Chin. Geogra. Sci. 2020 Vol. 30 No. 6 pp. 1052–1064
https://doi.org/10.1007/s11769-020-1156-6

Springer Science Press
www.springerlink.com/content/1002-0063

Spatiotemporal Evolution of Ecological Security in the Wanjiang City Belt, China

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Abstract: Ecological security is the foundation and guarantee of sustainable development, and its importance is increasingly widely recognized and valued by the world. The Yangtze River Basin is an important ecological security barrier in China and the Wanjiang City Belt (WCB) along the Yangtze River is directly related to the ecological security pattern of the entire basin. Based on the Driver-Pressure-State-Impact-Response (DPSIR) model and a geographical information system (GIS) platform, an ecosystem security evaluation index system was constructed to measure and evaluate the evolution of ecosystem security in the WCB, China. Results showed that: 1) From 2000 to 2018, the overall level of ecological security in the study area was in a state of either early warning or medium warning, but the level of ecological security in each prefecture-level city was significantly different. 2) From the perspective of the evolution of the ecosystem, the value of its comprehensive evaluation index dropped from 4.255 in 2000 to 3.885 in 2018. From the perspective of subsystems, the value of Pressure comprehensive evaluation index is much higher than that of other subsystems, indicating that during the rapid development of the social economy, the pressure on the natural environment tended to rise, and triggered changes in the State and Response subsystems. 3) The coefficient of variation (*CV*) of the Driver was much higher than other factors influencing the ecological security system. There are large differences in the economic development and ecological evolution of the cities in the WCB. This study has improved the theoretical research on regional ecological security, and has certain practical guiding significance for building a beautiful, green and sustainable China and promoting global ecological security.

Keywords: ecological security; complex ecosystem; spatiotemporal evolution; spatial difference; Wanjiang City Belt (WCB)

Citation: CAO Yuhong, LIU Meiyun, ZHANG Yu, CHEN Chen, CAO Weidong, 2020. Spatiotemporal Evolution of Ecological Security in the Wanjiang City Belt, China. *Chinese Geographical Science*, 30(6): 1052–1064. https://doi.org/10.1007/s11769-020-1156-6

1 Introduction

Since the United Nations sustainable development strategy was proposed in 'Our Common Future' in 1987 (WCED, 1987), the world has been actively developing a green economy and giving attention to protection of the ecological environment. At the time the sustainable development strategy was proposed, the main consideration for protecting the ecological environment was the mutual relationship between the contemporary and next generations (Braun et al., 2015; Rak and Pietrucha-Urbanik, 2019). Over the past three decades, major changes have taken place in the world, and our understanding of and attention to the ecological environment have developed substantially (Camarero et al., 2013). The issue of ecological security has become an important goal that human societies need to consider. Ecological security, i.e., the security of complex ecosystems, refers to the state in which the natural resources and ecological environment of a country or region can continuously meet the needs of socio-economic development, while at the same time socio-economic devel-

Received date: 2020-01-07; accepted date: 2020-05-04
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41571124)
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opment is not subject to constraints and threats from natural resources and the ecological environment (Huang et al., 2014; Ewertowska et al., 2016). With the full implementation of the Yangtze River Economic Belt development strategy and the acceleration of the pace of construction of an ecological civilization in China, the evaluation and protection of ecological environment safety must be given priority.

An eco-security system for a region should include sustainable development and security within the regional ecosystem (He et al., 2017). Preventive measures can be taken to mitigate or eliminate potential threats, transforming unsafe factors into safe factors (Sekovski et al., 2012; Terrado et al., 2013; He et al., 2017). Eco-environmental safety assessments and early warnings have become a research focus and provided a method to measure the development of regional ecological security based on the causal circle between the socio-economic and ecological environments (Wursthorn et al., 2011; Cumming and Allen, 2017; Rybaczewska-Błażejowska and Masternak-Janus, 2018). Previous studies have considered several aspects of ecological security. 1) Watersheds, urban agglomerations, villages, peninsulas, islands, and wetlands have been used in case studies. Due to the range of different geographical conditions, researchers have established ecological security (early warning) evaluation index systems (Feng et al., 2018; Peng et al., 2018; Halkos et al., 2019). 2) Ecological security evaluation systems have been constructed based on single systems and complex natural and human social systems, including social systems, low-carbon tourism systems, atmospheric systems, aquatic ecosystems, land security systems (Fu et al., 2018; FU et al., 2019). 3) The research methods and models used in previous studies include the factor analysis method, entropy method, analytic hierarchy process, and the Pressure-State-Response (PSR), Driver-Pressure-State-Impact-Response (DPSIR), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) evaluation model (Xu et al., 2012; Rogan et al., 2016).

There are mature methods for the evaluation of eco-security systems and the implementation of early warning systems, which have laid the foundation for the construction and analysis of eco-security indicator systems. Various methods and models have been applied to measure the development of eco-security systems. Some researchers have analyzed the evolution of regional ecological security based on the local ecological footprint and ecological service value as determined by a principal component analysis (Xie et al., 2010; Antonio and Manuel, 2015). Predicting the development and status quo of an eco-security system is necessary for sustainable development (Campbell and Brown, 2012). To ensure the construction and protection of an ecological civilization, it is important to develop an evaluation index system for an eco-security system. Studies to evaluate eco-security systems and develop early warning systems need to be conducted, specifically to analyze the mutually influencing factors and constraints between the ecological environment and the sustainable development of a social economy. This will promote the sustainable and coordinated development of natural, economic, and social systems (Menoni et al., 2014; Houshyar and Morgavi, 2018).

