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An integrated ecological security early-warning framework in the national nature reserve based on the gray model

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ABSTRACT

Nature reserves (NRs) play a pivotal role in minimizing habitat loss and protecting wild animals and plants, which are critical for human ecological security. However, focusing only on the construction of ecological security patterns of NRs without understanding their ecological security early-warning situations and their driving factors may fail to achieve protection goals. This study constructed an ecological security early-warning framework and index system based on the Driving force-Pressure-State-Impact-Response (DPSIR) framework model. The gray model (GM) was used to predict the ecological security early-warning situation, and the Geo-detector model was applied to explore the driving factors of the ecological security early-warning system in the Baishuijiang National Nature Reserve (BNNR). The results showed that the average ecological security index (ESI) value increased from 0.2796 in 2005 to 0.3171 in 2017, with an average increase of 11.82%. The ecological security early-warning index (ESEWI) value increased from 0.3171 in 2018 to 0.3622 in 2030, which was an average increase of 12.46%. These results indicated that the ecological security situation continually improved from 2005 to 2030. By 2030, the number of towns with a “no warning” grade increased to four, the number of towns with an “extreme warning” grade was zero, and the proportion of areas with early-warnings decreased from 100% to 33%. The q values of per capita forest land areas and per capita grassland areas were both 0.9334, which indicated that environmental characteristic factors were the primary driving factors in ecological security early-warning. Our results demonstrated that the ecological security early-warning index system based on the DPSIR model and grey model can well prediction ecological security situation and provide scientific support for the ecological protection and management of NRs.

1. Introduction

Global climate change and the rapid pursuit of economic development have led to a series of ecological and economic problems, such as desertification, environmental pollution, resource depletion, a sharp decrease in biodiversity, a decline in ecosystem services and poverty (Liu et al., 2022; Salvati & Carlucci, 2014). The succession of ecosystems and changes in ecological environmental quality directly affect human health, security and sustainable development (Peng, Li, & Nan, 2021). NRs are established to provide refuges for threatened species, which can benefit both humans and nature (Huang, Shao, Lin, & Y., 2019; Radeloff, Stewart, Hawbaker, Gimmi, Pidgeon, & Flather, 2010). They comprise approximately 14.9% of Earth’s land surface and support multiple ecosystems and organisms (Abman, 2018; Ma, Zhang, & Q., Hou, Y., L., Wen, Y., L., 2020). China has 2750 nature reserves of various types and levels, with a total area of about 1,471,700 km^2 (www.nrchina.org). NRs have proven to be an effective tool for regulating climate, maintaining regional ecological security and protecting biodiversity (Alagador, Cerdeira, & Araújo, 2014; Dong et al., 2016; Huang et al., 2019; Jouzi, Leung, & Nelson, 2020; Li, Gao, & Li, 2020; Wang et al., 2020; Xu, Fan, Liu, Dong, & Chen, 2019). However, most NRs are facing a conflict between nature conservation and economic development. (De Pourcq

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et al., 2017; Ma, Cai, Zheng, & Wen, 2019; Zhang et al., 2020). Therefore, it is of great significance to carry out ecological security early-warning research in NRs to coordinate the relationship between social and economic development and the ecological environment and to achieve a "win–win" situation in NRs (Ma et al., 2020).

