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Coupling coordination analysis and spatiotemporal heterogeneity between urbanization and ecosystem health in Chongqing municipality, China

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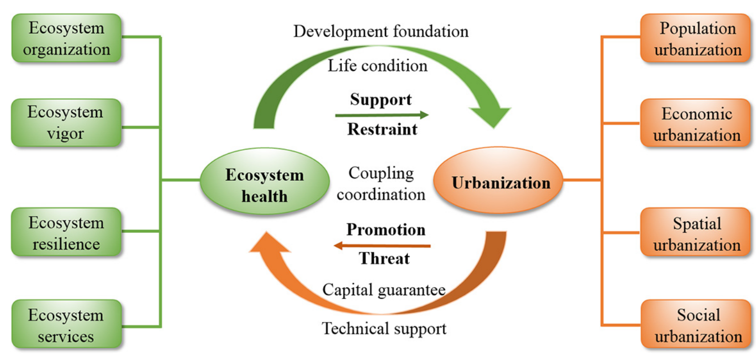
HIGHLIGHTS

- Urbanization level and ecosystem health level were evaluated based on information entropy method and V-O-R-S model, respectively.
- The coordination degree between urbanization and ecosystem health was measured by using the coupling coordination degree model.
- The interaction mechanism between urbanization and ecosystem health was explored by using the GTWR model.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid urbanization has seriously disturbed the structure and function of ecosystems and caused many eco-environmental problems, in turn, these problems also reduce the quality of urbanization and threaten the sustainable development of urban. Currently, most studies only focus on the impact of urbanization on ecosystem components (i.e., structure, functions or services), few studies have explored the coordination and spatiotemporal heterogeneity between urbanization and ecosystem health from a systematic view. Therefore, in viewing of this, this study integrated coupling coordination degree model (CCDM) and geographically and temporally weighted regression (GTWR) to measure the interaction relationship and spatiotemporal heterogeneity between urbanization and ecosystem health (UAEH) in Chongqing at the county scale from 1997 to 2015. Results showed that: 1) the degree of coordination between UAEH in Chongqing increased gradually from 1997 to 2015, developed from the moderately unbalance stage to moderately balance stage, and experienced a transition from urbanization lag to ecosystem health lag. Moreover, the coupling coordination degree showed a decreased spatial trend from the western to the eastern of Chongqing. 2) The restriction effect between UAEH gradually weakened from 1997 to 2015, and the synergistic effect between them gradually strengthened. Additionally, the interaction between UAEH tended to converge, and the negative effects between UAEH were mainly distributed in the central and western of Chongqing. In these area, population urbanization aggravated the deterioration of the natural ecosystem, in turn, the decline of ecosystem vigor and resilience also restricted the sustainable development of urbanization. Finally, this study also puts forward some corresponding policy recommendations based on each region's coupling type.

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1. Introduction

Since the reform and opening up, China's urbanization rate has increased from 17.92% in 1978 to 57.35% in 2017, which is 2.45 times the global growth rate in the same period (Liao et al., 2020). The tremendous achievements of urbanization have also promoted the rapid growth and sustainable development of economy. China's GDP has surpassed Japan to be the world's second largest economy in 2010 (Shi et al., 2020). However, economic prosperity relies on excessive energy consumption and uncontrolled resource exploitation, which has placed great pressure on the carrying capacity of resources and environment, causing a series of environmental pollution and ecological problems, such as traffic congestion, carbon emissions, air pollution, and ecosystem degradation (Tian et al., 2020; Dong et al., 2019a; Shi et al., 2019; Wang et al., 2019c). Meanwhile, in the process of pursuing urbanization, the rapid urban sprawl has greatly transformed landscape pattern, and a large number of ecological land has been occupied by urban residential land, industrial land and transportation land, which not only disturbed the structure and function of natural ecosystems, but also affects the material circulation and energy flow among different spheres (Xie et al., 2021; Peng et al., 2015). In turn, these problems also reduce the quality of urbanization and threaten the sustainable development of urban in the future. Therefore, clarifying the interaction mechanism and evolution laws between urbanization and eco-environment has become a hot topic and frontier (Sun et al., 2019). At present, many studies have explored the coupling relationship between urbanization and eco-environment from different perspectives, such as water environment quality (Liu et al., 2020b), air pollution (Fan et al., 2020), energy and environmental effectiveness (Wang et al., 2019a), carbon emissions (Li et al., 2020), and geological ecological environment (Yang et al., 2020). These empirical researches provide an important reference for further qualitative and quantitative investigation on the relationship between urbanization and ecological environment. However, the eco-environmental indicators used in previous studies are directly or indirectly related to human factors, which cannot reflect the essence of the natural ecosystem (He et al., 2019; Xie et al., 2021). Few studies focus on the coupling relationship between urbanization and ecosystem components (i.e., structure, functions or services), which is not conducive to clearly exploring the interaction and the degree of influence between human-land system.

Regional ecosystem health refers to the ability of the ecosystem to maintain the integrity of its structure and function, and to guarantee the sustainable supply of ecosystem services under the interference of human activities, which has been regarded as the most direct reflection of evaluating regional ecosystem quality (Costanza, 1992; Kang et al., 2018). At present, Vigor-Organization-Resilience-Services (V-O-R-S) model has been widely used to assess the ecosystem health of different regions, which can not only measure the health status of spatial entities, but also quantify the supply capacity of ecosystem services (Peng et al., 2017; Pan et al., 2020). A healthy ecosystem is fundamental to maintain the survival of human society and the sustainable of urban development, in turn, high-quality urbanization can also provide financial guarantee and technical support to ensure ecosystem health; hence the two exist interactive coupling relationship (Chen et al., 2020; Liao et al., 2020). In recently years, many scholars have begun to focus on the relationship between urbanization and ecosystem health (UAEH) and conducted a lot of researches in different regions. For example, Wang et al. (2019c) discussed the impact of urbanization on ecosystem services at the urban agglomeration scale, and found that there was a linear negative correlation between ecosystem services and developed land expansion, while an inverse U-shaped correlation between ecosystem services and socio-economic factors. Aguilera et al. (2020) analyzed the impact of urban infrastructure expansion on coastal spatial connectivity, and found that the spatial connectivity of coastal ecosystem gradually reduced with the expansion of infrastructure. Li et al. (2017) used GWR model to explore the impact of urbanization on landscape pattern from the perspective of spatial heterogeneity, indicating that population density had a direct impact on landscape pattern compared with other socio-economic factors. Chia and Shu (2009) applied various quantitative techniques to analyze the response of landscape diversity to urbanization, results showed that there was an inverse U-shaped correlation between the two. Taking the Taihang Mountains as an example, Li and Tan (2018) explored the impact of population emigration on vegetation coverage, and found that population emigration had a significant and positive impact on vegetation coverage, and this impact gradually weakened with the increase of elevation. However, the current researches need to be further improved from two aspects. In terms of indicator selection, few studies take ecosystem vigor, organization, resilience and services as a composite system to explore the relationship between UAEH. Meanwhile, urbanization is a multidimensional process involving population growth, economic development, urban expansion and lifestyle and consumptive behavioral changes (Dong et al., 2019b; Jia et al., 2020). Previous studies usually focus on one specific aspect of urbanization, ignoring other socio-economic indicators, which cannot comprehensively and scientifically evaluate the urbanization level. In terms of research content, most studies mainly focus on the impact of urbanization on ecosystem health, ignoring the interactive coupling relationship between UAEH, which is not conducive to achieve ecological protection and high-quality urban development (Cui et al., 2019a). Moreover, the coupling coordination degree model (CCDM) in previous studies has been widely used to express the overall efficacy and coordination effect between urbanization and eco-environment (Wang et al., 2019b; Liao et al., 2020), while it cannot well analyze the influence mechanism and evolution law between these two subsystems from the perspective of spatiotemporal heterogeneity. Thus, it is imperative to introduce a spatiotemporal model to analyze the specific effects of influence factors.

Any geographical objects or attributes are related to each other in space based on Tobler's First law of geography (Li et al., 2017). In other words, the change of local spatial attribute will have a significant impact on the surrounding areas. Therefore, the characteristic of spatial dependence must be taken into account when exploring the influence mechanism, otherwise it will lead to deviation in the evaluation results of the model (Chen et al., 2020). Existing exploration of the influencing factors of ecosystem health have ignored the fact that the components of ecosystem health are interrelated and affected by material circulation, energy flow and information transmission, displaying significant spatial spillover effect (Tian et al., 2020; Peng et al., 2015; He et al., 2019). Meanwhile, in the process of urbanization, the factors of production between regions are transmitted to each other, such as labor, industry and capital, which means that the health of the local ecosystem may also be affected by the urbanization of the surrounding areas (Xie et al., 2021). At present, scholars have realized this problem and consider the spatial non-stationary correlation on the basis of ordinary least squares (OLS) regression. For example, Xing et al. (2021) used the geographically weighted regression (GWR) model to explore the relationship between urbanization and ecosystem services. Chen et al. (2019) analyzed the spatial correlation between ecosystem services and land use change at the county scale based on the GWR model. Compared with the global regression, the GWR model can effectively reflect the spatial relationship between each location by establishing a local regression equations, which can provide location guidance for decision making (Chen et al., 2019). However, some studies have also found that there are differences in the impact of population growth and economic development on the ecological environment at different stages of urbanization (Peng et al., 2016; Fan et al., 2020). That is to say, the relationship between urbanization and ecological environment changes with time. Therefore, the time factor cannot be ignored either. For this reason, Huang et al. (2010) proposed the geographically and temporally weighted regression (GTWR) model considering the time factor for better explain the relationship between variables from the perspective of spatiotemporal heterogeneity, which greatly improves the accuracy of model simulation.

The effectiveness of the GTWR model has been proved by many studies (Liang et al., 2019; Shi et al., 2020; Ariken et al., 2021).

Therefore, in viewing of this, this study integrated the CCDM and GTWR model to measure the interaction and spatiotemporal heterogeneity between UAEH in Chongqing at the county scale from 1997 to 2015. Compared with the previous research, this study mainly has the following three innovations and contributions. 1) Method innovation. A new method GTWR is introduced to explore the interactive relationship between UAEH, which not only effectively expands the application scope of GTWR, but also it fully considers relevance, diversity and spatiotemporal heterogeneity in the theme of urbanization and ecosystem health. 2) Perspective innovation. Compared with previous studies only focusing on the impact of urbanization on ecosystem components (i.e., structure, function, and services), this paper used the CCDM to explore the coordination relationship between urbanization and ecosystem health from a systematic perspective. 3) The contribution of this study is that we explored coordination relationship and spatiotemporal heterogeneity between urbanization and ecosystem health in Chongqing, which is conducive to identify the potential causes of conflict and provide a basis for policymakers to achieve high-quality urban development.

The structure of this paper is as follows. Section 2 presents the study area, data sources and conceptual framework. Section 3 describes research methods. Section 4 demonstrates the research results and discussion. Section 5 draws the main research conclusions and provides policy implications.