Based on the concept of an eco-security system, this study combined a mathematical model, analytical method, and a geographic information system (GIS) to conduct an ecological security assessment of the Wanjiang City Belt (WCB) in Anhui Province, China and produce a dynamic spatial and temporal visualization. The study aim is: 1) to explore the impact and changes of human social and economic activities on the ecological security system in the WCB; 2) to measure the overall ecological security level of the region and its characteristics and laws of spatial and temporal evolution, and 3) to try to provide research for the development and protection of rapidly developing regions. The study also considered the future dynamic trends of ecological security through the development of a composite ecosystem index system, which differed from previous studies of ecological security, in which static index systems were used. This provided a scientific basis for further improving regional ecological security systems and maintaining the stability of the regional ecological structure, which provided a scientific basis and practical reference for building a beautiful, green and sustainable China and promoting global ecological security.

2 Materials and Methods

2.1 Study area

In 2010, the State Council formally approved the 'Plan for Demonstration Area for Undertaking Industrial

Transfer in the Wanjiang City Belt', including the cities of Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chizhou, Chuzhou, Xuancheng, and Lu'an (only Jin'an district and Shucheng County are included) in Anhui Province, China. The WCB is located in the middle and lower reaches of the Yangtze River (Fig. 1), which is adjacent to the Yangtze River Delta region. There is a diversity of plains, hills, and mountainous terrain across the region (Cao et al., 2019a). Under the combined effect of market forces and support from preferential government policies, various economic activities have rapidly progressed, and industrialization and urbanization are occurring significantly faster than in the surrounding areas. In the past 20 years of development, regional ecological security systems have undergone quantitative and qualitative changes. There are also differences in the internal space of the region. Therefore, the WCB is an ideal experimental region for studying ecological security of the areas along the Yangtze River (Cao, 2018; Cao et al., 2019b).

2.2 Methods

2.2.1 DPSIR model

The DPSIR (Driver-Pressure-State-Impact-Response) model is a conceptual model of an evaluation index system widely used in environmental systems. It is developed as an index system for measuring the environment and as an index system for measuring the environment and sustainable development. It was used to build a multi-layered ecosystem indicator system for use in industrial transfer demonstration zones in the WCB. As the Driver (D) of changes in the regional eco-security system, the sub-system D consisted of four target layers of population, investment, trade, and consumption. A total of five indicators were selected. Pressure (P) reflected the competition caused by D in regional resource utilization and protection of the ecological environment. It consisted of the target layers of population, society, and environment, with a total of 12 selected indicators. The sub-system State (S) as the embodiment of the specific results obtained under the joint action of D and P. It consisted of the target layers of society and environment, with a total of seven selected indicators. The sub-system Impact (I) was used to describe the eco-environmental effects of changes in the integrated ecological system of the region. It consisted of the target layers of society and environment, with a total of five selected indicators. The sub-system Response (R) referred to the corresponding measures and countermeasures adopted by human society that were applied to adjust the ecosystem to achieve sustainable and healthy development. It was divided into target layers of society and environment, with a total of seven selected indicators.

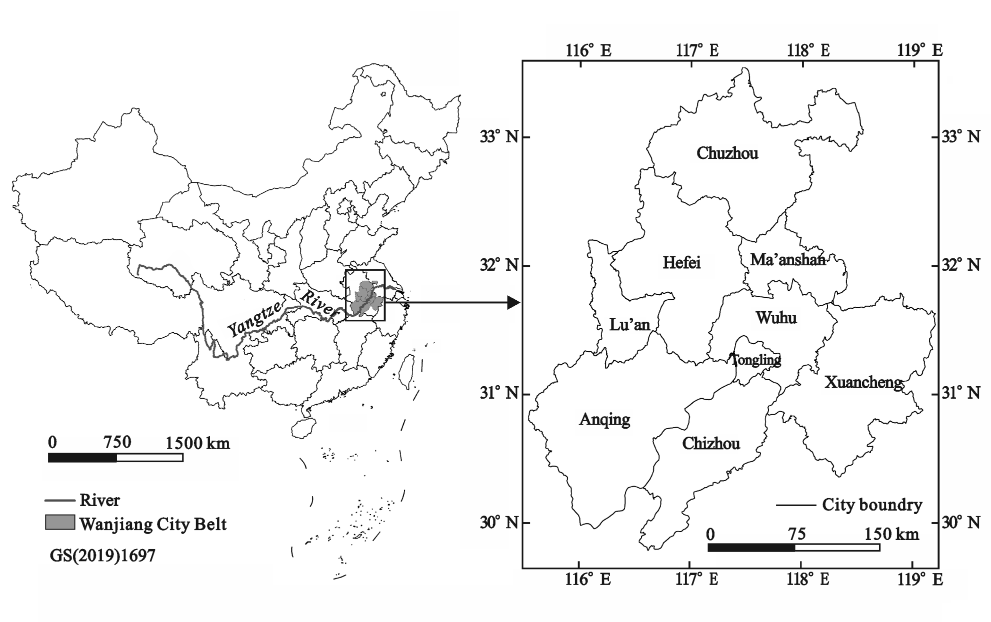

Fig. 1 Geographic location and administrative divisions of Wanjiang City Belt (WCB), China

2.2.2 Framework of an ecological security

On the basis of comprehensive consideration of the existing ecological security system construction principles and data availability, typicality and scientificity, combined with the actual situation of the case area, based on the logical framework of the DPSIR model to try to build a multi-layer structure eco-security system for use in industrial transfer demonstration zones in the WCB. An eco-security system for a region should include sustainable development and security within the regional ecosystem (He et al., 2017). It should provide stable, balanced, and abundant ecological services and support for human societies in the region. Based on the basic logical framework of the DPSIR model, an indicator system is established through three aspects of society, economy and ecological environment to form a natural-ecological-social composite system (Fig. 2).

2.3 Evaluation method of ecological security evolution

2.3.1 Determining the values of the eco-security system

Based on the proportion of weights and standardized values of the corresponding indicators in each criterion layer, the eco-security index value of each criterion layer could be determined.

$$Z_{ix} = \sum_{j=1}^{n} \left(W_j \times R_{ij} \right) \quad (1)$$

In the above formula, Z_{ix} represents the eco-security index value of i-th city x criterion layer, W_j is the comprehensive weight of j-th index, and R_{ij} represents the numerical value of j-th index of i-th city in the WCB.