Ecological security is the most basic and universal demand for human survival and development (Norton et al., 1992; Peng et al., 2021). Ecological security early-warning is an important measure for maintaining coordinated and sustainable development of ecological environmental protection and social economy in NRs (Chen & Wang, 2020; Pan, Su, & Wang, 2016; Shaheen et al., 2020), which refers to the evaluation and prediction of regional ecological environmental quality changes and possible environmental hazards by combining qualitative and quantitative methods (Liu & Chang, 2015; Lumbroso, 2018). The establishment of the Global Environmental Monitoring System in 1975 was the beginning of ecological security early-warning research (Munn, 1973). Currently, ecological security early-warning research has already made plenty of achievements in concept, connotation and theory (Bae & Park, 2014; Barnard, Altwegg, Ebrahim, & Underhill, 2017; Park, Lee, Lee, Kim, & Lee, 2019; Xie, He, Choi, Chen, & Cheng, 2020). These researches have involved many aspects, e.g. land, agricultural, forest, food security, urban, and strategic emerging industries (Guo, Wei, Ren, Luo, & Zhou, 2020; Jiao, Wang, Hu, & Xia, 2021; Lu et al., 2019; Qi, Zhong, & Liu, 2015; Sun, Miao, & Yang, 2018; Xie et al., 2020). However, few studies have focused on the ecological security early-warning of NRs, especially national nature reserves (NNRs). The ecological security early-warning prediction has been the focus of NRs in recent years through evaluation, prediction and warning of the ecological security situation and its evolutionary trend in society, economy and environment (Mudereri et al., 2021). Then, according to an analysis of the causes of ecological hazards, preventive measures are formulated in advance (Bahraminejad, Rayegani, Jahani, & Nezami, 2018; Chen & Wang, 2020; Feng, 2021). Therefore, constructing a scientific and reasonable ecological security early-warning framework and index system is the key to the NR ecological security early-warning.

Due to different research objectives, areas, and available data, the framework model used to construct the index system is also different. At present, Pressure-State-Response (PSR) model, Drive force-Pressure-State-Impact-Response (DPSIR) model and their derived models, such as Drive force-Pressure-State-Response (DPSR) model and State-Danger-Immunity (SDI) model, are the main framework models used to construct the ecological security early- warning index system (Bahraminejad et al., 2018; Chen & Wang, 2020; Gong, Shi, & Wei, 2012; Huang, Peng, Wei, & Wan, 2020; Ke et al., 2020). In terms of ecological security early-warning methods, logistic regression has been used to test the correlation between ecological security early-warning and related factors (Sun et al., 2018). Models such as Markov model (Xie et al., 2020), ecological footprint model (Yang et al., 2018), system dynamics model (Tan & Wang, 2010), multi-scale biogeography urban growth model (Xia, Zhang, Wang, & Liu, 2020), and gray model (GM) have also commonly been used (Chen & Wang, 2020). However, NR ecological security early-warning is different in society, economy and environment from that of other areas (Bahraminejad et al., 2018; Liao, Xie, Liu, Zhu, & Wu, 2021). Therefore, it is necessary to construct a set of ecological security early-warning evaluation framework and index system and choose an appropriate ecological security early-warning method suitable for the characteristics of NRs to promote the high-quality development of NRs in China.

The BNNR is one of the three panda reserves in China, which was established in 1978 and listed as an international biosphere reserve by "Man and the Biosphere Programme" of the united nations educational scientific and cultural organization in 2019 (Rong et al., 2019; Wang et al., 2021).Its main task is to protect the natural ecological environment and biodiversity of giant pandas and other rare and endangered wildlife (Guo, Li, & Cui, 2015). Because strict management policies were implemented in the BNNR, the panda habitat was protected, the number of pandas increased, and the ecological environment was restored (Rong et al., 2019). However, these policies restrict resident access to nature resources and change their production and lifestyle. This has resulted in an increasingly intensified conflict between economic development and ecological protection, which has a negative influence on ecological security in this area (Han, 2019). To make a scientific early warning for the ecological security of the BNNR, we proposed an integrated ecological security early-warning framework and index system to identify the ecological security early-warning situation of the BNNR based on the DPSIR model. Then, we used the GM to predict the ecological security early-warning trend. Finally, we applied the Geo-detector to explore the driving factors of the ecological security early-warning situation. The findings of this study are expected to assist in achieving an understanding of the balance between human activities and the natural environment in the NR area.