2. Study area, data sources and conceptual framework

2.1. Study area

Chongqing (105°11′–110°11′E, 28°10′–32°13′N), as a bridge connecting the East and West of China, is located in Southwest China, with a total area of about 82,400 km^2 (Fig. 1). Chongqing is composed of four development areas: Metropolitan Economic circle (MEC), One-hour Economic Circle (OEC), Southeast of Chongqing (SEC) and Northeast of Chongqing (NEC), including 38 districts and counties under its jurisdiction. Chongqing is a typical mountainous city, in which the western and central are located at the edge of Sichuan Basin, the main geomorphological types are hills and parallel valleys, with an average elevation of about 491 m. While it's southeast and northeast are located at the confluence of Daba Mountain and Wuling Mountain, the main geomorphological types are mountains, with an average elevation of about 869 m. In general, the mountains account for about 76% of the total area, and the geo-ecological environment is extremely sensitive and fragile. Additionally, Chongqing is also the intersection of the Yangtze River Economic Belt and New Silk Road economic Belt, with obvious location superiority. In 2015, Chongqing supported 30.16 million people, accounting for 2.53% of China's total population, and generated CNY 1.57 trillion, accounting for 2.32% of the national GDP. Since being directly administrated by the Chinese central government, the urbanization rate has increased from 31% in 1997 to 60.9% in 2015, and the average annual growth rate of GDP is 10.95%, which is 1.21 times the average annual growth rate of the whole country in the same period (Xie et al., 2017). There is no doubt that economic growth and population agglomeration have caused great changes in the ecological environment, and the contradiction between human and natural is gradually increasing.

The reason why Chongqing was chosen as the study area was mainly based on the following two aspects. 1) Due to land shortage and complex topography in mountainous cities, the government meets the needs of economic growth through land reclamation and vegetation destruction, which have exceeded the carrying capacity of ecological and environment, leading to many eco-environmental problems, such as rocky desertification and soil erosion. Therefore, how to coordinate the relationship between economic development and ecological protection of mountain cities will become a new challenge for policy makers (Jia et al., 2020). 2) China is also a mountainous country, with mountains accounting for about 2/3 of the country's land area. The 18th National Congress pointed out that China will more focus on the development of urbanization in ecologically fragile areas and strive to achieve ecological protection and high-quality urban development in the future. Therefore, finding a development model of mountain cities is conducive to realizing the coordinated between urbanization and ecological environment, and also provides an important reference for other mountain cities.

2.2. Data sources

According to the previous research and the local actual situation, this study selected eight indicators from the four aspects of population, economy, social and spatial to construct a comprehensive urbanization evaluation mode based on the principles of comprehensiveness and typicality (Table 1). All urbanization data were obtained from Chongqing Statistical Yearbook of 1998–2016 (http://tjj.cq.gov.cn/zwgk_233/tjnj/).

Additionally, based on previous research and data availability, a comprehensive ecosystem health assessment framework was constructed

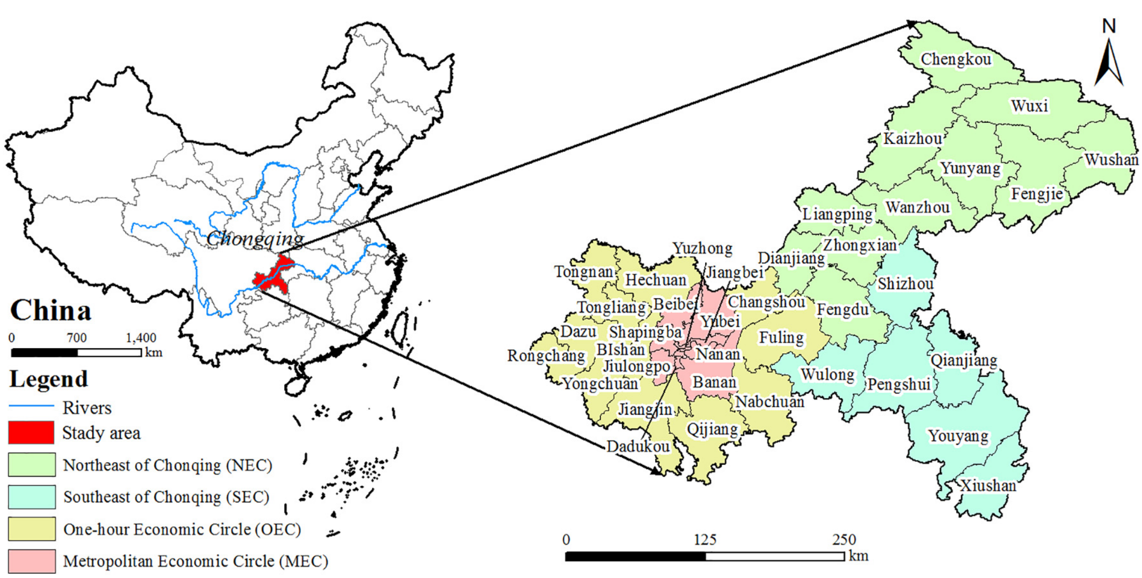

Fig. 1. Spatial range of the study area.

from four aspects: vigor, organization, resilience and services (Peng et al., 2015; He et al., 2019). Specifically, the normalized difference vegetation index (NDVI) data was used to monitor the growth status of vegetation and reflect the ecosystem vigor, which mainly come from the Resource and Environment Research Center of the Chinese Academy of Sciences (http://www.resdc.cn/). 300-m land use and land cover (LULC) maps was adopted to evaluate ecosystem organization, resilience and services, which mainly acquired from the European Space Agency (ESA) Climate Change initiative land cover (CCI-LC) (http://maps.elie.ucl.ac.be/CCI/viewer/), with an overall accuracy of about 71.1%. According to the land use division method proposed by Liu et al. (2018), the land use data are divided into six categories, namely farmland, forestland, grassland, water area, construction land and unused land.

Noted that all data need to be standardized before calculations in order to eliminate the positive or negative effects of different dimensions and magnitude on the evaluation indicators (Cui et al., 2019a), the specific calculation formula is as follows.

$$X_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad (1)$$

$$X_{ij} = \frac{\min(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} \quad (2)$$

where X_{ij} is the original value of indicator j in year i; min (X_j) and max (X_j) are the minimum value and maximum value of indicator j in all years, respectively.

2.3. Conceptual framework

Most studies have indicated that there was a complex interaction relationship between UAEH (Fig. 2). On the one hand, urbanization has a dual impact on ecosystem health, the negative effects are mainly reflected in energy consumption, land use change and road network expansion, while the positive effects are mainly reflected in capital guarantee, technical support and the promotion of residents' awareness of environmental protection (Cheng et al., 2019; Cui et al., 2019b; Liu et al., 2020a). Specifically, in terms of negative effects, 1) cities with rapid economic growth tend to exploit resources and consume energy to meet the demand for numerous ecosystem goods and services, which leads to the imbalance between the supply and demand of ecosystem services and threatening the survival of human society. 2) Population agglomeration and industrial transformation also increase the demand for residential and industrial land, a large number of ecological land are destroyed and transferred to construction land, which reduces the ecosystem vigor and resilience. 3) Road network expansion not only makes the landscape patches more fragmentation, but also causes large-scale air pollution and local heat island effect (Shi et al., 2019). In terms of positive effects, 1) Developed economy can provide sufficient capital guarantee to preserve ecological functions, and promote the development of service industry and increase beneficial environment effects. 2) As a gathering area of talents, capital and high technology, cities can provide technical support for the development of green industry, thereby improving eco-environment quality. 3) Rapid urbanization can also improve the awareness of environmental protection and change people's way of transportation. On the other hand, a healthy ecosystem is fundamental to support the sustainable development of urbanization, which not only provide material products and services for human survival and economic development, but also improve the living environment and life quality of residents. However, the deterioration of ecosystem will restrict urban development through ecological quality, ecosystem function, population migration and policy intervention (Tian et al., 2020). Therefore, clarifying the coordination relationship and internal mechanism between UAEH is conducive to formulating effective policies that help to maximize the benefits of urbanization and minimize the negative environment impacts.

3. Research methods

The research methods and main processes adopted in this study are shown in Fig. 3, including the following procedures: (1) selecting the appropriate evaluation indicators for urbanization and ecosystem health through literature research. (2) Calculating the values of urbanization and ecosystem health by using the liner weighted sum method and V-O-R-S model, respectively. (3) Analyzing the coupling coordination degree between UAEH at the county scale by adopting the CCDM. (4) Exploring the spatiotemporal heterogeneity between UAEH based on the GTWR model. The specific research methods are described as follows.

3.1. Evaluation of urbanization

The index value of urbanization level is calculated mainly based on the following two procedures. 1) Referring to previous research (Liang et al., 2019), the entropy method was employed to determine the weight of each indicator in the urbanization system. Entropy method is a weighting method based on the dispersion degree of the evaluation indicators, which has been widely used in many fields due to its objectivity, comprehensive and less complexity (Cheng et al., 2016). In general, the larger the entropy value is, the more balanced the system structure is, the smaller the coefficient difference is, and the smaller the index weight is. On the contrary, the greater the weight of the index. 2) The linear weighting method was adopted to calculate the index values of urbanization and its subsystems. The specific calculation steps are as follows.

(1) Calculating the proportion of the indicator j for county i.

$$S_{ij} = X_{ij} / \sum_{i=1}^{n} x_{ij} \quad (3)$$

(2) Calculating the entropy value of the indicator j.

$$e_j = -k \sum_{i=1}^{n} s_{ij} \ln s_{ij} \, k = 1/\ln(n) \quad (4)$$

Table 1
Indictors for measuring urbanization level (UL).

