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Analysis of Spatial Relationship Based on Ecosystem Services and Ecological Risk Index in the Counties of the Chongqing

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Abstract: The rapid development of the regional economy in China has led to the rise of local ecological risks. It is very important to provide enjoyable ecosystem services to residents while reducing ecological risks. In order to understand spatial relationships between ecosystem services and ecological risks, we took Chongqing as an example in this study to assess the spatial relationship between ecosystem services and ecological risks at the county scale based on the ES-DPSIR system. The main findings include: (1) significant variation in the spatial distribution of the comprehensive ecosystem service index, where the lowest ecosystem service index (0.013) was found in the main urban area of Chongqing and the scores gradually increased outward from this center, reaching 0.689 in the outermost areas, (2) the increase of the comprehensive ecological risk index from east to west, ranging from -0.134 to 0.333, (3) the spatial relationship between ecosystem services and ecological risks was prominent, with 52.63% of the districts and counties being imbalanced or mild imbalanced, and (4) the significant differences between development trends of ecosystem services-ecological risks, including 60.53% being imbalanced districts and 30.47% mildly balanced. Overall, it was necessary to improve the relationship between ecosystem services and ecological risks in Chongqing by reducing ecological risks., and these research results could provide effective approaches and technical support for improving regional ecological security and enhancing ecosystem service capabilities.

Keywords: ecosystem services; ecological risk; spatial relationships; driving factors; Chongqing

1. Introduction

Nowadays, increasing demand for ecosystem services is essential for our daily lives, but rapid economic development has caused a profound impact on the environment (Shi et al., 2020), resulting in unprecedented changes in the structure and function of these ecosystems. Meanwhile, irresponsible city planning, development and other human activities have caused many ecological and environmental issues (Fan et al., 2016; Li et al., 2013), leading to increased regional ecological risks (Li et al., 2020). The decline of ecosystem services and deterioration of regional environments is extremely unfavorable for the long-term development of humans. Based on this predicament, ensuring regional ecological security has become a key issue for humans. Ecosystem services guarantee sustainable development and provide various services and benefits to humans (Fu et al., 2010), while ecological risks focus on the environmental effects caused by both nature and society (Skiter et al., 2015). Associations between ecosystem services and ecological risks have been found.

Therefore, it is necessary to assess the coordination between ecosystem services and ecological risks and to explore mutual feedback mechanisms from the perspective of the human-land system, which can improve regional ecosystem service capabilities and prevent regional ecological risks, hence promoting the coordinated development of ecosystem services and ecological risks.

Various studies have been conducted on ecosystem services and ecological risks, where ecosystem services and ecological risks were usually treated as two separate topics. Studies on ecosystem services mainly focused on ecosystem service evaluation (Hua and Huang, 2021; Hua and Ouyang, 2021), ecosystem service relationship evaluation (Xu et al., 2018; Yang et al., 2015; Hao et al., 2017), and driving mechanism identification (Guan et al., 2021; Liu et al., 2021). At present, a research paradigm of “function-pattern-scale-relation-drive” has been formed in studies on ecosystem services. On the other hand, studies around ecological risks mainly focus on the ecological risk index system development (Jogo and Hassan, 2010), model development (Larson, 2002), ecological risk evaluation (Ma et al., 2018; Ce et al., 2022; Lu et al., 2019; Wan et al., 2022; Zhang et al., 2016), ecological security pattern development (Liu et al., 2022; Wei et al., 2022), ecological risk early warning/simulation (Cao et al., 2022), and ecological risk spatial identification (Cheng et al., 2021). Overall, studies on ecological risk research have also formed a unique paradigm, one of “pattern-scale-drive-warning-recognition”. With the deepening of research, ecological risks and ecosystem services have shown the development characteristics of independent to integrated, and the integration of the two can effectively correlate ecological processes and human well-being, and have become the research frontier and hotspot of ecological security (Peng et al., 2015; Kang et al., 2016). Research on the integration of ecological risks and ecosystem services has focused on integrating ecosystem services into ecological risk assessment systems (Xing et al, 2020; Ma et al., 2018). Wang et al (2019) and Ouyang et al (2020) conduct ecological risk assessment based on ecosystem services and ecosystem health, which provides a new perspective for ecological risk management. Xie et al (2021) Ecological zoning based on ecosystem services and ecological risk characteristics of ecological functional areas. Based on ecosystem service functions to determine relevant ecological risks, it has become a new research direction to propose management strategies of risk areas (Deacon et al., 2015; Malekmohammadi et al., 2014). In addition, the correlation between ecosystem services and ecological risks has also been explored, mainly using correlation analysis (Li and Gao., 2019) and grey relationship analysis (Ji et al., 2021). Although some studies have explored the relationship between ecosystem services and ecological risks, there is still no research on the degree of impact of ecological risks on ecosystem services and the impact of their functions, so it is difficult to further reveal the essence of the relationship. In view of the lack of research on the spatial relationship and driving mechanism of ecosystem services and ecological risks, coupled with the background of the current rise of ecological risks in local areas and the dysfunction of ecosystem services, the analysis of their relationship and driving mechanism are key issues that need to be solved to ensure regional ecological security and improve the ecosystem services.

Chongqing is located in Southwest China, with complex topography, landforms, climate, hydrology and other natural features. It is an important ecological area for the upper reaches of the Yangtze River and is significant to the local ecosystem. With the rapid development of the regional economy, the reduction of ecosystem services and increase of ecological risks in some areas, led to difficulties in the harmonious coexistence between man and nature, challenging the sustainable development of the regional economy. Especially in recent years, driven by economic development, the environmental development of various districts and counties in Chongqing has gradually highlighted huge differences. Based on the current background and situation, we selected Chongqing as the research object to explore the following questions: How to scientifically identify the spatial relationship and evolution trend between ecosystem services and ecological risks at the district and county scales? What are the drivers of the ecosystem services-ecological risk spatial relationship? In order to solve the above scientific problems, taking Chongqing’s county as the research scale, firstly, the ES-DPSIR system was constructed from the two dimensions of ecosystem service and ecological risk, and secondly, the spatial relationship and development trend of the ecosystem service dimension comprehensive index and the ecological risk dimension comprehensive index were

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measured respectively, and finally, the driving force was discussed. It is hoped to provide a basis for the optimization and management of the relationship between ecosystem services and ecological risks, and reduce ecological risks while improving regional ecosystem services.

