustration, the integration project of intercity rail transit in the Min Delta can set up different levels of stations according to the hotspots of urban expansion to drive the development and construction of the stations and the areas along the routes.

(4) **(4) The geographical location factor is an external force of urban expansion.** The locations of government agencies and built-up areas are tied to spatial expansion. Moreover, neighborhood and spillover effects are also important manifestations of regional integrated development. As the central metropolis of the Min Delta, Xiamen City is increasingly assuming a more significant radiation role and will eventually integrate and grow in concern with neighboring cities and counties.

5.3. Suggestions for spatial development of the Min Delta

5.3.1. Planning suggestions for the major function-oriented zone

The UEI can reflect the spatial agglomeration area of urban growth in the Min Delta, and will also be the key areas for future urban development. According to the ecological protection scenario, the UEI index for each administrative district by 2035 is shown in Fig. S4. Quanzhou has the top four spots, followed by the districts outside Xiamen Island and the Zhangzhou central urban area, and the districts in the NW inland are arranged behind. Xiamen has a high development demand and insufficient reserve land resources. The Quanzhou Central Urban Area will experience the most intense future urban expansion, but at the same time, coastal and inland mountainous areas will differ significantly. Zhangzhou has good ecological resources; however, its economic development has lagged. In summary, Xiamen is in the process of coordinating the development of the surrounding urban areas, Quanzhou will soon have a stable structure of "one district and two wings," and Zhangzhou will have long-term task of expanding the central area and actively assisting with Xiamen's westward expansion.

Therefore, Xiamen should be consolidated as the leading economic center; Quanzhou should build a new central engine with comprehensive service functions; Zhangzhou should highlight eco-agricultural cooperation and the coastal tourism industry. Based on this, the Min-Delta's future spatial growth pattern is projected into four main categories: optimized development zones (ODZs), key development zones (KDZs), general development zones (GDZs), and restricted development zones (RDZs).

Among them, the main function of ODZs and KDZs are development and construction, while the main function of GDZs and RDZs are ecological protection. ODZs emphasize "dual-core" structure, including Xiamen and Quanzhou city center; KDZs take over the population and industry transfer from ODZs, and strengthens the "point-axis" structure of near and medium term development; GDZs is an important part of the multi-cluster model in the long term; and RDZs includes agricultural industry zone and ecological cultivation zone, with ecosystem protection and coastal recreation functions as its main focuses (More details are given in Fig. S5 and Table S4).

5.3.2. Planning suggestions for the urban development structure

Based on the main function zoning, the development of the urban structure of the Min Delta should be guided by the following suggestions: (1) Xiamen should put into strategy of "decentralizing the island and widening the bay," and encourage the transition from a centripetal to a polycentric development pattern; (2) Quanzhou should implement the strategy of "integration around the bay and expansion of the two wings", and strengthen ties with Xiang'an district of Xiamen; and (3) Zhangzhou should put into strategy of "eastward movement of the urban center and expansion across the Jiulong River to the south", direct the industrial upgrading of the urban central area, and promote the integrated development of Xiamen and Zhangzhou.

Therefore, taking into account the background of the integrated development of the Min-Delta region, and giving full consideration to the national policy, the current layout and the scenario simulation results, it is suggested to develop "Xiamen-Quanzhou" dual-core structure, building a "point-axis model" with complementary functions and distinct hierarchy in the near future, and form a "multi-cluster network model" with a high degree of urban integration and spatial linkage in the long term (Fig. 12). In the near and medium term, "Xiamen central city" and "Quanzhou central city" will be the two guiding cores, and key development zones will be linked along the main traffic arteries, so as to achieve the development goal of complementary functions and orderly urbanization. In the long term, based on the advantageous industries of the three cities, the region will cultivate six distinctive metropolitan areas and towns, so as to achieve the goal of functionally different and spatially linked development.

5.4. Research limitations and future work

This study has the following research limitations. Firstly, this study attempts to integrate several models to establish the research framework, but the specific approaches can be further optimized. For example, the Markov model is chosen for the prediction of land use scale, while given the resource and environmental carrying capacity limits, future study can employ the System Dynamics model to dynamically include water resource or land resource constraints into scale prediction. Moreover, space constraint settings can be paired with quantitative studies on ecological security patterns and ecosystem services to create a more scientific restricted construction areas for ecological red line protection. Secondly, although this study designed three scenarios based on the actual situation, it did not set more refined simulation conditions given the focus of the study, the future study should focus on setting scientific scenario planning and land use conversion rules, optimizing future urban growth patterns from the perspective of the synergistic development of "social-economic-ecological" systems, and providing more useful guidance for the coordinated and sustainable development of economic growth and ecological protection. In addition, after calibration and revision, although the 1995–2015 data used in this study are relatively accurate, in view of the timeliness, future studies can further update and supplement the 2015–2020 data to expand the length and validity of the study's time series.