System	Subsystems	Indicators	Units	References
Urbanization	Population urbanization	Urban population density (+)	People/km^2	Ariken et al. (2021)
		Proportion of urban population (+)	%	Chen et al. (2020), Cheng et al. (2019)
	Economic urbanization	Per capital GDP (+)	Yuan	Cui et al. (2019a)
		Proportion of secondary and tertiary industries in GDP (+)	%	Fan et al. (2020), Li et al. (2020)
	Spatial urbanization	Per capita road area (+)	m^2	Liao et al. (2020)
		Proportion of built-up area (+)	%	Yang et al. (2020)
	Social urbanization	Number of doctors per million people (+)	People	Wang et al. (2019b)
		Number of college students per million people (+)	People	Tian et al. (2020), Yang et al. (2020)

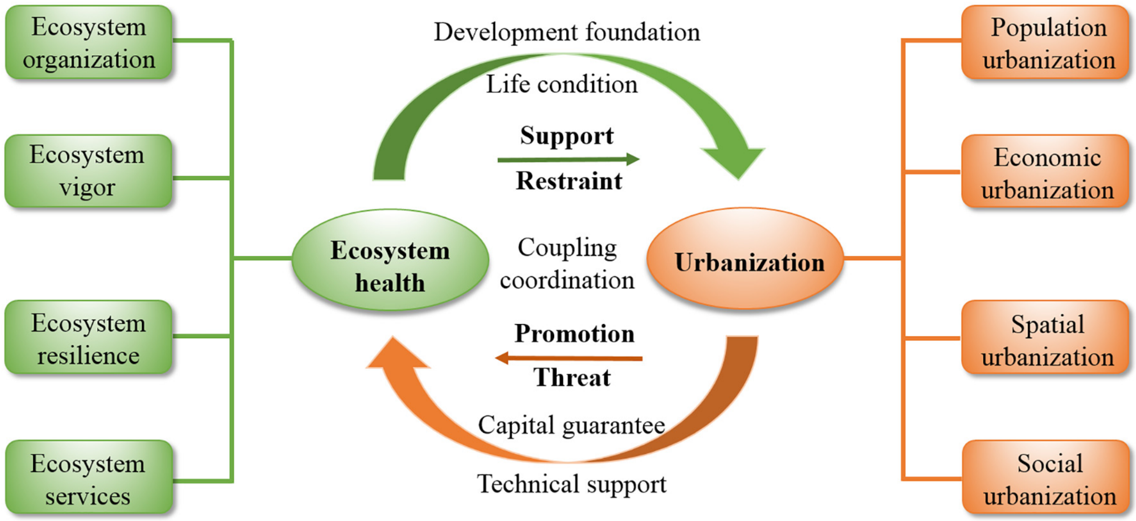

Fig. 2. Conceptual framework of the interactions between urbanization and ecosystem health.

(3) Calculating the weight of the indicator *j*.

$$w_i = (1-e_j)/\sum_{j=1}^{p} 1-e_j \quad (5)$$

(4) Calculating the index value of urbanization system.

$$S_{\lambda i} = \sum_{j=1}^{p} w_j x_{ij} \quad (6)$$

where $S_{\lambda i}$ represents the index value of the city i in the λ year, w_j stands for the weight value of indicator j, x_{ij} stands for the standard value of indicator j for city i in the λ year, and n represents the number of indicators.

3.2. Evaluation of ecosystem health

Ecosystem health can directly and comprehensively reflect the quality of regional ecosystem, which mainly includes four elements: vigor, organization, resilience and services. Based on the assessment method proposed by Peng et al. (2015), the V-O-R-S model was applied to evaluate regional ecosystem health. Noted that each element needs to be normalized to 0–1. The specific calculation method of the ecosystem health index was as follows:

$$EHI = \sqrt[4]{EV \times EO \times ER \times ES} \quad (7)$$

where *EHI* is the ecosystem health index, which ranges from 0 to 1. Based on the equal-interval method, we divide the ecosystem health index into five grades: weak (0–0.2), relatively weak (0.2–0.4), ordinary (0.4–0.6), relatively well (0.6–0.8) and well (0.8–1). Ecosystem vigor is generally defined as ecosystem metabolism or net primary productivity. In this study, NDVI was used to reflect the ecosystem vigor, which has been widely applied in regional ecosystem health assessment due to its effective in monitoring the quality of ecological environment (Peng et al., 2017; Liao et al., 2018).

1) Ecosystem organization refers to the structure stability and complexity of regional ecosystem. In this study, landscape pattern

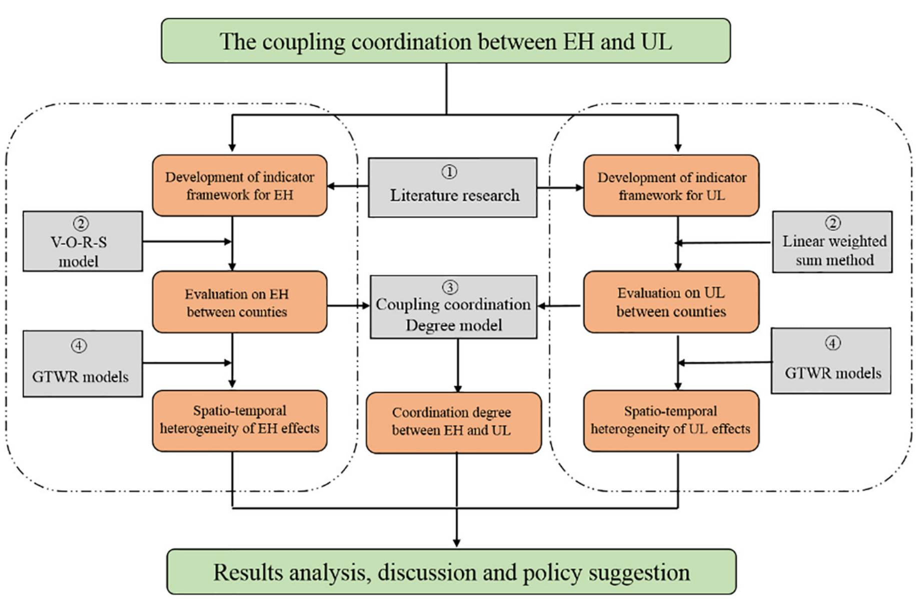

Fig. 3. The coupling coordination evaluation framework.

index, including landscape heterogeneity and landscape connectivity, was used to evaluate ecosystem organization (Kang et al., 2018; He et al., 2019). Specifically, Shannon's diversity index (SHDI) and mean patch fractal dimension index (MPFD) were used to reflect landscape heterogeneity. Landscape connectivity index mainly included two aspects: one is the connectivity of overall landscape, which was characterized by landscape fragmentation index and landscape contagion index, and the other is the connectivity of important ecological patches, such as forest land, grass land and water, which was measured by the fragmentation index and cohesion index. Furthermore, referring to previous studies and expert knowledge, the weights of landscape heterogeneity, overall landscape connectivity and connectivity of important ecological patches are assigned to 0.35, 0.35 and 0.30, respectively (Peng et al., 2015; Pan et al., 2020). The specific calculation method is as follows:

$$EO = 0.35LH + 0.35LC + 0.30IC = (0.25SHDI + 0.10MPFD) + (0.25FN_1 + 0.10CONT) + (0.07FN_2 + 0.03COHE_1 + 0.07FN_3 + 0.03COHE_2 + 0.07FN_4 + 0.03COHE_3) \quad (8)$$

where EO stands for ecosystem organization. FN_1 and $CONT$ represent landscape fragmentation index and landscape contagion index, respectively; FN_2, FN_3 and FN_4 refer to the landscape fragmentation index of forest land, grass land and water, respectively; $COHE_1$, $COHE_2$ and $COHE_3$ refer to the cohesion index of forest land, grass land and water, respectively.

2) Ecosystem resilience represents the ability of the ecosystem to maintain its own structural stability under the interference of human activities (Rapport et al., 1998), which is measured based on the area-weighted ecosystem resilience coefficients (ERC) for all land use types (Table S1). Specifically, according to expert knowledge and relevant references (Peng et al., 2017; Pan et al., 2020), the coefficient of ecological resilience is obtained. The specific calculation formula is as follows:

$$ER = \sum_{i=1}^{n} A_i \times ERC_i \quad (9)$$

where ER stands for ecosystem resilience, n represents the number of land use types, A_i represents the area ratio of land use type i.

3) Ecosystem services represent the ability of ecosystem to provide products and services for human beings. Ecosystem services can be quantified form two aspects: one is the ecosystem service coefficient of different land use types (Xie et al., 2017), which is obtained by calculating the ratio of the ecosystem service value of a certain land type to the mean ecosystem service value of all land use types. The other is the spatial neighboring coefficient of different land use types (Table S2), which is determined based on the actual condition of Chongqing and related literature (Peng et al., 2015). The specific calculation formula is as follows:

$$ES = \sum_{j=1}^{n} ESC_j \times \left(1 + \frac{SNE_j}{100}\right)/n \quad (10)$$

where ES stands for ecosystem services, ESC_j represents the ecosystem services coefficients of the pixel j, SNE_j represents the sum of the spatial neighboring coefficient of the pixel j, n means the number of pixel.

3.3. Coupling coordination degree model (CCDM)

In this study, the CCDM was applied to investigate the interactive coupling relationship between UAEH. This model has been widely used in many fields to measure the degree of interaction and coupling level between two or more systems, which determines the development trend of integrated system from disorder to order (Shi et al., 2020; Liao et al., 2020). In detail, we first calculated the coupling degree between UAEH by using formula (11), then measured the coupling coordination degree between UAEH by using formulas (12) and (13) on the basis of coupling degree analysis. The specific formula is as follows;

$$C = \sqrt{(U_1 \times U_2)/((U_1 + U_2)/2)^2} \quad (11)$$

$$T = \alpha U_1 + \beta U_2 \quad (12)$$

$$CD = \sqrt{C \times T} \quad (13)$$

where C refers to the coupling degree between UAEH, T represents the comprehensive evaluation index between UAEH, and CD denotes the coupling coordination degree between UAEH. U_1 and U_2 refer to urbanization comprehensive index and ecosystem health comprehensive index, respectively. The two subsystems are equally important to the evaluation of the degree of coordination between UAEH, thus they are given the same weight, that is, $\alpha = \beta = 0.5$ (Liao et al., 2020; Shi et al., 2020). Referring to previous research (Ariken et al., 2021), we divide the coupling coordination degree between them into five levels; highly balanced, moderately balanced, basically balanced, moderately unbalanced and seriously unbalanced (Table 2).

3.4. Geographically and temporally weighted regression model (GTWR)

The GTWR has been widely used to measure the degree of influence on the explanatory variables (Huang et al., 2010), which has obvious advantages in reflecting spatiotemporal heterogeneity in different regions than traditional statistical models, such as the spatial econometrical model. Specifically, the GTWR can more directly to display the geostatistical relationship between variables in each sample region at any time, thus effectively reflecting the evolutionary relationship between variables in spatial-temporal scenario (Cheng et al., 2016). Therefore, the GTWR model was used in this study to explore the spatial-temporal differences between UAEH. The specific formulas are as follows.

$$y_{it} = \alpha_0(m_i, n_i, s_i) + \sum_{i=1}^{k} (m_i, n_i, s_i) x_{it} + \phi_{it} \quad (14)$$

where y_{it} refers to the ecosystem health index of county i in time t, x_{it} is the urbanization index of county i in time t, ψ_{it} represents the random factor of county i in time t, and α_i (m_i, n_i, s_i) represents the value of geographical location i, which is used to measure the impact of urbanization on ecosystem health in county i at time t. Similarly, when the dependent variable is urbanization index, the function can also measure the impact

Table 2
The standard of the coupling coordination degree.