2. Materials and Methods

2.1. Study area

As the only municipality directly under the Central Government in Western China, Chongqing is an important site for China's "One Belt, One Road" strategy. With a land area of 82,400 km2, there are important water systems such as the Yangtze River and Jialing River flowing through the area, providing abundant water and superior natural river resources. By the end of 2020, the population of Chongqing reached 3.205 million, and the GDP exceeded 25,000 billion yuan (a 3.9% increase from the previous year), where raw materials, manufacturing and service industries contributed 7.2%, 40.0% and 52.8% of the GDP, respectively. With the rapid development of the economy, Chongqing's ecological environment is facing severe problems and challenges. The frequent occurrence of environmental issues (i.e. chemical pollution, soil erosion, landslides, deterioration of ecological environment quality and imbalance of ecological structures) in some areas have become a bottleneck for coordinated development between industry, the environment and the economy. It is crucial to understand how to promote the simultaneous improvement of regional ecosystem services and ecological security together with the rapid development of the economy. In this study, Chongqing is divided into several different areas according to economic, social, and topographical characteristics, including the main urban area, Western Chongqing, Southeastern Chongqing, and Northeastern Chongqing. The main urban areas include Yuzhong, Dadukou, Jiangbei, Shapingba, Jiulongpo, Nan'an, Beibei, Yubei, and Banan districts; the western area includes Fuling, Changshou, Jiangjin, Hechuan, Yongchuan, Nanchuan, Qijiang, Dazu, Bishan, Tongliang, Tongnan, and Rongchang; the northeast area includes Wanzhou, Kaizhou, Liangping, Chengkou, Fengdu, Dianjiang, Zhongxian, Yunyang, Fengjie, Wushan, and Wuxi; and the southeast area includes Qianjiang, Wulong, Shizhu, Xiushan, Youyang, and Pengshui.

2.2. Data

All of the data used in this study are from the Data Center for Resources and Environmental Sciences, the Chinese Academy of Sciences (https://www.resdc.cn), including information on land use and cover, soil type, rainfall, and evaporation in 2020. All data were converted to a unified projected coordinate system in ArcGIS. Statistical data, including per capita GDP and disposable income are from the 2020 Statistical Yearbook for each district and county of Chongqing.

2.3. Governing equations of a capacity model

2.3.1. Research framework

Ecosystem services refer to the benefits that humans receive from ecosystems and play an important role in maintaining the stability of the ecosystem environment and sustainable development. Ecological risk refers to the possibility that an ecosystem will be affected by all elements outside the ecosystem that pose a threat to the ecosystem. The effects of uncertain events or disasters in the region on ecosystems and their components can lead to damage to ecosystem structure and function. From the perspective of the relationship between the two, the decline of ecosystem services will lead to a decline in the stability of the ecosystem and increase the ecological risk. Ecosystem services include supply, regulation and cultural services, including water conservation, soil conservation, carbon sequestration, biodiversity, etc. Ecological risk is mainly evaluated based on the "driver-pressure-state-impact-response model", which includes natural, ecological, economic, and social impact driving indicators.

In this study, a double-index ES-DPSIR model was developed based on the ecosystem services index (ESI) and ecological risks index (ERI). The ecosystem service index included three level I indicators (i.e. supply, regulation, and culture), and eight level II indicators (i.e. food production, water supply, soil conservation, air purification, etc.). The ecological risk index included five level I indicators (driving force, pressure, state, impact, and response), and 18 level II indicators (i.e. per capita GDP, population, urbanization level, population growth rate, etc.). The comprehensive ecosystem services index and ecological risk index were evaluated to assess their potential for coordination and driving mechanisms. The overall framework is shown in Figure 1.

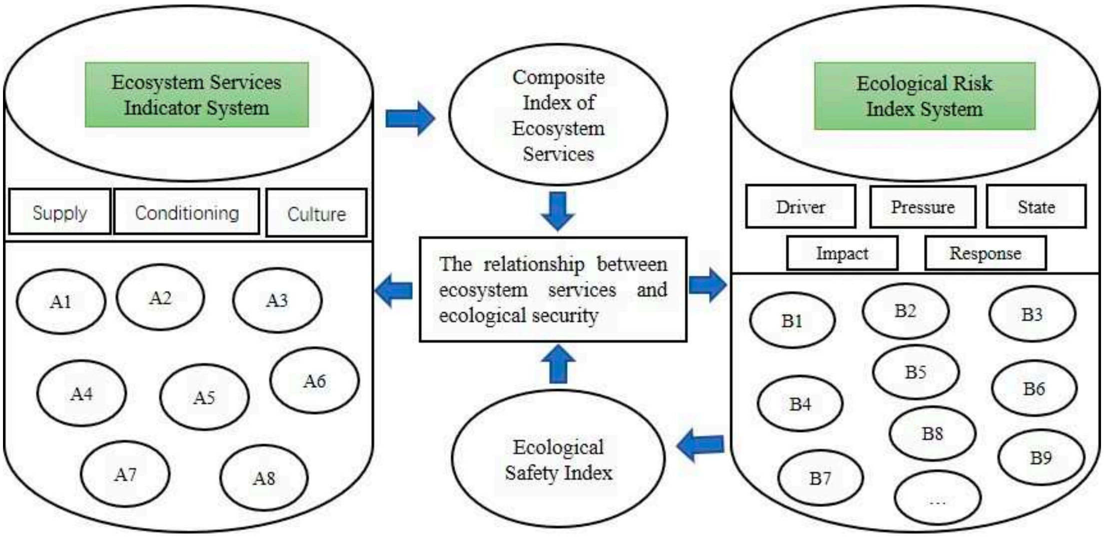

Figure 1. The framework of this study.

2.3.2. Calculation of comprehensive ecosystem services index

(1) Development of the ecosystem service index system.

The comprehensive ESI represents the overall condition of all regional ecosystem services, and thus the indicators need to be representative and comprehensive. Eight ecosystem services from three level I indicators were selected to develop the ESI system. The weight of each indicator was calculated using the entropy weight method. Details on the ESI system is shown in Table 1.

Table 1. The indicators of ecosystem services index system.

Index system	Level I index	Level II index	Abbr.	Description	Unit	Weight
Ecosystem service index	Supply	Food production	A1	The ability of ecosystems to provide food	t	0.0901
	Regulation	Water supply	A2	The ability of ecosystems to provide water	mm	0.1971
		Soil conservation	A3	The ability of ecosystems to maintain soil	t	0.0962
		Air purification	A4	The ability of ecosystems to purify pollution	t	0.1110
		Carbon storage	A5	The ability of ecosystems to store carbon	t	0.1129
		Habitat quality	A6	The ability of ecosystem to maintain biodiversity	-	0.1642

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		Climate regulation	A7	The ability of ecosystems to regulate climate	KWh	0.0979
	Culture	Leisure	A8	The ability of ecosystems to provide residents with travel and leisure	10,000 people	0.1305

(2) Calculation of ecosystem services index

In this study, the Level II indicators of the ESI were calculated based on statistical surveys and InVEST models. The detailed methodology for the calculation of each indicator is shown in Table 2.

Table 2. Methodology for the calculation of ecosystem service index.