2. Study area and data sources

2.1. Study area

The BNNR is located in the southern part of Gansu province, northwest China between E104°16′–105° 25′, N32°36′–33°00′ (Fig. 1). Protecting the giant panda population and its habitat is the main target of the BNNR, which covers an area of 1857.5 km^2 (Liu et al., 2022). It is also recognized as a highly contributing to biodiversity and the most concentrated area of endangered animals and plants (Liu, Zhao, Wen, Teng, & Li, 2009). The BNNR is characterized by high mountains having high elevation in the northwest and low elevation in the southeast, with an altitude of 595–4072 m, and the topography is steep. The BNNR is a transition zone between subtropical and warm-temperate climate types. Its average temperature is approximately 15 ℃, and its annual precipitation is approximately 800 mm. The relative humidity is 50–70%, and there is 17 h of sunshine per day on average (Liu et al., 2022). The dominant vegetation type is forest, with high coverage in the BNNR, which reaches 87.3%. With increasing elevation, the sequence of vegetation types is mountain subtropical evergreen broad-leaved forests, mountain evergreen broad-leaved and deciduous broad-leaved mixed forests, mountain deciduous broad-leaved forests, warm-temperate needle-leaved and deciduous broad-leaved mixed forests, mountain cold-temperate needle-leaved forests, subalpine frigid shrubs and meadows (Wang et al., 2021). There are 8 genus and 18 species of bamboo in the reserve, which are staple bamboo of pandas (i.e., *Fargesia denudate, F. rufa, F. scabrida, F. obliqua*) (Hu & He, 2020; Rong et al., 2019). The Natural Forest Protection Program (NFPP) has been implemented in the BNNR since 2000, which has effectively controlled forest degradation and made a good recovery and development of forest resources (Li et al., 2021; Wang et al., 2021).

In regard to administrative division, the BNNR belongs to Wenxian county and Wudu district of Longnan city. There are six towns in Wen County, including Tielou (TL), Danpu (DP), Liujiaping (LJP), Fanba (FB), Bikou (BK) and Zhongmiao (ZM). There are three towns in Wudu District, including Luotang (LT), Fengxiang (FX), and Sancang (SC). The population of this study area is approximately 110000, and the agricultural population accounts for 90%. According to statistics, the population growth rate of the study area is only "10‰-12‰". The population density is only approximately 52 people / km^2, but the population cultivated land density is as high as 968 people / km^2. The production activities of the BNNR are still dominated by traditional agriculture under natural conditions, namely the cultivation of grain crops such as maize and wheat, which accounts for >90% of the total sown area. However, most farmland is distributed on steep hillsides with poor quality soil, and the crop yield is low. Most residents of the BNNR feed livestock (i.e., cattle, sheep, pig and chicken) at home to increase household income or supply their own consumption (Han, 2019 ; He, 2018; Wei, Feng, & Fan, 2008; Zhang, 2015).