Category	Level	Degree	Function	Type
Coordinated development	0.8 < CD ≤ 1	High balanced	UL < EH	Urbanization lag
			UL ≈ EH	Systematic balanced
			UL > EH	Ecology lag
Transformation development	0.6 < CD ≤ 0.8	Moderate balanced	UL < EH	Urbanization lag
			UL ≈ EH	Systematic balanced
			UL > EH	Ecology lag
	0.4 < CD ≤ 0.6	Basically balanced	UL < EH	Urbanization lag
			UL ≈ EH	Systematic balanced
			UL > EH	Ecology lag
Uncoordinated development	0.2 < CD ≤ 0.4	Moderate unbalanced	UL < EH	Urbanization lag
			UL ≈ EH	Systematic balanced
			UL > EH	Ecology lag
	0 < CD ≤ 0.2	Serious unbalanced	UL < EH	Urbanization lag
			UL ≈ EH	Systematic balanced
			UL > EH	Ecology lag

Note: UL and EH stand for urbanization level and ecosystem health, respectively; UL ≈ EH means to|UL-EH| ≤ 0.1.

of ecosystem health on urbanization. The α_i (m_i, n_i, s_i) matrix form of the α (m_i, n_i, s_i) is calculated based on previous studies (Shi et al., 2020; Ariken et al., 2021).

4. Results and discussion

4.1. The temporal trends of urbanization and ecosystem health

From 1997 to 2015, the urbanization level showed a gradual upward trend in Chongqing (Fig. 4a), especially since 2000, it entered a period of rapid development due to the implementation of the western development strategy. Population growth, economic development and urban expansion had a significant impact on the improvement in the urbanization level. The proportion of economic urbanization increased gradually from 1997 to 2015, which played a key role in promoting urbanization process (Tian et al., 2020). Population urbanization demonstrated a trend of rapid growth first and then slow increase. Spatial urbanization increased steadily and had not changed significantly since 1997. Social urbanization displayed a slow increasing trend, while it still maintained at a low level. The above results indicated that the development of urbanization in Chongqing mainly depended on the transformation of rural population to urban population and the expansion of built-up land in the early stage (1997–2009), while economic development and population growth were the main factors driving the development of urbanization in the middle and later stage (2010–2015). Most studies also confirmed that Chongqing is development from extensive population and land expansion to high-quality economic and social urbanization (Yang et al., 2020; Shi et al., 2020).

Fig. 4b shows the changing trend of ecosystem health and its four subsystems in Chongqing from 1997 to 2015. Specifically, the ecosystem health index displayed a volatility and slow rising trend. The average value of ecosystem health increased from 0.59 in 1997 to 0.61 in 2015, indicating that the ecosystem quality was gradually improving and basically maintained at a relatively healthy level. The changing trend of ecosystem vigor was similar to that of ecosystem health, indicating that ecosystem vigor played a key role in improving the regional ecosystem health. Xie et al. (2021) also found that vigor factor was the basic condition for determining ecosystem health. Ecosystem organization showed a downward rapidly before 2010, then it was relatively stable after 2010. Compared with the other three subsystems, the average value of ecosystem organization had a notable decrease of 3.78%, which was mainly attributed to large-scale urban expansion and infrastructure construction (i.e., road network) (Kang et al., 2018). Moreover, there was a similar change trend between ecosystem services and ecosystem resilience, displaying a trend to first decrease then rise slowly, and basically maintained a relatively low level, which reduced the quality of the ecological environment and hindered the sustainable development of socio-economy to some extent.

Fig. 4c displays the synergistic process between urbanization and ecosystem health from 1997 to 2015. Results showed that there was an "N" shape relationship between urbanization and ecosystem health. That is, with the increase of the urbanization index, ecosystem health index demonstrated a trend to first increase then decline, followed by increase, which was not consistent with the results of previous studies (Liang et al., 2019). For example, Wang et al. (2019c) found that there was an "inverse U" shape correlation between ecosystem services and economic development and population growth. The main reason for these differences is that previous studies mostly employed a single indictor (i.e., per capita GDP and population density) to explore the relationship between urbanization and ecosystem health, ignoring other potentially important factors in the process of urbanization, such as industrial upgrading, population migration and urban expansion, all of which have significant impact on the change of regional ecosystem health (He et al., 2019; Shi et al., 2020). Specifically, in the first stage (1997–2002), the impact of urbanization on ecosystem health was insignificant due to low economic growth and slow population migration. Meanwhile, the multi-center group development model and ecological protection projects enhanced the vigor and resilience of the ecosystem and promoted the healthy development of nature ecosystem (Jia et al., 2020). In the second stage (2002−2010), with the implementation of

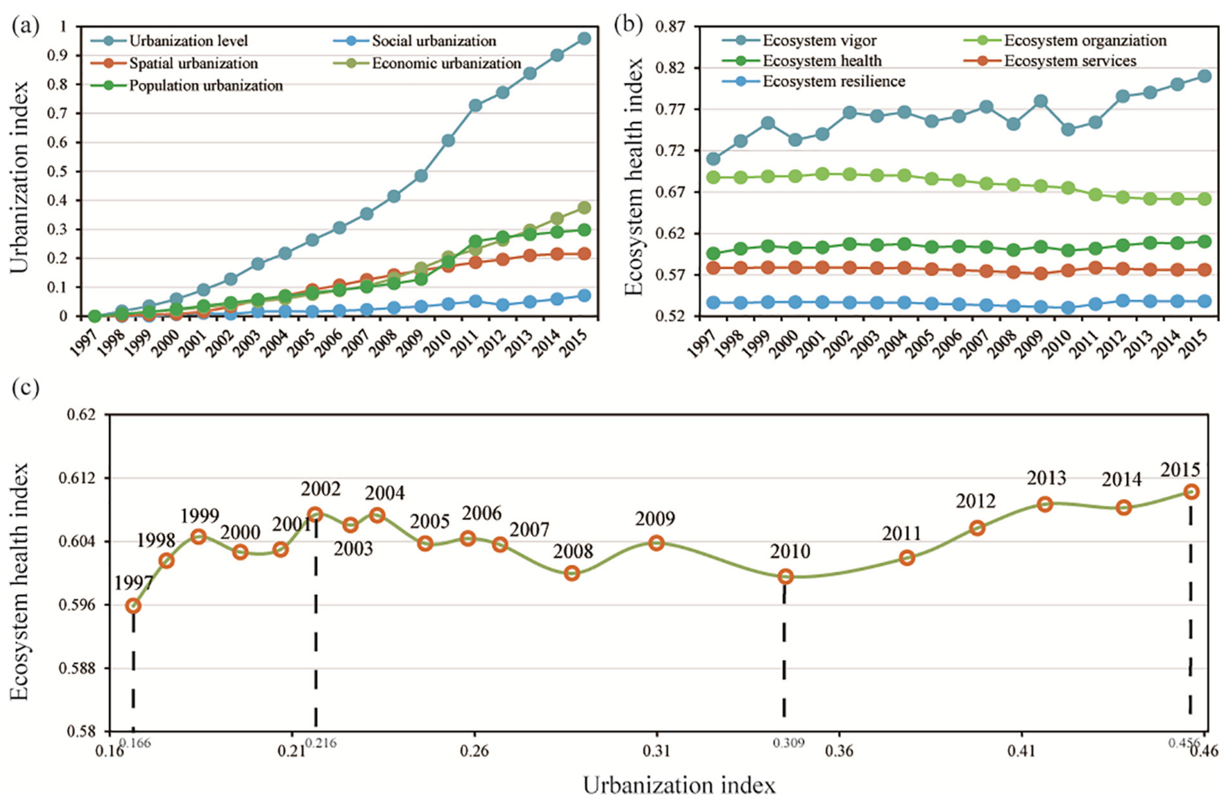

Fig. 4. The curves and synergistic evolution of urbanization and ecosystem health from 1997 to 2015 in Chongqing.

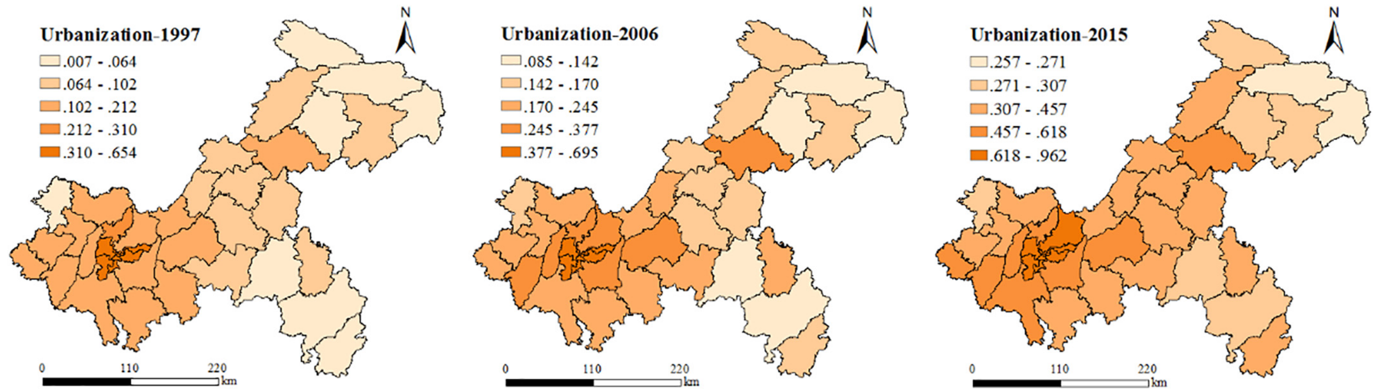

Fig. 5. The spatial pattern of comprehensive urbanization level at the county scale for selected years.

western development strategy and Urban-Rural Synthetically Reform (CMPG, 2007), large-scale urban expansion and urban-rural population migration seriously interfered with the ecosystem structure and function, and destroyed the balance between ecosystem services supply and demand, leading to ecosystem degradation and the reduction of ecosystem health level (Li et al., 2001). In the third stage (2010–2015), the ecosystem health index was gradually increasing, which was mainly attributed to the upgrading of industrial structure and the new-type urbanization road proposed by China's 12th five-year Planning (2011–2015). The tertiary industry in Chongqing has gradually become the pillar industry of economic development after 2010 (Tian et al., 2020), which provided financial guarantee and technical support to preserve ecosystem functions.

4.2. The spatial pattern of urbanization and ecosystem health

Fig. 5 shows the spatial pattern of urbanization level in Chongqing in 1997, 2006 and 2015. In 1997, the highest levels of urbanization were mainly distributed in MEC, especially Yuzhong District and Jiangbei District, with Yuzhong District having the highest value of 0.65. The lowest levels of urbanization were concentrated in SEC, with the values of all districts and counties less than 0.1, indicating that there was heavily polarization in the urban development of Chongqing at the county scale. In 2015, the urbanization level of MEC was still higher than peripheral areas, with the highest urbanization score in Yuzhong District (0.96), followed by Jiangbei District (0.81). The lowest levels of urbanization were mostly distributed in NEC, led by Wushan County and Wuxi County, with Wushan County having the lowest value of 0.25, indicating that the development of urbanization in SEC was faster than that in NEC in the past two decades. In general, the urbanization level of all districts and counties in Chongqing showed an upward trend from 1997 to 2015, although there were obvious regional differences. 1) MEC occupied the first echelon cities with strong siphon effect, gathering high-quality market resources, technical personnel and financial of Chongqing (Wang et al., 2019b). 2) OEC comprised second echelon cities, and its development benefited from the "fringe effect" of the metropolitan area. Moreover, with the integration development of Chengdu-Chongqing urban agglomeration, the agglomeration ability of urbanization elements in OEC was enhanced (Liu et al., 2017), and the development potential was gradually increased. 3) As the green barrier and ecological protection area of Chongqing, NEC and SEC constituted the third echelon cities, where the development of urbanization was relatively slow due to the restrictions of terrain and traffic (Jia et al., 2020).