Index	Method	Principle and formula	Description of the parameters
Food production	Statistical survey	Grain supply data from the Statistical Yearbook	-
Water supply	InVEST model (Sharp et al., 2021)	Quantitatively evaluate the water production capacity of the ecosystem based on the principle of water balance. $Y = \left(1 - \frac{AEP}{P}\right) \times P$	Y is the average annual water production, AEP is the annual actual evapotranspiration, and P is the average annual precipitation.
Soil conservation	InVEST model(Sharp et al., 2021)	Comprehensively evaluate the ability of the parcel to intercept upstream sediments based on the general soil loss equation. $USLE = R \cdot K \cdot LS \cdot (1 - C \cdot AP)$	USLE is soil conservation per unit area; R rainfall erosion factor; K soil erodibility factor; LS slope length and slope factor; C and AP are vegetation cover management factor and soil conservation measure factor, respectively.
Air purification	Air purification model (Xiao et al., 2014)	Assessed by the ability of vegetation to purify pollutants. $Q_{ap} = \sum_{i=1}^{m} \sum_{j=1}^{n} Q_{ij} \times A_i$	Q_{ap} is the air purification amount, Q_{ij} is the purification amount of vegetation i to the air pollutant j per unit area (i=1, 2, …, m, unitless, and j=1, 2, …, n, unitless). A_i is the area of vegetation i, m is the amount of vegetation i, and n is the amount of air pollutants.
Carbon storage	InVEST model (Sharp et al., 2021)	Comprehensively consider the carbon storage of carbon above ground, underground, in soil and in dead biomass. $C = C_{above} + C_{below} + C_{soil} + C_{dead}$	C is the total carbon storage; C_{above} is the aboveground biological carbon storage; C_{below} is the underground biological carbon storage; C_{soil} is the soil carbon storage; C_{dead} is the dead organic matter carbon storage.
Habitat quality	InVEST model	Habitat quality was assessed using the habitat quality module in the InVEST model.	Q is the habitat quality index, H is the habitat suitability of the ecosystem, D is the habitat degradation degree, K is

	(Sharp et al., 2021)	$Q=H\times\left(1-\left(D^z/\left(D^z+K^z\right)\right)\right)$	the half-saturation constant (half of the maximum degradation degree was used), and z is a normalized constant.
Climate regulation	Climate regulation model (Xiao et al., 2014)	The regulation capacity of vegetation and water were considered for climate regulation. $E_{pt}=\sum_i^3 EPP_i\times S_i\times TD\times 10^6/(3600*r)$ $E_{we}=E_w\times e\times 10^3/(3600)+E_w\times y$	E_{pt} is the energy consumed by the transpiration of farmland vegetation, E_{PPi} is the transpiration of heat consumption per unit area of vegetation i; S_i is the area of vegetation i; TD is the number of days when the daily maximum temperature is above 26 °C, E_{we} is the total energy consumed by the ecosystem to adjust temperature or humidity, E_w is the amount of evaporation, e is the latent heat of volatilization is (the heat required to evaporate 1 gram of water); y is the electricity consumption of the humidifier to convert 1m^3 of water into steam.
Leisure	Statistical survey	The number of tourists from the Statistical Yearbook was used	-

(3) Calculation of comprehensive ecosystem service index

Different ecosystem services indicate the ability of ecosystems to maintain and regulate human well-being. Thus, in order to accurately evaluate the comprehensive ESI, the indicators were normalized prior to further assessment. The weight of each normalized ESI indicator was evaluated using entropy weight. The comprehensive index was then calculated using the comprehensive score method. The formulas for the comprehensive ESI are shown below:

$$ESS_{pq}=\frac{ES_{pq}-\min\left\{ES_{pq},\ldots,ES_{nq}\right\}}{\max\left\{ES_{pq},\ldots,ES_{nq}\right\}-\min\left\{ES_{pq},\ldots,ES_{nq}\right\}} \tag{1}$$

where ESS_{pq} is the normalized ecosystem service q in indicator p, max(ES_{pq}-ES_{nq}) is the maximum value of each indicator, and min(ES_{pq}-ES_{nq}) is the minimum value of each indicator.

$$ESI=\sum W_d\times ESS_d \tag{2}$$

where W_d is the weight of each ESI indicator, and ESS_d is the normalized value of ecosystem service.

2.3.3. Calculation of comprehensive ecological risk index

(1) Development of the ecological risk index system

As an indicator of the potential threats to the ecosystem, the ecological risk is the result of various factors in the ecological environment. Thus, it is important to accurately and comprehensively select the indicators for the ERI system. In this study, an ERI system was developed based on Driver-Pressures-Status-Impacts-Responses (DPSIR) framework, and the corresponding weight of each index was calculated using the entropy weight (Table 3).

Table 3. Driver-Pressures-Status-Impacts-Responses (DPSIR) index system.

indicator system	Level I indices	Level II indices	Abbr.	Description	Unit	Weight
	Driver	GDP per capita	B1	Indication of economic level	Yuan	0.0628

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Ecological risk indicator system		Population	B2	Indication of population distribution	1×10^4 people	0.0452
		Urbanization	B3	Indication of the structure of urban and rural residents	%	0.0613
		Natural population growth	B4	Indication of the population growth	%	0.0203
	Pressures	Large industrial energy consumption	B5	Indication of the resource consumption	1×10^4 t	0.1396
		Agricultural fertilizer application rate	B6	Indication of the environmental pollution	t	0.0516
		Atmospheric SO_2 concentration	B7	Indication of the environmental pollution	ug/m^3	0.0396
	Status	Domestic water consumption	B8	Indication of residents' living standard	1×10^8 m^3	0.0594
		Per capita disposable income	B9	Indication of the living standard	Yuan	0.0484
		Forest cover rate	B10	The quality of the ecological environment	%	0.0348
	Impacts	Shannon diversity index	B11	Indication of landscape diversity and heterogeneity	-	0.0376
		Plaque area variation coefficient	B12	Indication of the impact of plaque changes on ecosystems	-	0.0444
		Agglomeration index	B13	Indication of the impact on the ecosystem from human activities	-	0.0485
		Plaque density	B14	Indication of the fragmentation of the landscape	count/km^2	0.0547
	Responses	Tertiary industry proportion	B15	Indication of the industrial structure	%	0.0594
		Cultivated area	B16	Indication of the regional land structure	1×10^4 Mu	0.0482
		Total water resources	B17	Indication of the regional policy response and environmental protection techniques	1×10^8 m^3	0.0738
		Rainfall	B18	Indication of the quality of the ecological environment	mm	0.0705

DPSIR= Driver-Pressures-Status-Impacts-Responses.

(2) Calculation of index of comprehensive ecological risk index

Ecological risks are the effects of potential accidents and disasters on the ecosystem or its components, which may damage the structure and function of the ecosystem and therefore threaten the safety of the ecosystem. The risks to the ecosystem come from various sources. In order to accurately and comprehensively assess the ecological risk, the ERI in Chongqing was assessed based on the DPSIR frameworks in this study. Details of the calculation are shown as follows:

$$ERI = \sum_{c=1}^{n} R_c \times a_c \tag{3}$$

where R_C is the weight of index C, and a_C is the normalized value of index C.