To evaluate the development of eco-security systems in prefecture-level cities of the WCB, it was necessary to perform the following calculation to assess the criteria layers in the eco-security system:

$$Z_i = Z_{i\mathrm{D}} + Z_{i\mathrm{P}} + Z_{i\mathrm{S}} + Z_{i\mathrm{I}} + Z_{i\mathrm{R}} \quad (2)$$

In the above formula, Z_i is the comprehensive index value of the i-city eco-safety system, and $Z_{i\mathrm{D}}$, $Z_{i\mathrm{P}}$, $Z_{i\mathrm{S}}$, $Z_{i\mathrm{I}}$, and $Z_{i\mathrm{R}}$ represent the measured eco-security values of the five criteria layers, D, P, S, I, and R. The value of Z_i therefore represents the degree of development.

2.3.2 Classification and cartographic division of the eco-security zone

According to the existing method used to grade ecological safety systems, values of the eco-security system are related to the grades, which could be combined with the actual situation in the WCB. The eco-security index

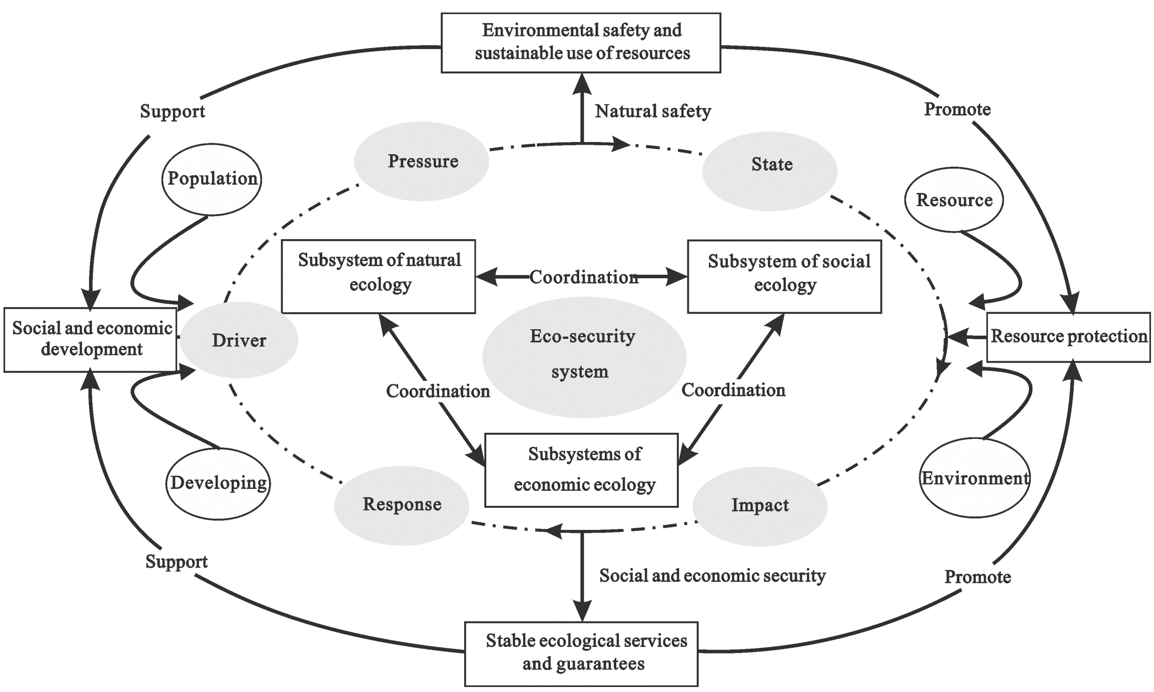

Fig. 2 The framework of an ecological security and evaluation system of Wanjiang City Belt, China

(Eq. (1)) was divided into four grades, with a description and explanation for each level of eco-security (Table 2). Finally, maps of the eco-security zone were constructed with the support of ArcGIS 10.2.

2.3.3 Coefficient of variation (CV)

The *CV* (also known as the coefficient of dispersion or standard deviation) can accurately reflect the degree of dispersion of an indicator in a region (Leh et al., 2013), and can eliminate the impact of the magnitude and average value on the degree of dispersion of the samples. It can be used to measure the relative differences and time series changes of urban ecological security systems and their sub-systems. The formula is:

$$CV_x = \frac{S_x}{\overline{S}} \tag{3}$$

In the formula, CV_x is the *CV* of the urban ecological security system at criterion layer x of a certain city/region, and $\overline{S}$ and S_x are the average and standard deviation of the urban ecological security system and five criterion layers, respectively.

2.4 Data sources and processing

2.4.1 Data sources

The indicator data selected for use in this study were mainly obtained from the Statistical Yearbook of Anhui Province from 2001 to 2018 and the statistical yearbooks of the prefecture-level cities in the WCB (https://data.cnki.net/Yearbook/Navi?type=type&code=A#). In addition, part of the data comes from the *Economic Census Yearbook*, *Urban Statistical Bulletin and Urban Yearbook* (https://data.cnki.net/yearbook/Single/N2020050229). The administrative boundaries used for mapping were derived from the National Basic Geographic Information Center and the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn).

2.4.2 Dimensionless standardization

The inconsistency of nature and the measurement units of various indicators in eco-security evaluation systems results in problems of complexity and diversity. Thus, it is necessary to standardize the data of each indicator to produce dimensionless units. The linear dimensionless standardization method was used to standardize the data of various indicators.

Positive indicator:

$$X'_{ij} = \left[\left(X_{ij} - \min X_j\right) / \left(\max X_j - \min X_j\right)\right] \times 100 \tag{4}$$

Negative indicator:

$$X'_{ij} = \left[\left(\max X_j - X_{ij}\right) / \left(\max X_j - \min X_j\right)\right] \times 100 \tag{5}$$

In the above formula, X'_{ij} represents the value of the j-th evaluation index of the i-th city, while $\min X_j$ and $\max X_j$ are the minimum and maximum values of the j-th evaluation index in each year during the study period.