Fig. 6 displays the spatial pattern of ecosystem health in Chongqing in 1997, 2006 and 2015. In 1997, the counties with the well and relatively well level were mainly distributed in SEC and NEC, dominated by Chengkou county and Wuxi county, in which Chengkou had the highest ecosystem health score of 0.98. The counties with the weak and relatively weak level were concentrated in MEC and OEC, led by Yuzhong District and Dadukou District, with Yuzhong District has the lowest ecosystem health score of 0.04, revealing that the higher the urbanization level, the larger demand for ecological regulation. From 1997 to 2015, although the distribution pattern of ecosystem health in Chongqing remained basically unchanged, there were differences in the change rate of ecosystem health in different regions. Specifically, 1) the average value of ecosystem health in MEC showed a downward trend (Fig. S1), from 0.41 in 1997 to 0.36 in 2015, and the type of ecosystem health also changed from ordinary to relatively weak. Population agglomeration and economic development increased the consumption of ecosystem services related to human activities, and the literature has shown that the impact of economic development and population growth on the ecosystems is reflected in the expansion of built-up land, which damaged the ecosystem structure and function, leading to ecosystem deterioration (Peng et al., 2017; Liao et al., 2020). 2) The

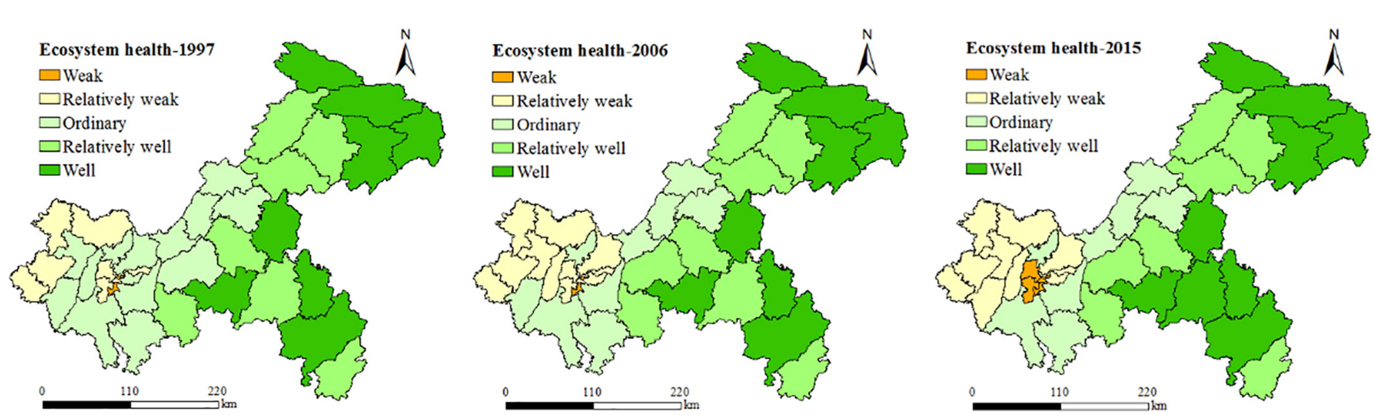

Fig. 6. The spatial pattern of ecosystem health at the county scale for selected years.

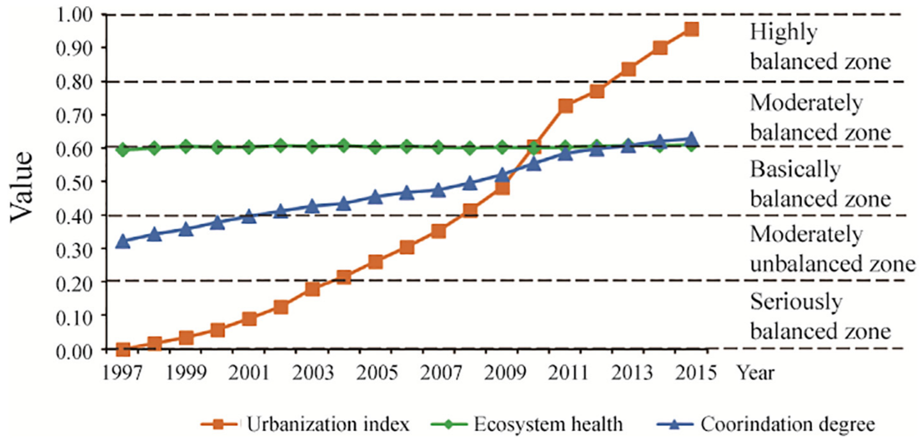

Fig. 7. Changes in the average coordination degree between UAEH in Chongqing, 1997–2015.

average value of ecosystem health in OEC also denoted a downward trend, from 0.53 in 1997 to 0.52 in 2015, which was basically maintained at the ordinary health level. A large number of infrastructure (i.e., road network and public housing) has been constructed due to the industrial transfer and population migration in MEC, resulting in the increase of landscape fragmentation and the decline of ecosystem organization. (Xie et al., 2021). 3) The mean value of ecosystem health in NEC and SEC showed an upward trend, from 0.77 in 1997 to 0.79 in 2015, which was basically at the relatively well level. In recent years, with the implementation of the Grain for Green Project and the main function zone planning, the interference intensity of human activities to the natural ecosystem of these areas has gradually decreased (Yang et al., 2020), which is conducive to the restoration of vegetation and the improvement of eco-environmental carrying capacity.

4.3. The temporal trend of the coupling coordination degree

Based on the CCDM, we measured the coordination degree between UAEH in Chongqing from 1997 to 2015 and identified the development types. Fig. 7 showed that the coordination degree between UAEH increased from 0.32 in 1997 to 0.63 in 2015, and the coupling coordination type had also changed from moderately unbalanced stage with urbanization lagged to moderately balanced stage with eco-environment lagged, indicating that Chongqing has made remarkable achievements in improving the coordination between UAEH. Additionally, we also found that the time node of change in coordination degree types was basically consistent with the first year of the implementation of the Five-Year Plan in China, and many studies also indicated that national policies have significant impact on the coordinated development between UAEH (Liang et al., 2019; Ariken et al., 2021). Specifically, the development of urbanization mainly depended on the transfer of rural surplus labor force to urban due to the housing market reform in the first stage (1997–2001), and the urbanization lag was the main reason for the incoordination between UAEH (Yang et al., 2020). In the second stage (2001−2012), the economic development center of Chongqing focused on the reform of state-owned enterprises and proposed "building the capital economic circle" to promote the rapid development of urbanization, while disorderly urban expansion and low land use efficiency had exerted great pressure on resources environment carrying capacity, leading to obviously decline in the eco-environment quality. In 2012, with the rise of ecological civilization as a national strategy, Chongqing has implemented many specific measures to enhance the coordination between economy, society, and environment, such as ecological compensation system, environmental protection tax and green finance, which promotes the coordination between UAEH (Jia et al., 2020). Although the coordination degree between UAEH has crossed three types from 1997 to 2015, the coupling coordination degree between two subsystems was far from the highly balanced stage, indicating that there was still big room to improve the coupling coordination degree between UAEH.

4.4. The spatial pattern of coupling coordination degree

Fig. 8 shows the spatial pattern of the coordination degree between UAEH in Chongqing in 1997, 2006 and 2015. It can be observed that all counties of Chongqing had a significant improvement in the coordination degree from 1997 to 2015. Most counties in 1997 were in seriously unbalanced and moderately balanced stage. By 2015, most counties in Chongqing were located in basically balanced and moderately balanced stage. However, there were significant differences in the coordination

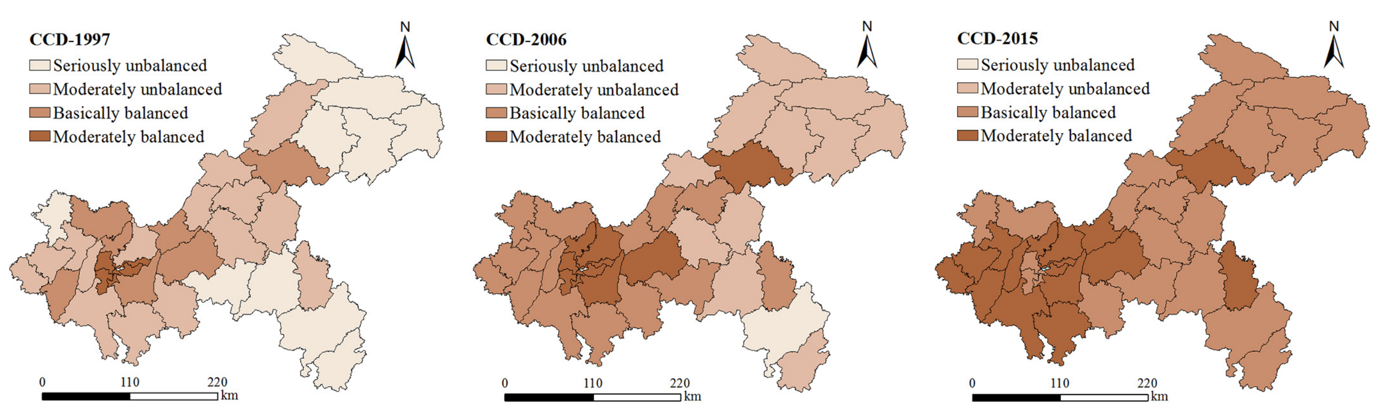

Fig. 8. The coordination degree between UAEH at the county scale for selected years.

degree among different counties. In general, the coordination degree in MEC and OEC were higher than that in NEC and SEC. MEC, as the core area of Chongqing, plays a leading role in promoting ecological protection and high-quality urban development. In recently years, various sustainable measures in MEC have been implemented to improve the quality of urbanization. According to Yang et al. (2020), the metropolitan area has optimized the industrial structure and forms a development model of high-technology industries and modern manufacturing industries. Based on Chongqing Statistical Yearbook of 2015, the "energy consumption per RMB10000 GDP" in MEC was only 0.346 tons of standard coal equivalent compared with NEC and SEC. Therefore, the development of urbanization in this region is less dependent on resource consumption, which leads to a higher coordination degree between UAEH. Meanwhile, the government in MEC and OEC are also more willing to invest large amount of capital to develop resource-saving and environment-friendly industries for pursuing better environmental quality (Liao et al., 2020). However, the economic development in NEC and SEC mainly relies on resource output and infrastructure construction, which destroys the integrity of the ecosystem to some extent. Meanwhile, the transfer of high pollution and high emission industries from MEC and OEC has also aggravated the environmental pollution in these areas, leading to ecosystem deterioration (Jia et al., 2020). In fact, the local government has taken a series of policies to deal with the problem. For example, "policy on establish the development model of ecological industry, ecological agriculture and ecological services" proposed by the 12th Five-Year of Chongqing. "Policy on establish the eco-economic corridor in SEC" issued by the Chongqing Municipal Government in 2017. These measures further promote the coordination between economic development and ecological protection. However, the coordination between UAEH in NEC and SEC needs to be further improved due to the low land use efficiency (Xie et al., 2021).