2.3.4. Development of the ES-DPSIR Model

The coordinated development of ecosystem services and ecological risks is highly associated with the well-being of humans. In order to evaluate the coordination between them, a double indices based ES-DPSIR model was developed in this study. The principle of this model is to assess the degree of coordination through dispersion, where the larger dispersion indicates the lower degree of coordination. The coordination was calculated as follows:

$$EC = 2 \times \left[\left(\frac{ESI \cdot ERI}{ESI + ERI} \right)^{-2} \right]^{1/2} \tag{4}$$

where EC is the coordination degree (from 0 to 1). Higher values of EC indicate the relatively high coordination between ecosystem services and ecological security. The coordination was divided into 5 levels using the equidistant method, including dissonance (0.0-0.2), mild dissonance (0.2-0.4), mild coordination (0.4-0.6), moderate coordination (0.6-0.8), and high coordination (0.8-1.0).

The evolution trends of ecosystem services and ecological security were characterized by the coordinated development index:

$$ED = \left(EC \cdot ET \right)^{1/2} \tag{5}$$

$$ET = a \cdot ESI + b \cdot ESI \tag{6}$$

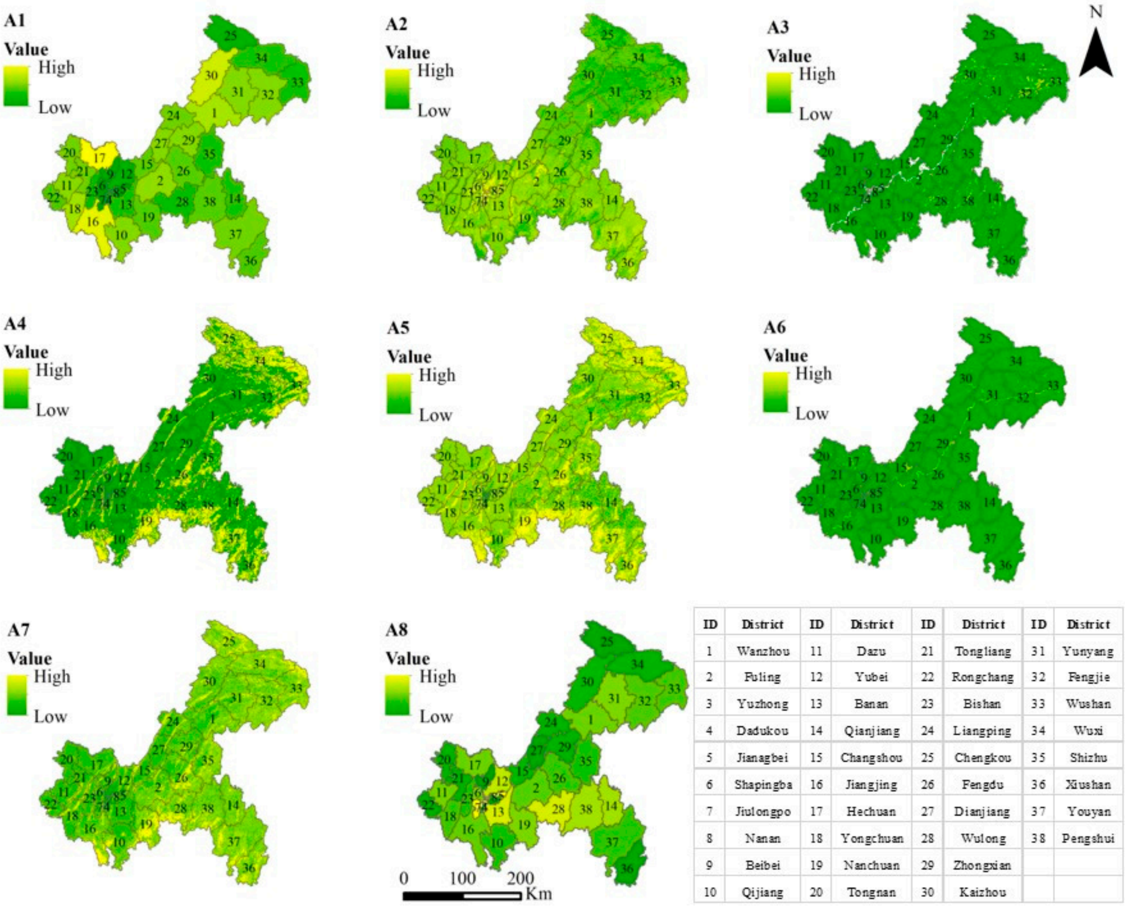
where ED is the coordinated development degree, ET is the weighted ESI and ERI. In this study, 0.5 was used for both a and b, since ecosystem services and ecological risks are equally important to the ecosystems. The coordination development degree was divided into 5 levels using the equidistant method as well, including highly coordinated (0.8-1.0), moderately coordinated (0.6-0.8), mildly coordinated (0.4-0.6), mildly dysregulated (0.2-0.4) and dysregulated (0.0-0.2).

3. Results

3.1. Analysis of the comprehensive ecosystem service index (ESI)

The results of the ESI in Chongqing are shown in Figure 2. The distribution of different ESIs showed significant spatial differences. Low grain production areas (< 1.1×10^5 t) were mostly found in the main urban area due to the high urbanization and the dominance of construction in land use. The highest grain production was found in Kaizhou, Wanzhou, Hechuan, Jiangjin and Yongchuan, with the production ranging from $4.44\text{-}6.91\times10^5$ t. The low water supply areas were mainly in Northeastern Chongqing (197-660 mm), while the high water supply was mainly found in the southeastern and western regions of Chongqing (up to 1564 mm). In 2020, the soil conservation service in Chongqing was moderate, with the overall value between $0\text{-}1.15\times10^3$ t, indicating a stable soil conservation service function. The highest soil conservation service function was found in some areas in the northeastern and southeastern regions of Chongqing. Significantly higher values of air purification services were found in the southeastern and northeastern regions of Chongqing, which was closely associated with the distribution of forests. The lush vegetation covered in the southeastern and northeastern regions of Chongqing could assist with air purification. The overall carbon storage in Chongqing was relatively high, with more than 6 t in most areas, indicating a good carbon sequestration ecosystem in Chongqing. Similar spatial distributions were found between climate regulation and habitat quality, with the lower score near the main urban area due to the higher population density and more frequent human activities in these areas. Higher tourist populations were found in Wanzhou, Yunyang, the main urban area and surroundings, which was mainly caused by the locally developed tourism resources and frequent economic activities. By contrast, lower tourist populations were found in Chengkou, Wuxi, and Xiushan, due to the inconvenient transportation and underdeveloped economies.