6. Conclusion

In this study, the Min Delta region, a rapidly urbanized area in SE coastal China, was taken as the research object. First, GIS spatial analysis and machine learning algorithms were combined to analyze the evolution pattern and driving mechanism of urban expansion. Then, by combining the FLUS models, the dynamic simulation of future land use patterns was carried out based on multi-scenario planning. The findings reveal that (1) Between 1995 and 2015, the Min Delta underwent a transition from rapid to stable expansion, and the built-up area gradually developed in an integrated manner: (2) A spatiotemporal process is the interaction of social, economic, and natural forces propelling the

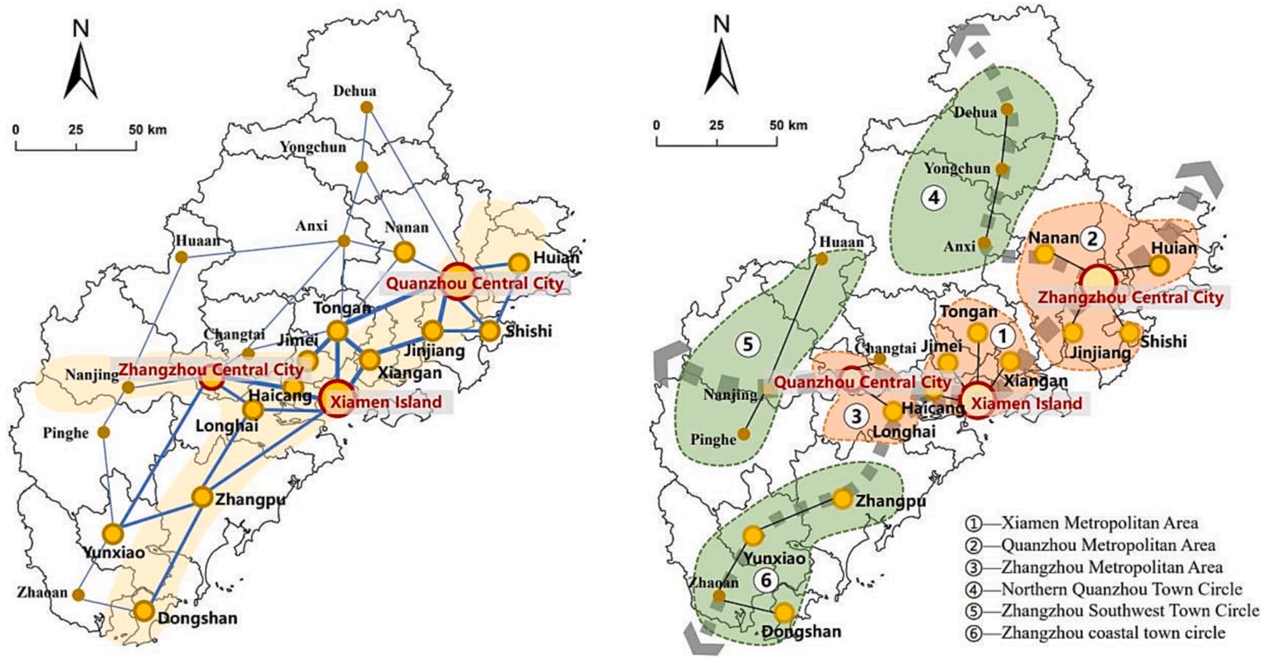

Fig. 12. Near-term “point-axis model” (left) and long-term “multi-cluster network model” (right) in the Min Delta Region.

urban expansion. To establish the baseline of urban development based on the self-resistance force, we should give full play to the driving and external forces, make rational use of, and fully develop the attraction force; and (3) Under the scenarios of natural and economic development, urban expansion will continue to occupy a large amount of ecological space. With the addition of ecological constraints, urban expansion slows and ecological resources are protected to a certain extent.

The coordination of intercity links and ecological resource endowments should serve as the foundation for future development of the Min Delta region. Xiamen should implement integrated development both within and outside the island. Quanzhou should emphasize the development of spatial agglomeration around the central urban area and gradually become the core driving point in the NE. Zhangzhou should concentrate on the economic development of the urban central areas, Longhai, and Nan’an, as a backup force to take over the population and industrial evacuation of Xiamen and Quanzhou. In the process of integrating the Min Delta region, a dual-core structure of “Xiamen-Quanzhou ” with radiation drive needs to be built soon, and the concept of multiple clusters and cores needs to be emphasized in the long term.

CRediT authorship contribution statement

Xiaoyang Liu: Conceptualization, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Yinfeng Li:** Software, Data curation, Writing – original draft. **Sen Zhang:** Methodology, Software, Validation, Writing – review & editing. **Qiang Niu:** Methodology, Resources, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Grant No. 52308078), the Postdoctoral Science Foundation of China (Grant No. 2022M712462), the Basic and Applied Basic Research Foundation of Guangdong Province (Grant No. 2021A1515110633), and the Basic scientific research projects of central universities in China (Grant No. 2042022kf1005).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111312.

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