4.5. The temporal differences between urbanization and ecosystem health

In order to clarify the interaction mechanism between UAEH, we applied GTWR model to explore the impact of urbanization and its subsystems on ecosystem health, and the impact of ecosystem health and its subsystems on urbanization from 1997 to 2015. The specific model calculation results and parameters were shown in Table 3, it can be seen that all the models have a high degree of interpretation and can effectively explain the relationship between UAEH.

Fig. 9(a)–(e) showed the impact of urbanization and its subsystems on ecosystem health at the temporal scale. In general, the positive impact of urbanization on ecosystem health was gradually weakened and tended to be stable after 2011, which was basically consistent with the EKC theory (Kijima et al., 2010). That is, population agglomeration and economic growth have significantly affected the structure, function and process of the ecosystem in the early stage of urbanization, causing many eco-environmental problems. When urbanization develops to a certain threshold, the environmental quality will gradually increase. Shi et al. (2020) pointed out that there was still a large gap in per capita GDP between Chongqing and the eastern coastal cities, and economic development had not broken though this threshold, indicating that Chongqing still face the pressure to deal with eco-environmental problems. Specifically, 1) the positive impact of population urbanization on ecosystem health had changed from weaken to strength, which was mainly related to the changes of government policies and market environment. In the context of the reform of state-owned enterprises in the mid-1990s, a large number of unemployed people gathered in large and medium-sized cities for work and live (Fan et al., 2020). Previous studies have indicated that the rapid increase in population density will result in large-scale urban expansion and ecological destruction. In 2006, Chongqing's 11th five-year Planning pointed out that local government should actively strength regional economic integration and promote the transformation and upgrading of the industrial structure for improving the ecological environment (Jia et al., 2020), and the impact of demographic factors on ecosystem health slowly declined. 2) The positive impact of economic urbanization on ecosystem health showed a tendency to be stable at first and then decline rapidly, which was consistent with previous studies. For example, Peng et al. (2015) found that economic growth had no significant impact on the ecosystem structure and function at the initial stage, while its negative impact on ecosystem services was gradually exposed with the development of urbanization. In 2007, Chongqing became the pilot area of the Urban-Rural Synthetically Reform in China, large-scale infrastructure construction (i.e., highway and railway) and built-up land were developed, which seriously interferes with ecosystem processes and its associated ecosystem function, leading to a decline in the supply capacity of ecosystem services (Mo et al., 2017). 3) The impact of spatial urbanization on ecosystem health had changed from positive to negative, which is mainly related to urban growth models, driving factors and government policies at different stages of urbanization (Kang et al., 2018). Before 2003, the expansion scale and growth rate of construction land was relatively small due to the limitation of topography and the implementation of natural forest resources protection projects, and it was mainly edge-expansion and filling type (Jia et al., 2020), which reduced the interference intensity of urbanization and increased the vigor and organization of the ecosystem. With the reform of state-owned enterprises and the upgrading of industrial structure in 2007, the demand for residential land and industrial land was gradually increasing, which destroyed the balance of the ecosystem to some extent (Xie et al., 2021). Meanwhile, the development of transportation infrastructure (i.e., high-speed roads and railway networks) gradually breaks through the limitation of topography, affects the composition and configuration of landscape pattern, resulting in the increase of landscape separation and the decrease of ecosystem resilience. 4) The negative impact of social urbanization on ecosystem health was gradually decreasing. For a long time, the most counties of Chongqing have adopted the development model of "pollution first and treatment later". Chongqing's economic growth mainly depended on the secondary industry during 1997–2005, with its average annual contribution rate of more than 58% (Jia et al., 2020). However, with the improvement of people's income and education level, the awareness of saving resources and protecting the environment was gradually enhanced (Liao et al., 2020).

Fig. 9(f)–(j) showed the impact of ecosystem health and its subsystems on urbanization at the temporal scale. In general, the negative effect of ecological environment on urbanization was strengthened first and then weakened, indicating that Chongqing had made great strides in improving the quality of ecological environment. In fact, with the implement of the main function zoning in 2006, Chongqing has divided priority development areas, restricted development areas, prohibited development areas and ecological protection areas (Yang et al., 2020), which enhanced the carrying capacity of the ecological environment, and promoted the coordination between UAEH to some extent. Specifically, 1) the effect of ecosystem organization on urbanization had changed from positive to negative. Rapid economic growth and

Table 3
The GTWR model calculation results and parameters.

Dependent variable	R^2	Bandwidth	Sigma	AIC_C	Spatiotemporal distance ratio	Residual squares
Urbanization index	0.9006	0.1219	0.0573	1924.294	0.5621	2.3676
Ecosystem health index	0.9451	0.1149	0.0462	2203.773	0.5418	1.5426

population agglomeration lead to disorderly built-up land expansion, especially the construction of transportation networks, which increases the fragmentation between landscape patches, interferes with materials circulation and energy flow, in turn, it restricts the sustainable development of urbanization. Mo et al. (2017) indicated that road network expansion was the main reason for the decline of ecosystem organization. After 2008, with the improvement of land use efficiency and the optimization of spatial pattern, landscape connectivity was gradually enhanced, and the restriction effects of ecosystem organization were gradually weakened (Xie et al., 2021). 2) The influence of ecosystem vigor on urbanization had changed from negative to positive. In 1999, with the implementation of the ecological restoration project, Chongqing government took many measures to improve the quality of the eco-environment, such as the closure of resource consuming industries, the establishment of ecological compensation system and so on, which increased the vegetation coverage and enhanced the vigor of the ecosystem. Previous studies have indicated that vegetation coverage plays a key role in the improvement of eco-environmental quality and the sustainable development of urban (Kang et al., 2018; He et al., 2019). 3) The impact of ecosystem resilience on urbanization was similar to that of ecosystem organization, and the negative impact had changed from strong to weak, which was mainly related to the economic development model and government policies. During the period of rapid urbanization, a large ecological land (i.e., forestland, grassland and wetland) has been transformed into industrial land, residential land and transportation land, which weakens the resistance of natural ecosystem to external interference, causing many eco-environmental problems (Xie et al., 2021). After 2010, Chongqing invested a lot of funds to establish ecological parks and green infrastructure, which enhanced the ecosystem resilience and promoted the sustainable development of urbanization (Jia et al., 2020). 4) The impact of ecosystem services on urbanization had changed from negative to positive, which was basically consistent with the change of ecological vigor. Sun et al. (2019) pointed out that the imbalance between supply and demand of ecosystem services was the root cause of ecosystem deterioration, which restricted the survival of human and the development of socio-economic. Therefore, in order to meet the demand for ecological products and services brought about by population growth, Chongqing has made great efforts

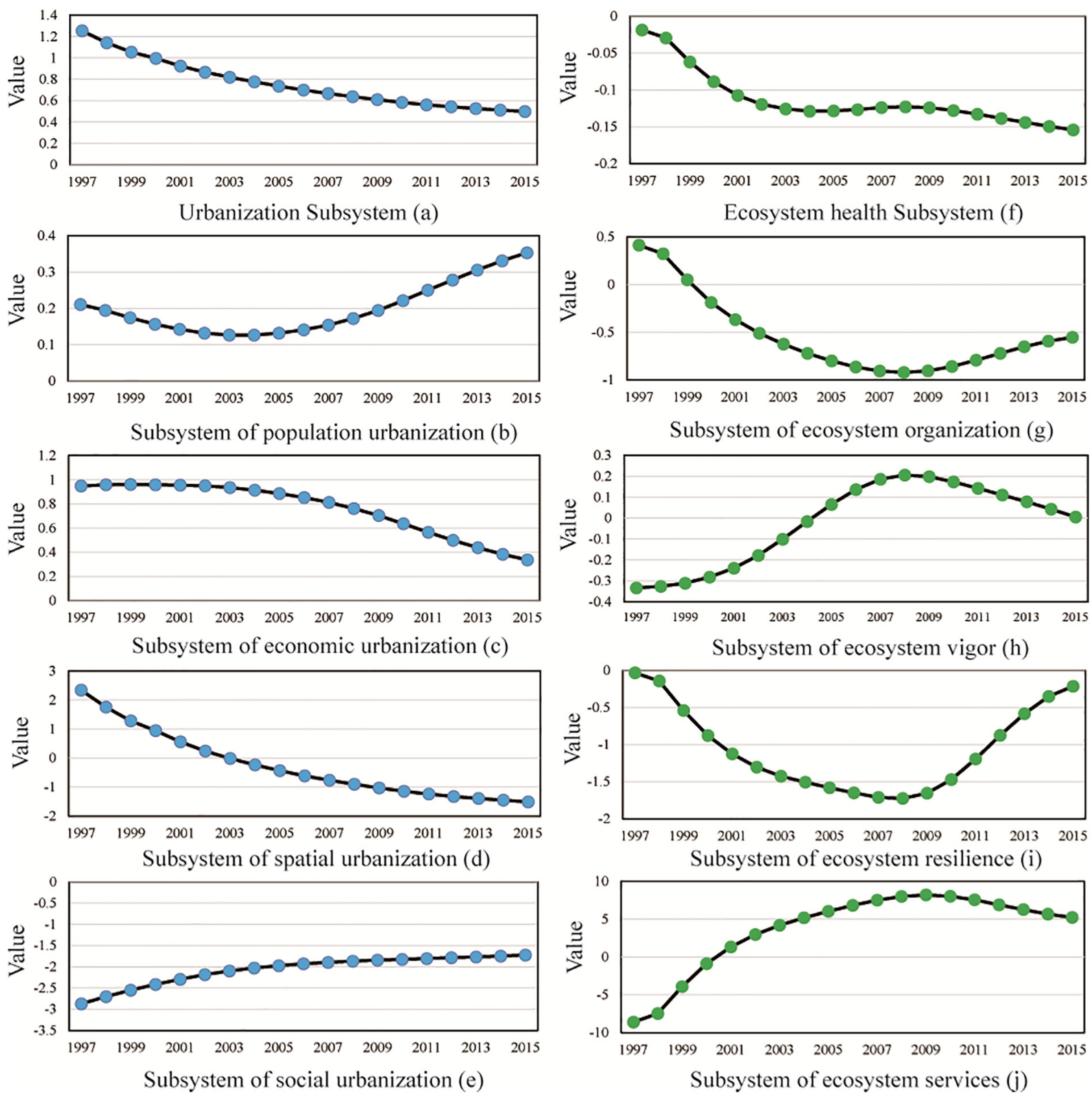

Fig. 9. The temporal differences between UAEH in Chongqing from 1997 to 2015.