The results of the ESI are shown in Figure 3. In general, the lowest ESI was found in the main urban area, with increasing scores the further out the region was. The ESI in the main urban areas (i.e. Beibei, Shapingba, Yuzhong, Jiulongpo, Yubei, Bishan, and Nan'an) ranged from 0.13-0.181. The low scores were mainly caused by serious restrictive effects on the environment from high urbanization and frequent human activities, which limited the capability of ecosystem services. A clear improvement in the ESI was found in the surrounding districts and counties of the main urban area (i.e. Dazu, Yongchuan, Ba'nan, Chaoshou, Liangping, etc), ranging from 0.182-0.268. A further improvement was found in Hechuan, Qijiang, Nanchuan, Fulin, Fengdu, Shizhu, Kaizhou, Chengkou, Qianjiang and Xiushan, ranging from 0.269-0.445. These areas covered 26.3% of the districts and counties in Chongqing, indicating that urban human activities gradually declined with increased distance from the main urban area. The highest ESI scores (0.446-0.689) were found in the outermost areas, which were least affected by the main urban area and had the highest level of ecosystem services. These areas include Jiangjin, Wulong, Pengshui, Youyang, Kaizhou, Yuyang, Fengjie, Wuxi and Wushan, covering 23.7% of the districts of Chongqing. Overall, the ESI scores and spatial trends suggested that the capacity of ecosystem services to function well was associated with the distance from urban economic activities, showing a concentric outward radiation pattern.



ID	District	ID	District	ID	District	ID	District
1	Wanzhou	11	Dazu	21	Tongliang	31	Yunyang
2	Fuling	12	Yubei	22	Rongchang	32	Fengjie
3	Yuzhong	13	Banan	23	Bishan	33	Wushan
4	Dadukou	14	Qianjiang	24	Liangping	34	Wuxi
5	Jianagbei	15	Changshou	25	Chengkou	35	Shizhu
6	Shapingba	16	Jiangjing	26	Fengdu	36	Xiushan
7	Jiulongpo	17	Hechuan	27	Dianjiang	37	Youyan
8	Nanan	18	Yongchuan	28	Wulong	38	Pengshui
9	Beibei	19	Nanchuan	29	Zhongxian		
10	Qijiang	20	Tongnan	30	Kaizhou		

Figure 2. Results of ecosystem service index in Chongqing in 2020.

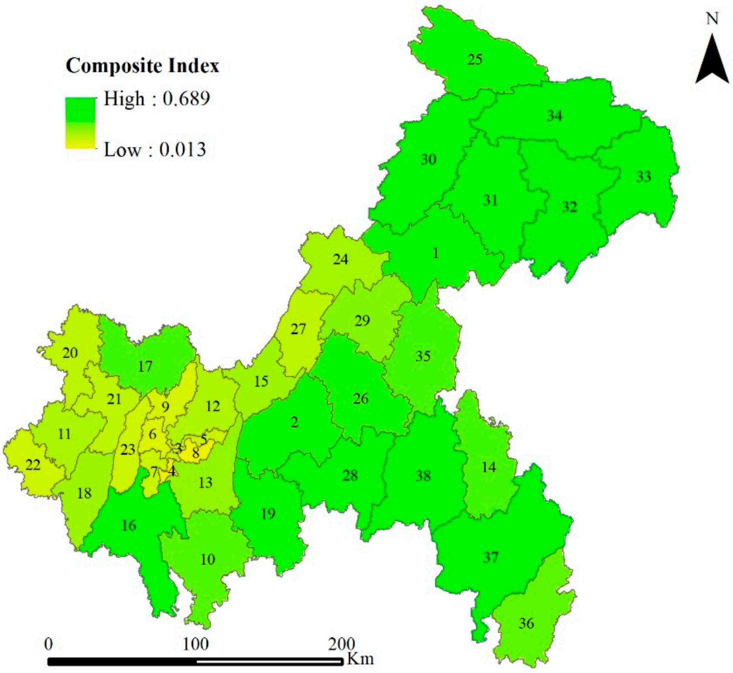


Figure 3. Results of the comprehensive ecosystem services index.

3.2. Analysis of the comprehensive ecological risk index (ERI)

Figure 4 shows the results of DPSIR in Chongqing in 2020, where significant spatial trends of indicators were also observed. Per capita GDP, urbanization, per capita disposable income, and domestic water consumption showed similar spatial trends, with the highest level in the main urban area and decreasing trends the further outward that the region was. This was mostly caused by the frequent economic activities in the main urban area. These economic activities also led to the lower forest coverage rate and cultivated land area in the main urban area, as well as the agricultural fertilizer application rate, as the usage of fertilizer was highly associated with the cultivated land area. Construction dominated land types in the main urban area, while cultivated land was distributed in other areas. Higher natural population growth rates were found in the southeastern and northeastern regions of Chongqing, which were associated with the local economy and population. Atmospheric concentrations of SO_2 were relatively stable across different districts and counties, possibly due to the airflow in the study area. The Shannon diversity index, plague area variation coefficient, agglomeration index and plague density were heavily affected by land use, surface landscape and human activities. For example, more plague fragmentations could also lead to a higher plague area variation coefficient and agglomeration index. Aquatic resources and rainfall also showed a high similarity in spatial trends, because the northeastern and southeastern regions of Chongqing received more humid and hot air from the southeast, resulting in more precipitation.

The results of the comprehensive ERI are shown in Figure 5, where the spatial trends are more random compared with the ESI. The lowest ERI was found in Fuling, Fengdu, Pengshui, Shizhu, Wanzhou and Fengjie, ranging from -0.143 to -0.039, indicating the lowest ecological risks in these areas. The higher vegetation coverage, cultivated area, water supply and development of the ecological environment could explain the ecological safety in such areas. The lowest ESI scores were found in Wuxi, Wushan, Yuyang, Youyang, Changshou, and Dazu, ranging from -0.040 to -0.086. Slightly higher ESI scores (0.087-0.144) were found in nine districts (23.7% of total districts and counties, including Tongnan, Hechuan, Tongliang, Yubei, etc), and further increased scores (0.145-0.236) were found in some areas in the western and northeastern regions of Chongqing (i.e. Yongchuan, Jiangjin, Ba’nan, Beipei, Kaizhou and Chengkou) while the highest scores (0.237 to 0.333) were found in Rongchang, Bishan, Nanchuan, Dianjiang, Liangping and Qianjiang. Overall, the northeastern and southeastern regions of Chongqing had much lower ERI scores, indicating compromised ecological safety in those areas. This was because of the fragmentation of the surface landscape, decreased vegetation cover caused by economic development and urbanization in main urban areas and west Chongqing, which eventually increased the local ecological risks.