2.4.3 Weight determination

To avoid the influence of subjective factors, the entropy value method was used to calculate the specific entropy and weight of each index (Zhang et al., 2018).

1) Calculation of the proportion of each indicator:

$$X_{ij} : R_{ij} = X'_{ij} / \sum_{i=1}^{m} X'_{ij} \tag{6}$$

2) Measurement of the entropy of each indicator:

$$e_j = -\left(\ln m\right)^{-1} \sum_{i=1}^{m} R_{ij} \times \ln\left(R_{ij}\right) (i = 1, 2, \cdots, m) \tag{7}$$

3) Calculation of the difference coefficient of each indicator:

$$g_j = \left(1 - e_j\right) / \left(n - \sum_{j=1}^{n} e_j\right) (j = 1, 2, \ldots, n) \tag{8}$$

If the value obtained is large, the corresponding index has a strong influence in the evaluation system.

4) Calculate the objective weight of each indicator:

$$W'_j = g_j / \sum_{j=1}^{n} g_j \tag{7}$$

Through the calculations undertaken in the above steps, the weights of the indicators of the eco-security assessment were finally obtained (Table 1).

3 Results and Analysis

3.1 Time series analysis of ecological security evolution

From 2000 to 2018, the plotted curve of the mean value of eco-security index was relatively smooth. The index value of all cities was relatively stable in the range of 0.27–0.65, and did not change much over time. The

Table 1 Evaluation index system and weight of ecological security system in Wanjiang City Belt

Criteria layer (Index weight)	Target layer	Indicator layer (unit)	Indicator attribute	Index weight
Driver (D)	Population	Permanent residents (ten thousand people)	Negative correlation	0.0220
(0.2195)	Investment	Fixed assets investment (billion)	Positive correlation	0.0534
	Trading	Total import and export (billion dollars)	Positive correlation	0.1077
	Consumption	Annual per capita consumption expenditure of urban households (yuan (RMB))	Positive correlation	0.0158
		Average per capita living expenditure of rural households (yuan (RMB))	Positive correlation	0.0207
Pressure (P)	Population	The population density (person/km^2)	Negative correlation	0.0280
(0.2198)		Natural population growth rate (%)	Negative correlation	0.0186
	Society	Urban per capita housing construction area (m^2/person)	Negative correlation	0.0212
		Unit cultivated land grain output (t/km^2)	Positive correlation	0.0228
		The area of built-up area accounts for the proportion of the city area (%)	Negative correlation	0.0184
		Cultivated land area accounts for the proportion of the city area (%)	Positive correlation	0.0203
	Environment	Pesticid use intensity per unit of cultivated land area (kg/km^2)	Negative correlation	0.0226
		Fertilizer use intensity per unit of cultivated land (kg/km^2)	Negative correlation	0.0119
		Industrial wastewater discharge intensity per unit area (t/km^2)	Negative correlation	0.0154
		Sulfur dioxide emission intensity per unit area (t/km^2)	Negative correlation	0.0134
		Environmental pollution emergencies (number)	Negative correlation	0.0113
		Direct economic losses caused by environmental pollution emergencies (10000 yuan (RMB))	Negative correlation	0.0159
Status (S)	Society	Per capita fiscal revenue (yuan/person)	Positive correlation	0.0554
(0.2416)		Urbanization rate (%)	Positive correlation	0.0475
		The added value of the secondary industry accounts for the proportion of GDP (%)	Negative correlation	0.0217
		Per capita cultivated area (m^3/person)	Positive correlation	0.0296
		Per capita water resources (m^3/person)	Positive correlation	0.0592
	Environment	Industrial solid waste discharge per 10000 yuan (RMB) GDP (t)	Negative correlation	0.0171
		Industrial smoke (dust) emissions per 10000 yuan (RMB) of GDP (t)	Negative correlation	0.0112
Influences (I)	Society	Engel coefficient of urban residents (%)	Negative correlation	0.0243
(0.1124)		Per capita net income of rural households (yuan (RMB))	Positive correlation	0.0181
		The added value of the tertiary industry accounts for the proportion of GDP (%)	Positive correlation	0.0425
	Environment	Annual average temperature change rate (%)	Negative correlation	0.0169
		Good days of ambient air quality (d)	Positive correlation	0.0107
Response (R)	Society	Science and technology expenditure accounts for the proportion of fiscal expenditure (%)	Positive correlation	0.0328
(0.2067)		Education expenditure as a share of fiscal expenditure (%)	Positive correlation	0.0311
		Number of medical and health institutions per 10000 people	Positive correlation	0.0393
		Agricultural mechanization level (kW/km^2)	Positive correlation	0.0231
	Environment	Comprehensive utilization rate of industrial solid waste (%)	Positive correlation	0.0259
		Green area coverage in built-up areas (%)	Positive correlation	0.0131
		Per capita afforestation area (km^2/person)	Positive correlation	0.0413

Table 2 Grade division and early warning state of regional ecological security in Wanjiang City Belt

Grade	Exponential interval	State description (evaluation)	State
I	[0.0, 0.35)	Low eco-security (It means that the regional eco-security system is seriously damaged, the function of the system has been lost and it is difficult to recover, the human and ecosystem are in an unbalanced state, and human activities seriously threaten the regional ecosystem.)	High warning
II	[0.35, 0.45)	Low level of eco-security (It means that the regional eco-security system is obviously damaged, the system function is greatly threatened, and the reconstruction or recovery faces greater difficulties. The human and ecological systems are in an unbalanced state to some extent, and human activities obviously affect the ecosystem.)	Medium warning
III	[0.45, 0.55)	General level of eco-security (It means that the regional eco-security system is under certain damage. Although the system function is affected, it can still maintain the basic operation. The relationship between human and ecosystem faces certain threats. Human activities have certain influence on the ecosystem.)	Early warning
IV	[0.55, 1.00]	Higher level of eco-security (It means that the function of the regional eco-security system has been less damaged, it can be controlled in time, the relationship between human and ecosystem is more coordinated, and the impact of human activities on the ecosystem is less.)	Ideal state

plotted curves for each city fluctuated over time, with a general decline in the eco-security index values of three cities, while the values for the other cities increased slightly. A detailed analysis revealed that Hefei was ranked first in the development of an eco-security system, and the city had almost always been in an ideal state (Grade IV), although it was in the level III early warning state in 2013 and 2014. Wuhu and Xuancheng were always in the early warning state (Grade III). The eco-security system of Lu'an and Anqing were in the medium warning state (Grade Ⅱ) most of the time, but occasionally reached the high warning state (Grade Ⅰ). Other cities were in the secondary and tertiary states (Fig. 3).