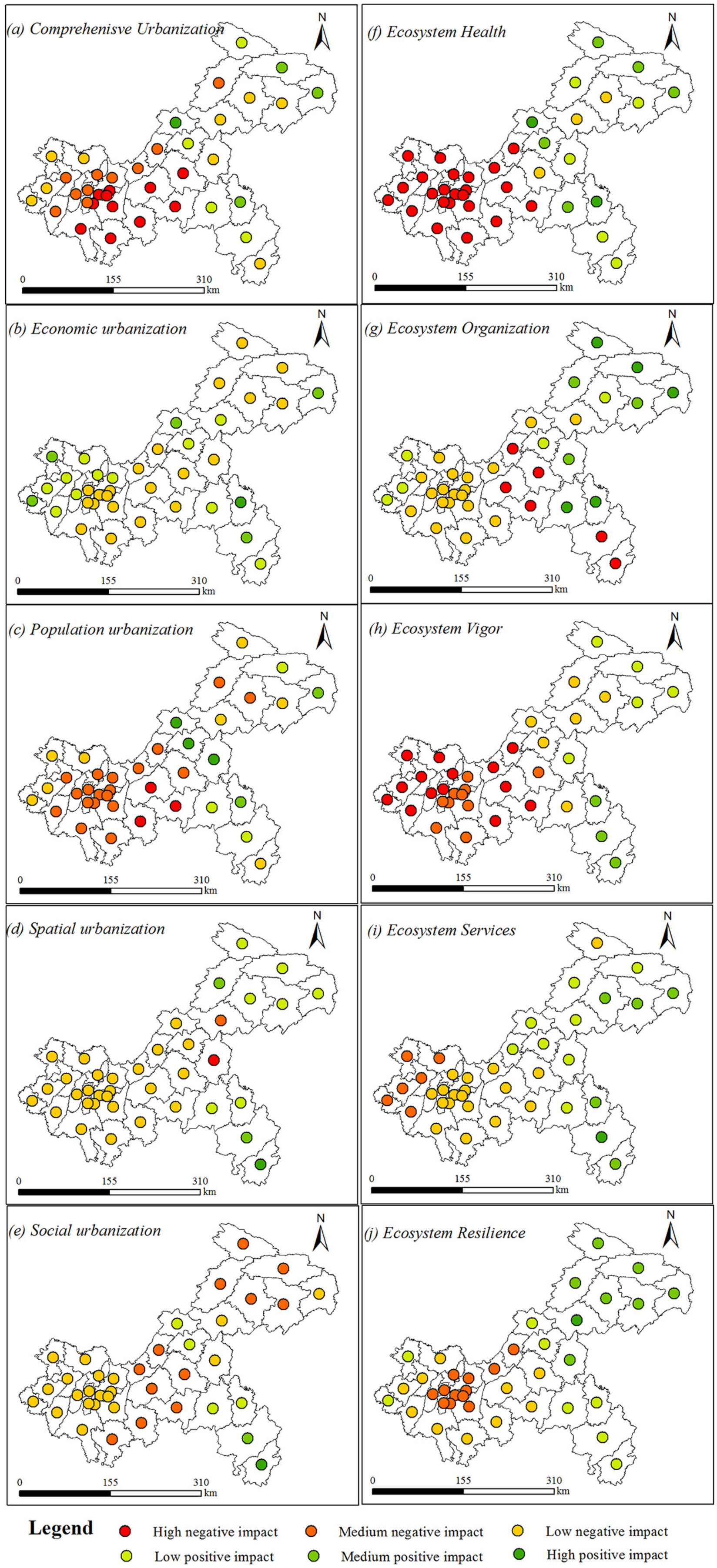

Fig. 10. The spatial differences between UAEH in Chongqing from 1997 to 2015.

to improve the quality of eco-environment and guarantees the sustainable supply of ecosystem services by increasing investment in green industries and high-tech industries.

4.6. The spatial differences between urbanization and ecosystem health

Based on the parameter results of GTWR model, we calculated the annual average impact coefficients of the interaction between UAEH in all counties in Chongqing from 1997 to 2015, and divided these coefficients into six grades: high negative impact, moderate negative impact, low negative impact, high positive impact, medium positive impact and low positive impact.

As shown in Fig. 10(a)-(e), urbanization improved the ecosystem health in NEC and SEC, but aggravated the deterioration of the ecosystem in MEC and OEC. This implied that there were significant differences in the development level of urbanization in Chongqing, with urbanization lagging behind in NEC and SEC due to complex topography, whereas it was excessive in MEC and OEC due to economic and policy advantages (Shi et al., 2020). Therefore, it is imperative to make different plans according to the differences of topography and economic development patterns for promoting the coordinated development between UAEH. Specifically, 1) economic urbanization improved the eco-environmental quality of SEC and OEC, but aggravated the environmental pollution in cities dependent on heavy industrial of MEC and NEC. Chongqing was in the middle stage of urbanization, and the pillar of economic development was still the secondary industry. Shi et al. (2019) pointed out that the secondary industry with high pollution and high energy-consumption in MEC had aggravated environmental pollution and ecosystem degradation. However, the economic development in NEC mainly relied on resource exploitation and infrastructure construction, which destroyed the surface vegetation and interfered with the ecosystem's balance. In contrast, the environmental quality of other cities had been improved due to the benefits brought by the rapid development of tourism (Peng et al., 2015). 2) Population urbanization improved the eco-environment quality of SEC, but aggravated the deterioration of the eco-environment in other areas of Chongqing, especially in MEC. Since 1997, a large number of surplus labor force have entered the metropolitan area seeking employment opportunities, which exerts great pressure on resource environment carrying capacity and causes many eco-environmental problems. Meanwhile, Liang et al. (2019) indicated that a large number of tourists and service personnel have caused a rapid increase in population density and urbanization rate, which aggravates ecosystem degradation. By contrast, as a major labor output region in Chongqing, the decline of population density in SEC alleviates the pressure on the ecological environment and ensures the sustainable supply of ecosystem services (Jia et al., 2020). 3) Spatial urbanization improved the eco-environmental quality in NEC and SEC, but aggravated the deterioration of the eco-environmental in MEC and OEC. Rapid economic growth and population agglomeration have intensified the demand for land resources and infrastructure, which has led to the expansion of urban land and road networks, and destroys the ecosystem's balance. Peng et al. (2017) indicated that the expansion of built-up land is the direct driving factor of ecosystem degradation than economic development and population growth. In Wanzhou District and Shizhu County, spatial urbanization had a significant negative impact on the ecosystem health, which was attributed to the increase in the demand for construction land brought about by the construction of the Three Gorges Project for the resettlement of immigrants (Li et al., 2001). 4) Social urbanization improved the quality of the ecological environment in SEC, and aggravated the deterioration of the ecological environment in other areas of Chongqing, especially in MEC and NEC. Economic growth mainly depends on the secondary industry with high pollution and high emission in MEC, which improves the income of urban residents, in turn, aggravates environmental pollution. However, Liao et al. (2020) indicated that with the increase of people's income level and the demand for high-quality environment, the awareness of environmental protection was also gradually enhanced, which is conducive to the ecological environment's improvement in quality. Moreover, the use of big data network also reduces paper consumption and improves the quality of the ecological environment (Xie et al., 2021).

As shown in Fig. 10(f)-(j), ecosystem health restricted the development of urbanization in MEC and OEC, while improving the quality of urbanization in NEC and SEC. The reason for this difference was mainly related to the carrying capacity of resources environment and the geo-ecological environment (Yang et al., 2020). The high-density construction land and population aggregation in MEC and OEC have exceeded the carrying capacity of resources environment, leading to ecosystem deterioration, in turn, which restricts the sustainable development of urban. However, the interference of human activities to the ecological environment in NEC and SEC was relatively small, maintaining a high carrying capacity of ecological environment. Specifically, 1) ecosystem organization promoted the quality of urbanization in NEC, while restricted the development of urbanization in MEC and SEC. The large-scale expansion of industrial land and traffic land in MEC increased the landscape patch's fragmentation, and destroyed the ecosystem's balance (Kang et al., 2018). Previous studies have indicated that the increase of landscape fragmentation will lead to many environment issues, such as urban heat island, air pollution and geological disasters (Shi et al., 2019; Li et al., 2017). Liangping District and Dianjiang District as the main producing areas of national agricultural products, a large area of agricultural land reduced landscape heterogeneity and affected the ecosystem quality (Xie et al., 2021). Meanwhile, in the context of the Urban and Rural Synthetically Reform, the governments of Youyang County and Xiushan County have invested a lot of funds to establish concentrated settlement areas and transportation infrastructure to solve the problem of scattered rural settlements, which interferes with the ecosystem's balance to a certain extent (Jia et al., 2020). 2) Ecosystem vigor was beneficial to urbanization development in NEC and SEC, but restricted urbanization development in MEC and OEC. The main indicator of ecosystem vigor was vegetation coverage in this study. In recent years, the large-scale urban construction in MEC and OEC had destroyed the surface vegetation, reduced the ecosystem vigor, and caused a series of eco-environmental problems (Yang et al., 2020). While as the ecological protection areas and restricted development areas, the implementation of ecological protection projects in NEC and SEC has significantly improved the vegetation coverage and promoted the quality of the eco-environment. 3) Ecosystem services promoted urbanization development in SEC and NEC, but restricted urbanization development in MEC and OEC. Population agglomeration in MEC and OEC has intensified the demand for ecosystem products and services, while large-scale urban expansion and highly polluting industries have aggravated the imbalance between supply and demand of ecosystem service, and seriously threatened the ecosystem health (Sun et al., 2019). As soil retention areas and water conservation areas, the development of tourism and green industry in NEC and SEC had further improved the quality of the eco-environment and ensured the sustainable supply of ecosystem services (Yang et al., 2020). 4) Ecosystem resilience promoted the development of urbanization in NEC and SEC, but restricted the development of urbanization in MEC. The large-scale expansion of built-land in MEC had seriously disturbed the ecosystem's balance, causing a decline in the resistance of natural ecosystems to external disturbances (Xie et al., 2021). The construction land in Chongqing increased by about 1538.4 km^2 from 1997 to 2015, of which the metropolitan area accounted for 42.25%, which has exceed the carrying capacity of resources and environment, resulting in ecosystem degradation.

5. Conclusions and policy implications

Rapid urbanization not only promotes economic growth and social development, but also causes many eco-environmental problems. These problems are mainly concentrated in two aspects:

1) environmental pollution caused by industries with high pollution, high emissions and high energy consumption, such as haze, water pollution and solid waste pollution. 2) The disorderly urban expansion brought about by population agglomeration and economic growth has occupied a lot of ecological land, which has seriously disturbed the structure and function of the ecosystem. Currently, most studies only focus on the interactive relationship between urbanization and environmental pollution, ignoring the coordination relationship and internal mechanism between urbanization and ecosystem structure and function, which is not conducive to clarify the relationship between human-land system.