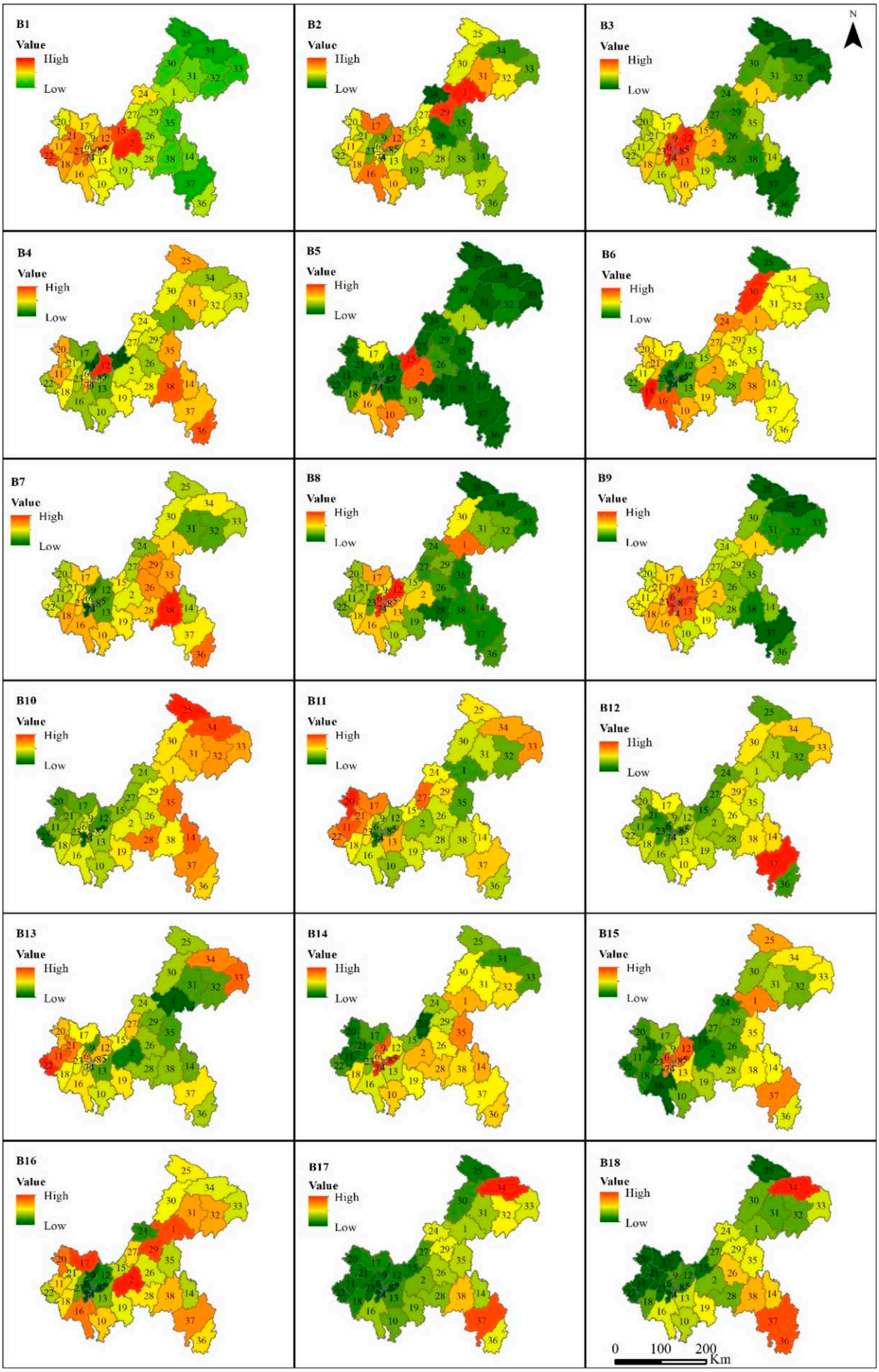


Figure 4. Visualization results of the DPSIR model.

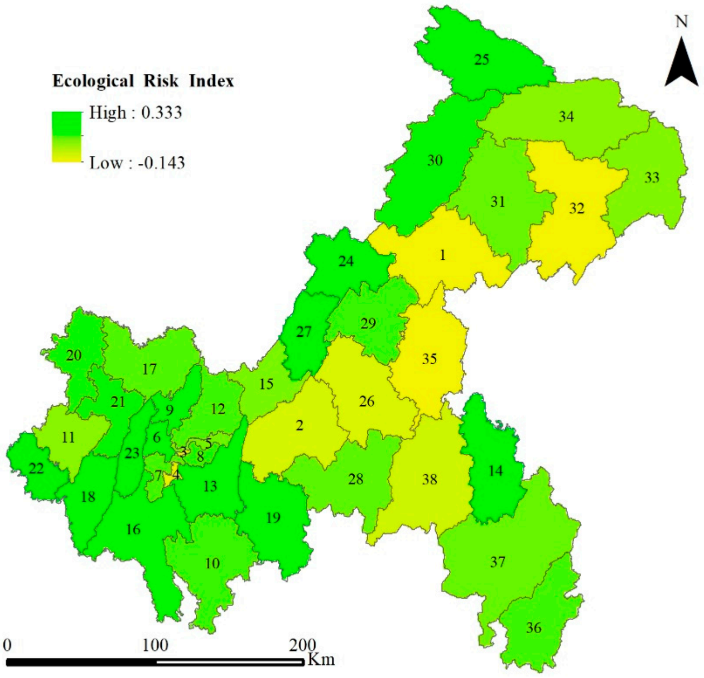


Figure 5. Results of the comprehensive ecological risk indices (ERI).

3.3. Analysis of the ES-DPSIR model

The coordination between ecosystem services and ecological risks in Chongqing showed an increasing trend from west to east (Figure 6, left panel). For example, imbalanced areas were found in the west (i.e. Rongchang, Tongnan, Beipei, and Bishan) and main urban areas, accounting for 31.58% of all the districts and counties. The coordination of Dazu, Yongchuan, Yubei, Jiangbei, Ba'nan and other districts and counties had increased, and it was in a state of mild imbalance. In terms of spatial distribution, ecosystem services-ecological risks were mainly distributed at the junction of western, northeastern and southeastern regions of Chongqing, accounting for 52.63% of the total districts and counties. Combining the results of ecosystem services assessment (Figure 3) and ecological risk assessment (Figure 5), the low ecosystem service index and high ecological risk in these areas were an important reason for the imbalance. The districts and counties with the highest coordination degree are Pengshui, Fengjie and Wuxi, which are in a highly coordinated state. As show the results of Figures 3 and 5, the composite index of ecosystem services and ecological risk in these areas were at a high level, indicating that these areas had a high contribution to ecosystem services, but at the same time had potentially large ecological risk. On the whole, the spatial relationship between ecosystem services and ecological risks in Chongqing's districts and counties had great contradictions, and further management and regulation of the relationship between the two needs to be carried out.