From 2000 to 2018, the D values of Hefei, Ma'anshan, Wuhu, and Tongling were always higher than the average level of the WCB, while in the other cities the value was always lower. The average D value was relatively stable in the range of 0.055–0.087. Hefei had the highest D value, and was ranked first among all cities, while Lu'an was ranked last. The largest fluctuation of D occurred in Hefei, while there was relatively little fluctuation in the other cities. The average P value was relatively stable in the range of 0.125–0.139. The P values for Ma'anshan and Tongling indicated a lower level of development, with the largest fluctuation over time, while there was relatively little fluctuation in the other cities. The S values were aggregated at the start of the study period but then tended to diverge, with the differences between cities increasing. The largest interannual fluctuations in S values were observed for Chizhou and Tongling, while the values in other cities were relatively stable. The average I value during 2000–2018 was relatively stable in the range of 0.047–0.060. The largest fluctuation in I values were observed for Hefei and Lu'an, while there was relatively little fluctuation in the other cities. The average R value was relatively stable in the range of 0.079–0.100. The urban R value curve shifted from a diffusion to aggregation state, resulting in decreasing differences in the R value between cities.

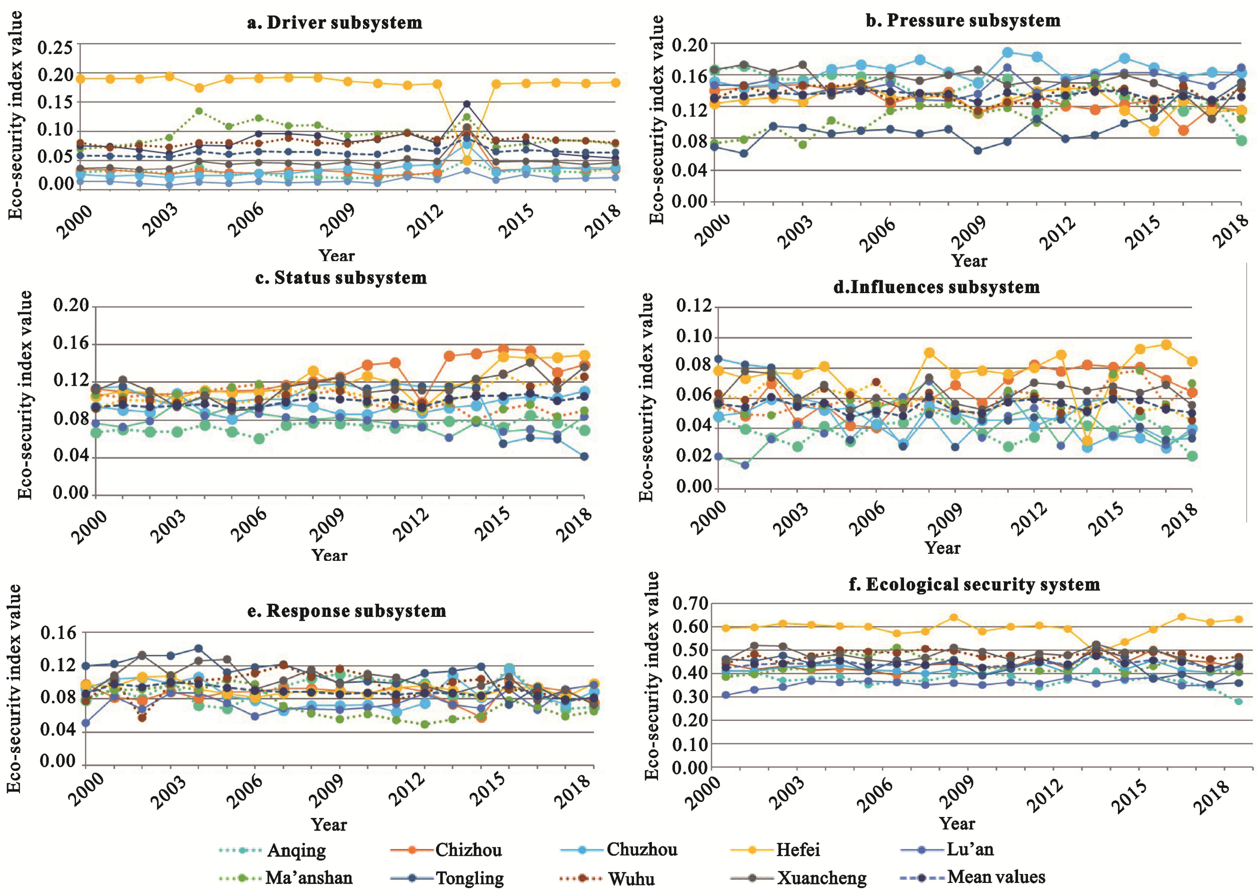

Fig. 3 The development trend of the eco-security system and its criterion layers in various cities of Wanjiang City Belt, China

3.2 Spatio-temporal differences of ecological security pattern

3.2.1 Spatio-temporal characteristic

According to the ecological security value of each city calculated at four time points according to Eq. (1), cluster classification is performed by GIS, and the result is shown in Fig. 4. In 2000, Hefei was in a safe state with the highest eco-security value. This was followed by Tongling and Xuancheng, which were in the early warning state. The eco-security system was the most vulnerable in Lu'an in the west, which was in the high warning state. In 2006, Hefei was still the city with the highest eco-security, with Tongling, Wuhu, and Ma'anshan following closely behind, and the rest of the cities are in the Medium warning state. In 2012, the front line cities of Hefei-Wuhu-Xuancheng were all at a relatively high level ecological safety quality, the ecological quality of the north and south wings was at a lower level. Ecological security was almost the same across the study area in 2012 and 2018, only the level of ecological security in Anqing had deteriorated, changing from a medium warning to a high warning.