Therefore, in viewing of this, based on the comprehensive index of urbanization and ecosystem health, this study integrated the CCDM and GTWR model to measure the interaction and spatiotemporal heterogeneity between UAEH in Chongqing at the county scale from 1997 to 2015. Results showed that: 1) the urbanization level showed a gradual upward trend from 1997 to 2015, and the development of urbanization has changed from the initial stage driven by population growth and urban expansion to that driven by population increase and economic development in the middle stage. The urbanization level in MEC and OEC was higher than in NEC and SEC. Ecosystem health denoted a fluctuated upward trend from 1997 to 2015. Meanwhile, ecosystem vigor had a significant and direct impact on ecosystem health in all assessment indicators. The ecosystem in NEC and SEC was healthier than that in MEC and OEC. The synergistic evolution between UAEH fluctuates periodically, which was mainly affected by government policies and market changes. 2) From 1997 to 2015, the coordination degree between UAEH showed an upward trend in Chongqing, developed from the moderately imbalance stage to the moderately balance stage, and experienced a transition from urbanization lag to ecosystem health lag. Meanwhile, the coordination degree in MEC and OEC was higher than that in NEC and SEC. 3) GTWR model indicated that the interaction between UAEH tended to converge. The negative effects between UAEH in Chongqing were concentrated in the economically developed central and western regions, while the positive effects between UAEH were concentrated in the economically underdeveloped southeastern and northeastern regions. Population urbanization aggravated the deterioration of the ecosystem in MEC and OEC, in turn, the decline of ecosystem resilience and vigor also restricted the development of urbanization.

In order to improve the coordination degree between UAEH, we also put forward some effective and feasible policy recommendations taking into account the differences in topography, resource endowments and development models:

The coordination degree between UAEH in MEC and OEC was relatively high, but the weak ecosystem health was still the main factor restricting the development of urbanization. In terms of ecosystem vigor, the large-scale urban expansion in the metropolitan area has destroyed the surface vegetation, resulting in the reduction of biodiversity. At the same time, the pollution problems caused by high pollution industries also affect the growth of vegetation and interfere with the ecosystem's balance (Shi et al., 2020). Therefore, these areas should implement ecological restoration, strengthen green infrastructure construction, promote the transformation, optimization and upgrading of industrial structure for improving the carrying capacity of resources and environment (Liao et al., 2020). In terms of ecosystem organization, disorderly road network expansion increase the degree of landscape fragmentation, which hinder material circulation and energy flow. Therefore, these areas should further improve ecological corridors, and infrastructure construction should avoid forestland and farmland as much as possible to ensure the integrity of natural ecosystem patches. In terms of ecosystem resilience, population agglomeration and urban expansion exert tremendous pressure on the carrying capacity of resources and environment, resulting in a decline in the resistance of natural ecosystems. Therefore, in the process of urbanization, the government should carry out reasonable spatial planning to avoid blind urban expansion, improve land use efficiency and alleviate the pressure of ecological environment (Xie et al., 2021). In terms of ecosystem services, the rapid growth of population is accompanied by an increase in the demand for ecosystem products and services. However, unreasonable resource exploitation and urban construction destroy the balance between the supply and demand of ecosystem services. Therefore, these areas should close down resource-consuming industries, develop green service industries, establish nature reserves zone, and form a low-consumption, green, low-carbon ecosystem service system (Yang et al., 2020).

The coordination degree between UAEH in NEC and SEC was relatively low, and the urbanization lag was the main reason for the disharmony between them. In terms of economic urbanization, the region should abandon the traditional economic development model of resource output and energy consumption, which not only causes serious eco-environmental problems, but also restricts the sustainable development of urban. In the future, based on its own eco-environmental advantages, the region should develop tourism, green and innovative industries, and create a number of cultural tourism brands, such as the three Gorges tourist zone and the Gallery of Wujiang River, so as to enhance the influence and economic level of the region (Chen et al., 2020). In terms of population urbanization, these areas are facing a brain drain, with more than 5 million people going out to work in 2015, which affects the overall level of urbanization in the region. Therefore, the government should implement some advantageous policies to attract talents, improve urban public service and management capacity, encourage rural population to work near the city, and ensure that everyone enjoys the same public services. In terms of spatial urbanization, due to the limitation of topography, about 64.21% of the newly expanded land in this area with a slope of more than 25°, which increases the potential risk of geological disasters (Jia et al., 2020). Therefore, the region should fully consider the fragility and sensitivity of the geological ecological environment, make a reasonable spatial layout, avoid large-scale urban expansion and adopt multi-center development model, which is conductive to habitat conservation and reduce the risk of geological disasters. In terms of social urbanization, the government should improve the overall education level of residents, strengthen the publicity of ecological protection knowledge, and enhance the public awareness for environment-friendly lifestyle. This study hopes that the above policy recommendations can provide a green, low-carbon, innovative path to promote the ecological protection and the high-quality urbanization development.

CRediT authorship contribution statement

Weijie Li: Data curation, Writing – original draft. **Yong Wang:** Writing – review & editing. **Shiyou Xie:** Supervision. **Xian Cheng:** Conceptualization, Methodology, Software.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148311.

References

Aguilera, M.A., Gallardo, C., Núez, P., Varas-Belemmi, K., 2020. J. Environ. Manag. 276, 111297.
Ariken, M., Zhang, F., Chan, N.W., Kung, H.T., 2021. Ecol. Indic. 121, 107014.
Chen, J., Li, Z., Dong, Y., Song, M., Xie, Q., 2020. J. Clean. Prod., 123848
Chen, W., Chi, G., Li, J., 2019. Sci. Total Environ. 669, 459–470.

Cheng, J., Dai, S., Ye, X., 2016. China Econ. Rev. 40, 179–191.
Cheng, X., Long, R., Chen, H., Li, Q., 2019. Ecol. Indic. 104, 489–500.
Chia, T., Shu, L., 2009. Landsc. Urban Plan. 93 (3–4), 151–162.
CMPG, 2007. Chongqing Municipal People's Government, Chongqing (in Chinese).
Costanza, R., 1992. Toward an Operational Definition of Ecosystem Health. Ecosystem Health: New Goals for Environmental Management. Island Press.
Cui, D., Chen, X., Xue, Y., Li, R., Zeng, W., 2019b. J. Environ. Manag. 234, 189–199.
Cui, X., Fang, C., Liu, H., Liu, X., 2019a. Ecol. Indic. 96, 383–391.
Dong, F., Li, J., Wang, Y., Zhang, X., Zhang, S., Zhang, S., 2019a. Sci. Total Environ. 685, 631–658.
Dong, F., Li, J., Li, K., Sun, Z., Yu, B., Wang, Y., Zhang, S., 2019b. J. Clean. Prod., 118889
Fan, W., Wang, H., Liu, Y., Liu, H., 2020. J. Clean. Prod. 272, 122812.
He, J., Pan, Z., Liu, D., Guo, X., 2019. Sci. Total Environ. 673(JUL.10, 553–564.
Huang, B., Wu, B., Barry, M., 2010. Int. J. Geogr. Inf. Sci. 24 (3), 383–401.
Jia, L., Ma, Q., Du, C., Hu, G., Shang, C., 2020. Landsc. Ecol. 35 (11), 2449–2469.
Kang, P., Chen, W., Hou, Y., Li, Y., 2018. Sci. Total Environ. 636, 1442–1454.
Kijima, M., Nishide, K., Ohyama, A., 2010. J. Econ. Dyn. Control. 34 (7), 1187–1201.
Li, C., Li, Y., Shi, K., Yang, Q., 2020. Int. J. Environ. Res. Public Health 17 (10).
Li, H., Waley, P., Rees, P., 2001. Geogr. J. 167, 195–212.
Li, H., Peng, J., Yanxu, L., Yi'na, H., 2017. Ecol. Indic. 82, 50–60.
Li, W., Tan, M., 2018. Sci. Rep. 8 (1), 16954.
Liang, L., Wang, Z., Li, J., 2019. J. Clean. Prod. 237, 117649.
Liao, C., Yue, Y., Wang, K., Fensholt, R., Tong, X., Brandt, M., 2018. Ecol. Indic. 90, 416–425.
Liao, S., Wu, Y., Wong, S., Shen, L., 2020. Sci. Total Environ. 730, 138964.
Liu, H., Ma, L., Li, G., 2017. Geogr. Res. 36 (01), 97–108.
Liu, H., Huang, B., Yang, C., 2020a. Sci. Total Environ. 732.
Liu, X., Yu, L., Si, Y., Zhang, C., Lu, H., Yu, C., Gong, P., 2018. Remote Sensing Letters 9 (10), 972–981.
Liu, Y., Yang, L., Jiang, W., 2020b. Ecol. Indic. 119.
Mo, W., Wang, Y., Zhang, Y., Zhuang, D., 2017. Sci. Total Environ. 574, 1000–1011.
Pan, Z., He, J., Liu, D., Wang, J., 2020. Appl. Geogr. 124, 102293.
Peng, J., Liu, Y., Wu, J., Lv, H., Hu, X., 2015. Landsc. Urban Plan. 143, 56–68.
Peng, J., Shen, H., Wu, W., Liu, Y., Wang, Y., 2016. Landsc. Ecol. 31 (5), 1077–1092.
Peng, J., Liu, Y., Li, T., Wu, J., 2017. Ecol. Indic. 72, 399–410.
Rapport, D.J., Costanza, R., McMichael, A.J., 1998. Trends Ecol. Evol. 13 (10), 397–402.
Shi, K., Wang, H., Yang, Q., Wang, L., Sun, X., Li, Y., 2019. J. Clean. Prod. 231, 990–1004.
Shi, T., Yang, S., Zhang, W., Zhou, Q., 2020. J. Clean. Prod. 244, 118739.
Sun, Y., Liu, S., Dong, Y., An, Y., Shi, F., Dong, S., Liu, G., 2019. Sci. Total Environ. 681, 211–225.
Tian, Y., Zhou, D., Jiang, G., 2020. Ecol. Indic. 117, 106543.
Wang, J., Wang, S., Li, S., Feng, K., 2019a. Appl. Energy 254, 113650.
Wang, J., Zhou, W., Pickett, S., Yu, W., Li, W., 2019c. Sci. Total Environ. 662, 824–833.
Wang, Z., Liang, L., Sun, Z., Wang, X., 2019b. J. Environ. Manag. 243, 227–239.
Xie, G., Zhang, C., Zhen, L., Zhang, L., 2017. Ecosystem Services 26, 146–154.
Xie, X., Fang, B., Xu, H., He, S., Li, X., 2021. Land Use Policy 102, 105235.
Xing, L., Zhu, Y., Wang, J., 2021. Ecol. Indic. 121, 107028.
Yang, C., Zeng, W., Yang, X., 2020. Sustain. Cities Soc. 61, 102271.