The evolving trends of the spatial relationships between ecosystem services and ecological risks showed significant differences in different areas (Figure 6, right panel). In total, 60.53% of the districts and counties showed mildly dysregulated and dysregulated development. Dysregulated development was found mostly in the main urban areas and West Chongqing (i.e. Rongchang, Tongliang, Bishan, Jiangbei, Shapingbai, Jiulongpo, and Nan'an), while slightly dysregulated development was found in Tongnan, Dazu, Yongchuan, Yubei, Banan, Chagnshou, Dianjiang, Liangping, Zhongxian, Shizhu, Qianjiang, and Chengkou. Dysregulated development was mainly due to the low contribution of ecosystem services and the increase in ecological risks.. In addition, 39.49% of the districts showed mildly and moderately coordinated development, including Hechuang, Jiangjin, Qijiang, Nanchuan, Fulin, Wulong, Fengdu, Wanzhoum Kaizhaou, Yunyang, and Wushan with mildly coordinated development, and Pengshui, Youyang, Fengjie, and Wuxi with moderately coordinated development. The reason for coordinated development was the increased contribution of ecosystem services, but at the same time it had greater potential ecological risks. Therefore, more attention should be paid to the imbalanced and mildly imbalanced developed areas in the future to coordinate the improvement of ecological services and decrease ecological risks. Overall, the contradiction between the spatial relationship between ecosystem services and ecological risks in some areas of Chongqing was still prominent, and it was necessary to further improve ecosystem services and reduce ecological risks, and optimize the future development contradiction.

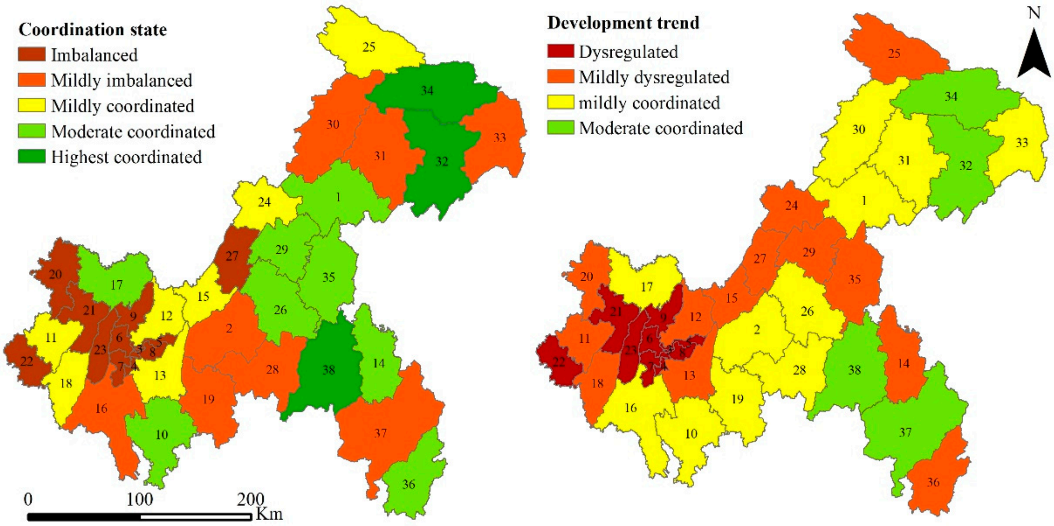


Figure 6. Spatial relationship and development trend of ecosystem services and ecological security in Chongqing.

4. Discussion

4.1. Advantages of the ES-DPSIR model in analyze the spatial relationships of ecosystem services and ecological risks

Ecosystem services and ecological risks are related to the well-being of humans (Zhan, 2016; Jiang et al., 2019). Ecosystem services can provide continuous and stable products and services for the development and daily lives of humans (Merrill et al., 2018), while ecological risk control can ensure the stability of our habitat (Li et al., 2019). A few studies have quantitatively evaluated the ecological services and ecological risks, with a focus on one or the other. There are very limited studies on the relationship between ecological services and ecological risks. However, these studies only assess the overall relationship between them, which is not effective in improving the balance between ecological services and risks or understanding their driving factors. In addition, existing studies lack the analysis of the relationship between the two from the morphology of spatial change, and the results are difficult to promote the coordinated optimization of ecosystem services and ecological security.

In this study, a double indices based ES-DPSIR model was developed to assess the relationships between ecosystem services and ecological risks on the basis of spatial patterns and to demonstrate the spatial relationships statues and evolution of trend between these systems. The result statuses indicated the levels of spatial relationships development between ecological services and ecological risks while the evolution predicted developments in the near future, which could help us better understand the relationship between ecological services and risks, and therefore make relevant policies to improve ecological safety.

4.2. Analysis of the driving factors of the spatial relationship development of ecosystem services and ecological risks

There are certain associations and interactions between factors in the ecosystem (Guan et al., 2021; Wang et al., 2022). Therefore, the spatial development of ecosystem services and ecological security is affected by complex ecological and environmental factors (Peng et al., 2020; Zeng et al., 2020; Zhang et al., 2018; Zhang et al., 2017). To optimize the spatial relationships development pattern of ecosystem services and ecological risks, the factor analysis model in SPSS 19.0 was used to analyze the driving factors of different indices in the ES-DPSIR model. According to the principles of factor analysis, principal components (PC) with eigenvalues greater than 1 were selected for further analyses (Zhang et al., 2018), with an accumulated contribution of 84.71% from the first six components. The score for each principal component is shown in Table 4, where the score of most components (except for PC 4 and 5) were above 0, including food supply, water supply, soil conservation, air purification, carbon storage, habitat quality, climate regulation and tourism. The positive scores from such indicators suggested that they could promote the spatial relationships that increased ecosystem services and reduced ecological risks. For example, in PC 1, the scores of water supply, air purification, carbon storage and habitat quality were greater than 0.15, indicating that these factors were positively associated with vegetation landscape structure and negatively associated with local ecological risks (Li et al., 2021; Gou et al., 2022). However, scores of indicators for different PCs varied in the DPSIR model, indicating the uncertainties of the driving factors. Among the scores of indices in the DPSIR model, per capita GDP, natural population growth rate, atmospheric SO_2 concentration, and plaque density showed negative scores for most of the PCs, with the minimum scores of -0.250, -0.497, -0.145, and -0.323, respectively, indicating the increase of regional ecological risk and reduce the function of ecosystem services. Per capita GDP and natural population growth rate represented the human interference with ecosystem services, especially in areas with high economic development and rapid population growth. This was mainly because of the decreased ecosystem service capacity and increased ecological risks, which were caused by plaque fragmentation and environmental pollution due to the excessive development of ecosystems (Zhang et al., 2022). Natural indicators, such as vegetation coverage, cultivated land, water resources, and rainfall showed positive scores in most PCs, indicating that those factors could promote the improvement of ecosystem services and ecological security in most cases, despite some restraints to a certain degree. The variation of scores might be caused by the interaction between indicators (Zhang et al., 2022). For example, excessive rainfall could result in soil erosion, debris flow and other geological disasters, which could decrease the vegetation coverage, damage the soil structure, worsen the surface fragmentation and eventually not conducive to the enhancement of ecosystem services and the stable improvement of regional ecological security.