In summary, the ecological safety quality of various cities in the WCB has evolved significantly. The ecological safety quality of Hefei has always been at a high level, despite the rapid expansion of its economic aggregate. This means Hefei has been in the ideal state with the Driver and the degree of influence on development being far ahead of the other cities in the WCB. Therefore, the highest comprehensive benefit was apparent for the Hefei composite system, the risk of triggering a crisis was the lowest, and the chance of survival and development was the greatest. Lu'an, Anqing, Xuancheng, and Wuhu all belong to cities with excellent ecological endowments. Wuhu and Xuancheng have maintained good ecological safety quality, while the quality of Lu'an ecological safety has been improved, Anqing has deteriorated significantly. Ma'anshan and Tongling are both resource-based cities, and the ecological safety quality has always been in a state of medium warning.

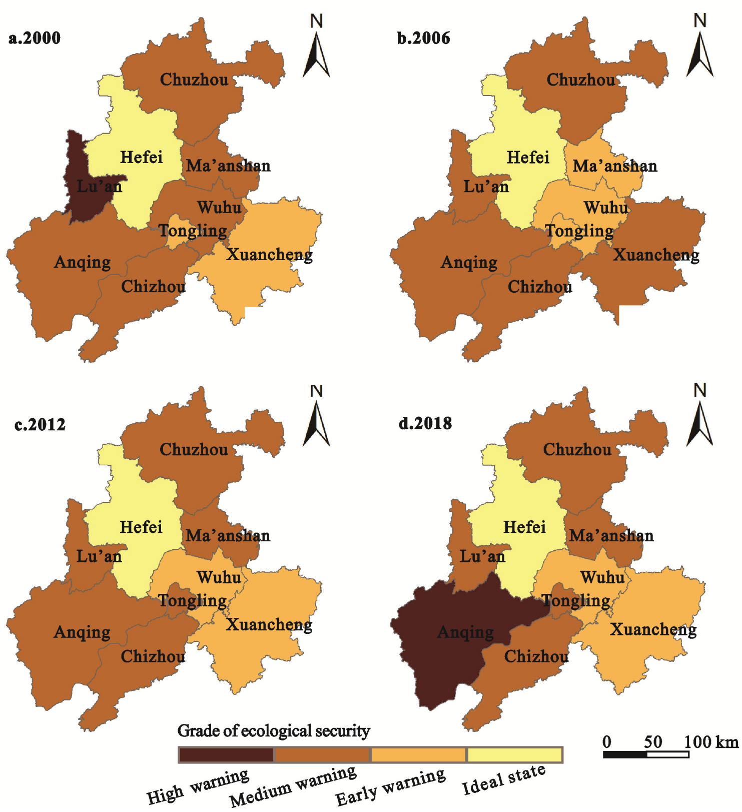

Fig. 4 The spatial distribution of the eco-security system in different prefecture-level cities from 2000 to 2018 in Wanjiang City Belt, China

3.2.2 Spatial differences of components

Based on the analysis of the five weighted components of the eco-security system, the weights of D, P, S and R were basically the same. These four sub-systems represented the main criteria layers of the eco-security system, while the I sub-system had a minimal (0.1124) (Table 1) impact on eco-security system. The average value of each component of each city was determined to obtain the spatial difference of the actual structural characteristics (Fig. 5).

The structural characteristics of the ecological security system were found to be undergoing regional adjustment and changes, and different components presented different spatial patterns. The highest D value occurred in Hefei, while the lowest value was observed in Lu'an. The highest P values were observed in Chuzhou, Lu'an, and Xuancheng, while the lowest values were observed in the resource-based cities of Tongling and Ma'anshan, indicating that the ecological security of these two cities is under great pressure. The highest S values were observed in Hefei and Chizhou, while the lowest levels were observed in the two cities west of them, Lu'an and Anqing. The highest I value was observed in Hefei, while the lowest levels were also observed in Lu'an and Anqing. The spatial pattern of R values was different from the other sub-systems, with the largest R values observed in Tongling and Xuancheng, while the lowest values were observed in Ma'anshan and Lu'an.

In terms of individual cities, Hefei had the highest values for three sub-systems, Xuancheng had the highest values for two sub-systems, while Wuhu had the second highest values for all sub-systems. The overall ecological security value of these three cities was high. Although it had the highest P value, Lu'an had the lowest overall level of ecological security. Anqing had the lowest S and I values and the second lowest D and R values, and it was therefore determined that the overall ecological security of Lu'an and Anqing was poor. The proportional contributions of the D and P sub-systems declined in most cities, with the internal structure of the eco-security system becoming more reasonable over time. This suggests that most cities had been in the early warning state. However, the social economy and ecological environment still faces multiple difficulties in transitional development and governance.