Table 4. Principal component loading scores.

indices	Principal component 1	Principal component 2	Principal component 3	Principal component 4	Principal component 5	Principal component 6
A1	0.061	0.064	0.079	0.110	-0.027	0.011
A2	0.246	0.029	0.059	-0.278	-0.026	0.063
A3	0.130	0.033	0.060	-0.022	0.015	0.020
A4	0.150	0.017	0.063	-0.038	-0.020	0.029
A5	0.186	0.110	0.069	-0.140	-0.049	0.197
A6	0.156	0.080	0.064	-0.023	0.024	0.045
A7	0.041	0.187	0.030	0.061	0.050	0.068
A8	0.057	0.099	0.381	0.037	0.058	0.029
B1	-0.045	-0.004	0.150	-0.096	0.098	-0.250
B2	0.003	0.350	0.148	-0.143	0.006	-0.160
B3	-0.065	0.022	0.089	0.040	-0.120	0.042

B4	-0.092	0.105	-0.046	0.027	-0.043	-0.497
B5	0.016	0.053	-0.145	0.016	-0.136	0.476
B6	-0.097	0.115	-0.064	0.200	0.006	0.035
B7	-0.145	-0.012	-0.084	0.380	-0.034	0.076
B8	-0.093	0.241	0.198	0.037	-0.103	-0.169
B9	-0.104	0.052	0.078	0.071	-0.077	0.046
B10	0.185	0.060	-0.054	0.189	-0.035	-0.013
B11	-0.031	0.013	0.024	-0.022	0.359	-0.074
B12	-0.055	0.043	0.126	0.287	0.004	-0.112
B13	-0.009	-0.086	0.173	0.048	0.301	0.046
B14	-0.020	-0.076	-0.028	0.107	-0.323	0.060
B15	0.050	-0.027	0.320	0.048	-0.001	-0.105
B16	0.020	0.187	0.002	-0.020	0.053	0.008
B17	0.012	-0.054	0.086	0.255	-0.004	-0.005
B18	-0.091	-0.123	0.059	0.464	-0.063	0.004

In summary, ecological service indicators, such as water supply, air purification, etc. were the driving factors for the maintaining regional ecological security. In addition, economic and social indicators, such as per capita GDP and natural population growth rate were the main reasons for the decline of ecosystem services and the increase of ecological risks, which could disrupt the spatial contradiction of ecosystem services and ecological risk. Several natural indicators, including rainfall, could generally promote the level of ecological risk in the region, but in some circumstances these indicators could also worsen the contradiction between them. Therefore, to improve the spatial relationships development of ecosystem services and ecological risks, it is necessary to improve ecosystem services, such as food production and air purification (especially water supply and soil conservation, etc.), which affect rainfall, vegetation cover and habitat quality (Li et al., 2021). At the same time, it is also important to adjust human activities, reduce landscape fragmentation, reduce pollution-related problems caused by land use and sewage discharge, and improve local biological safety.

4.3. Prospection

There must be some relationships between regional ecosystem services and ecological risks that are difficult to express directly (Zhang et al, 2019; Gou et al, 2022). In practice, the improvement of regional ecosystem services can promote the reduction of regional ecological risks and increase the pattern of regional ecological security (Jiang et al, 2019). However, affected by natural, man-made and other comprehensive factors, places with high ecosystem services do not necessarily have a high ecological security index, and may still face greater ecological risks. Therefore, it is of great significance to explore the relationship between ecosystem services and ecology. In this research, based on the innovation system of the dual index framework of ecosystem services and ecological risks, the coupled coordinated analysis model is introduced to explore the spatial relationship between ecosystem services and ecological risks at the county scales, and reflect their spatial change trends. The results show that the relationship pattern and future change trend can be explained in space, which can provide methods and path reference for related research.

Although the research well explains the spatial relationship between ecosystem services and ecological risks, and explores the control drivers of drivers on ecosystem services-ecological risk synergies, the impact on overall ecosystem services is not considered in the research. One of the reasons is that ecosystems are complex processes, and in order to accurately demonstrate mechanisms, more comprehensive influencing factors need to be considered. In addition, ecosystem service-ecological risk change is a continuous process of spatiotemporal dynamics, and the study of the change mechanism should pay attention to the analysis of spatiotemporal sequences. In future research, attention should be paid to considering more influencing factors and spatiotemporal sequences.

5. Conclusion

The study developed a double index system (ES-DPSIR) with ecosystem services and ecological risks, which assessed the comprehensive ecosystem service indices and the ecological risk index, respectively. The status of the spatial relationship and evolution trends for ecosystem services and ecological risks were also analyse. The main conclusions are as follows:

(1) The lowest comprehensive ESI was found in the main urban areas of Chongqing, with improvement increasing the further out a region was. The ESI values in the main urban areas (i.e. Beibei, Shapingba, etc.), city surroundings (i.e. Dazu, Yongchuan, etc.), and outermost areas (i.e. Jiangjing, Wulong, etc.) ranged from 0.13-0.181, 0.182-0.268, and 0.446-0.689, respectively.

(2) The spatial distribution of the ERI was more random compared with the ESI. The ERI values ranged from -0.146 to -0.039 in Fuling, Fengdu, etc., from -0.040 to -0.086 in Wuxi, Wushan, etc., from 0.087 to 0.144 in Tongnan, Hechuan, etc., from 0.145 to 0.236 in Yongchuang, Jiangjin, etc., and from 0.237 to 0.333 in Rongchagn, Bishan etc.

(3) The current situation of ecosystem services and ecological risk spatial relationship pattern is prominently different from east to west. Imbalanced statues were found in the main urban areas and Western Chongqing (i.e. Rongchang, Tongnan, Beibei, Bishan, etc.), while mildly imbalanced statues were found in Dazu and Yongchuan. Overall, 52.63% of the districts and counties in Chongqing had an imbalanced or mildly imbalanced status.

(4) The evolution trends of the spatial relationships between ecosystem services and ecological risks showed significant differences. In total, 60.53% of the districts and counties showed imbalanced and mildly imbalanced development. Imbalanced development was mainly found in the main urban area and Western Chongqing, and mildly imbalanced development was found in 12 districts or counties, including Tongnan and Dazu. The increase in ecological risks in the future was the main cause of the imbalance development. Overall, the evolution of relations was grim between ecosystem services and ecological risks in some areas of Chongqing was low, and further improvement of ecosystem services and decrease of ecological risks are needed in the future.

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