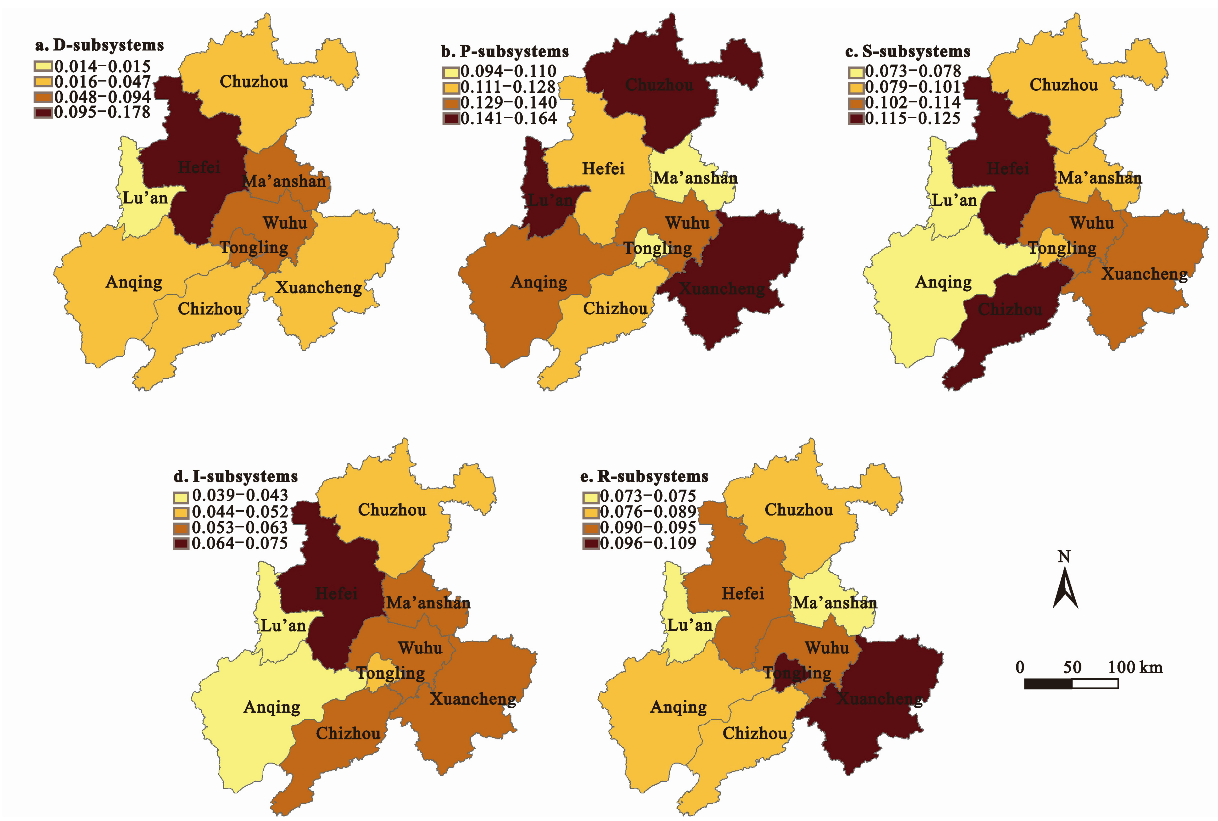

Fig. 5 Spatial differences of subsystem (Driver, Pressure, State, Impact, Response) in Wanjiang City Belt, China

Table 3 Development degree and coefficient of variation (*CV*) of the eco-security system and its five criterion layers

WCB	Name	Year			
		2000	2006	2012	2018
Development degree	Driver (D)	0.5836	0.6531	0.5908	0.5715
	Pressure (P)	1.3097	1.3894	1.2109	1.1867
	Status (S)	0.9415	0.9371	0.8418	0.9455
	Influences (I)	0.5630	0.5187	0.5342	0.4526
	Response (R)	0.8576	0.8997	0.7872	0.7286
	Eco-security system	4.2554	4.3979	3.9650	3.8849
Coefficient of variation (*CV*)	Driver (CV_D)	0.8846	0.8728	0.7628	0.7698
	Pressure (CV_P)	0.2622	0.1824	0.1775	0.2294
	Status (CV_S)	0.2110	0.2141	0.1568	0.3446
	Influences (CV_I)	0.3192	0.1799	0.2804	0.3930
	Response (CV_R)	0.2088	0.1844	0.1973	0.1437
	Eco-security system	0.1807	0.1546	0.1542	0.2185

3.3 Evaluation of the eco-security system

The whole ecological security system and its five sub-systems were compared at four time points, and results for the comparison of the development degree and *CV* were obtained (Table 3). Four key results were obtained. 1) The relationship among the five criterion layers in the eco-security system was P > S > R > D > I. This indicated the obvious importance of P in the eco-security system. 2) The CV_D was much higher than that for the overall eco-security system and the other criterion layers. Although the WCB consists of complete administrative regions, there are significant differences in the distribution of population and natural resources, the social and economic foundations, and the investment environment and policy support among prefecture-level cities. This resulted in large difference in the D values among the different cities. The ecological environment of the WCB has the feature of regional globality, especially in terms of the diffusion and treatment of pollutants. Because the cities of the WCB are located within a unified provincial administrative region, there are consistent ecological environment policies and regulations, as well as a similar social infrastructure. Therefore, there were few differences in the development of the P, S, I, and R sub-systems in the eco-security system. 3) The *CV* of the D sub-system in the various cities decreased from 0.8846 in 2000 to 0.7698 in 2018. The overall trend tended toward balanced development, while the spatial pattern of polarization did not change. On the one hand, due to the ongoing construction of industrial transfer demonstration zones, related industries and economies have been relatively decentralized; thus, promoting the equalization of regional D values. On the other hand, there were differences in the distribution of population and natural resources in the various cities, causing a wide disparity in regional D values (for example, Hefei absorbed various resources from the surrounding area due to policy intentions, forming a standing tall). 4) The eco-security system, as well as the P, S, I, and R sub-systems were in a state of balanced development, with little change in *CV* values.

4 Discussion

4.1 Future trends in ecological security of Wanjiang City Belt

Since the ecological safety system is a composite system, the spatial dynamic trend will develop over time. In order to better describe the future trend of the ecological security system, the comprehensive index values (Eq. 2) from 2000 to 2018 was used to make a linear prediction model according to time series (Table 4). According to the positive or negative slope of the linear prediction model, the future trend of the ecological security system can be judged. Generally, positive means that the system will be safer in the future, and negative means that the system will have potential safety hazards or deterioration. The slope for the whole WCB was negative, therefore the ecological security will be declining. The positive slopes of four cities (Chizhou, Chuzhou, Lu'an, and Wuhu) indicated a positive development trend, while the other cities had negative slopes. Based on the above analysis, the ecological security quality of the entire WCB has a risk of decline, but Chizhou, Chuzhou, Lu'an and Wuhu show a good development trend, while resource-based cities such as Ma'anshan and Tongling have a slight downward trend. These Cities with negative slopes are locations where the management and supervision of ecological security should be strengthened in the future.

Table 4 Linear simulation results of the interannual change of the comprehensive index value of the ecological security from 2000 to 2018 in the Wanjiang City Belt, China

Region/City	Prediction model	Slope	R^2	Region/City	Prediction model	Slope	R^2
WCB	$y = -0.0309x+4.5420$	–	0.6225	Anqing	$y = -0.0025x+0.3967$	–	0.2215
Chizhou	$y = 0.0023x+0.4163$	+	0.2019	Ma'anshan	$y = -0.0003x+0.4392$	–	0.0018
Chuzhou	$y = 0.0009x+0.4152$	+	0.0529	Tongling	$y = -0.0040x+0.4740$	–	0.2953
Hefei	$y = -0.0002x+0.5961$	–	0.0011	Wuhu	$y = 0.0005x+0.4736$	+	0.0240
Lu'an	$y = 0.0022x+0.3380$	+	0.3610	Xuancheng	$y = -0.0011x+0.4903$	–	0.0469

Notes: y represents the comprehensive index values, x is the sequence of years.

4.2 Future research prospect

By constructing an evaluation index for the ecological security system of the WCB and then conducting an empirical study, this study provided a scientific basis for government departments to fully understand and guide the coordinated development of regional resources and environmental security. However, there were some shortcomings in this research, which need to be addressed in future studies. The evaluation indicators need to be further supplemented and improved, such as the addition of social and environmental governance indicators, and the study of the sustainable development capacity of the entire river basin should be strengthened.

The WCB region is a complex system. Factors that affect the regional ecological security include not only economic globalization outside the region (e.g., global warming), but also socio-economic and technological factors within the region (Kattel et al., 2013; Lei et al., 2016). The development of the WCB has been substantially affected by economic globalization, and the region's ecological security is closely related to that of the world. By participating in globalization, if the region continually transforms and upgrades the development model according to the situation, promotes the construction of an innovative country, and makes technological innovation an important force for green development, it will improve the quality of the ecological environment, otherwise the risk to ecological security will increase. Global climate change poses new challenges to the world's ecological security, and the WCB is also affected. Therefore, there is a need to promote the transformation and upgrading of industries in the region, develop new green industries, and participate in managing global carbon sources and sinks, and carbon trading to significantly reduce CO_2 emissions. These measures will improve the ecological security of the region. This study was based on the DPSIR model and therefore mainly considered the models own influencing factors in the region, which is obviously not comprehensive enough.

In 2019, President Xi Jinping proposed a new sustainable development concept that requires mutual consultation, joint construction, inclusiveness, people-oriented and green development (http://www.xinhuanet.com/politics/xxjxs/2019-10/24/c_1125144509.htm), which pointed out the direction for regional ecological security protection research. In future studies, previously published papers and ecological science techniques should be combined (Qureshi et al., 2013; Estoque et al., 2014; Neri et al., 2016), and their inclusive scientific and technological characteristics will then improve the scientific validity of the urban ecological security concept. The importance of regional ecological security can be explored through a comprehensive assessment of the ecological integrity of human habitats, biodiversity protection, and environmental impacts (Caniani et al., 2016). In the future, it will be necessary to adopt this new concept to conduct further environmental protection countermeasure research.

5 Conclusions

Using the DPSIR model, an attempt was made to construct an indicator system for an ecological security system, and then to evaluate the ecological security system in the Wanjiang City Belt. Four main research findings were obtained.

(1) The overall level of ecological security in the Wanjiang City Belt is in a state of early warning and medium warning, but the level of ecological security in each prefecture-level city was significantly different. Among them, Hefei, the capital city of Anhui Province with the largest level of economic development, had the best level of ecological security, while Ma'anshan and Tongling, which are resource-based cities, ranked lower

in ecological security. Lu'an and Anqing have an underdeveloped economy and there are many potential ecological disasters in the area that resulted in the two cities having the worst level of ecological security.

(2) From the perspective of the evolution of ecosystem security in the study area, ecosystem security since 2000 has been relatively moderate downward evolution, the value of its comprehensive evaluation index fell from 4.255 in 2000 to 3.885 in 2018. However, in terms of the five subsystems of eco-security system, the State of ecological security showed a change after falling first and then rising, from 0.9415 in 2000 to 0.9455 in 2018, while other subsystems showed changes that first increased and then decreased. Pressure performance was the most prominent factor, and its comprehensive evaluation value was always higher than that of other indicator layers, indicating that pressure on the ecological environment was always present throughout the rapid development period. Subsystems such as State and Response also change with Pressure.

(3) The *CV* of the Driver development degree in the area was much higher than that of the other criteria layers of the ecological security system. There are large differences in the level of economic development and ecological evolution between the cities in the areas along the Yangtze River in Anhui Province. The low *CV* values for pressure, state, impact, and response also led to the overall ecological security becoming more balanced over time, indicating that there was not only a correlation between economic development in the region, but also a coordinated system-wide impact on the evolution of ecological security.

(4) In the future development trend, the overall ecological security quality of Wanjiang City Belt has a certain risk of decline, but the ecological security quality of each city varies greatly. The regional composite ecological security system was formed by the interaction of natural conditions and socio-economics, in which ecological endowment and economic development play a key role in the impact of ecological security of each city. The monitoring and governance of regional ecological security needs to be adapted to local conditions.

Acknowledgement

We thank Zhang Dapeng and Zhang Yizhen, graduate students of the School of Geography and Tourism, Anhui Normal University, for their assistance in data processing.

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