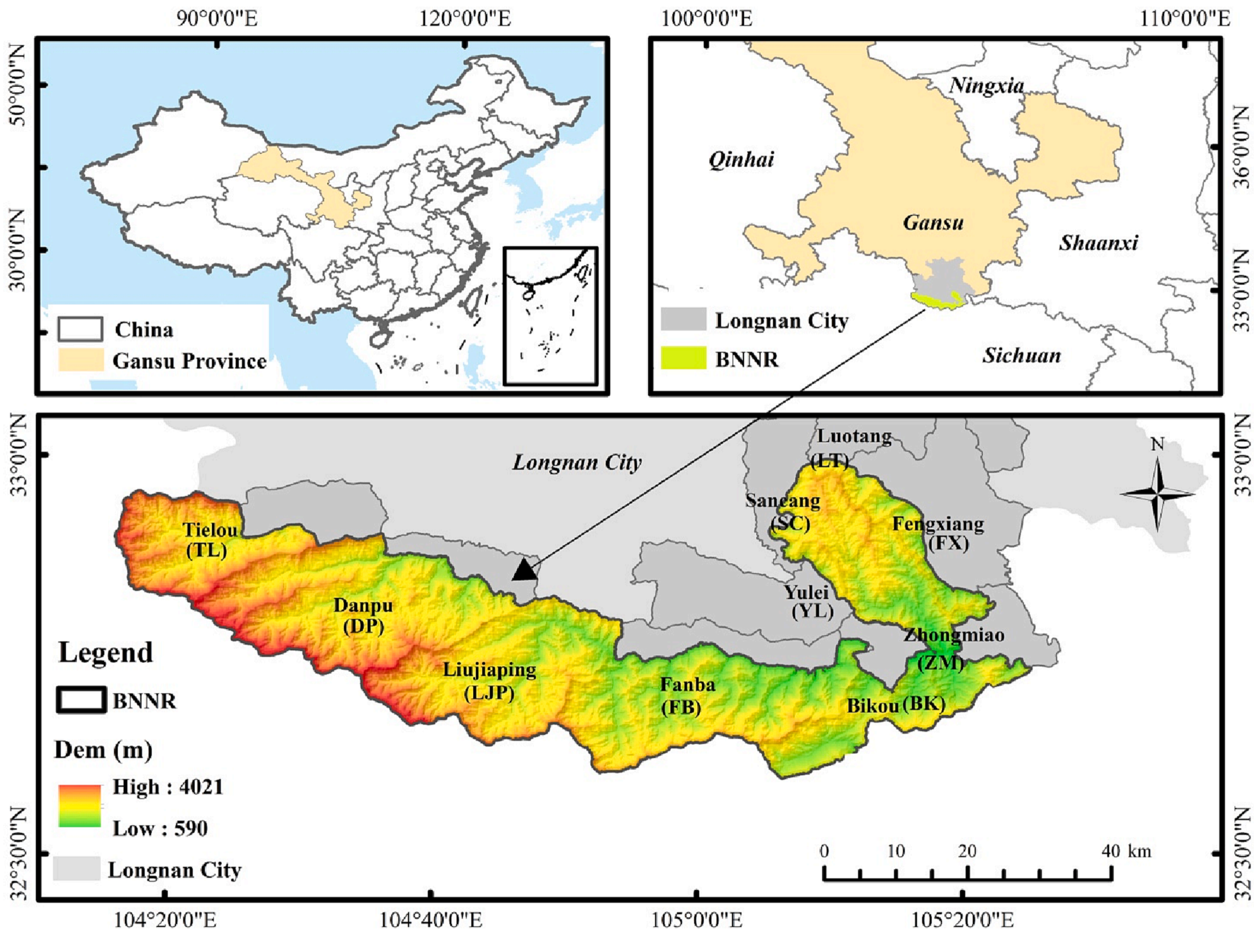

Fig. 1. The location of BNNR.

2.2. Data sources

Meteorological data, social and economic data, and land use/cover change data were used in this study. The annual mean temperature and annual mean precipitation of meteorological data were obtained from the National Earth System Science Data Center, National Science & Technology Infrastructure of China (https://www.geodata.cn). The social and economic data were obtained from Statistical Yearbooks from 2005 to 2017, including the Wenxian county statistical yearbook and Wudu district statistical yearbook of Longnan city. Land use/cover change data in our research included per capita forest land area, per capita grassland area, per capita cultivated area, per capita water area and per capita construction land area with a 30 m resolution downloaded from the Resource and Environment Data Cloud Platform, Chinese Academy of Sciences (https://www.resdc.cn). Landscape indices included Shannon's diversity index, and the largest patch index based on land use/cover change data were preprocessed by Fragstats 4.2 software (Mcgarigal, Cushaman, & Ene, 2012).

3. Methodology

3.1. Analytical framework

Ecological security early-warning is a complex problem, including ecological environmental, social and economic characteristics. Fig. 2 shows the analytical framework of ecological security early-warning in this study. This framework mainly includes five steps. First, an index system of ecological security early-warning was constructed based on the DPSIR model. Second, the index weights of ecological security early-warning were determined by combining the entropy value method (EVM) and analytic hierarchy process (AHP) method. Third, the ecological ESI values were calculated by applying the data from 2005 to 2017, and the ESI was graded, which reflects the ecological security situation in history. Fourth, according to the ESI values, ecological security early-warning index (ESEWI) values were calculated from 2018 to 2030 by the GM (1.1) model in MATLAB 2019 software. Then, the accuracy of the GM (1,1) model was examined, and the prediction results of the ecological security early-warning were graded. Finally, the key driving factors affecting ecological security early-warning were analyzed by Geo-detector.

3.2. DPSIR model

Since the ecological security of NRs is affected by many factors, their ecological security early-warning must comprehensively consider the influence of the natural environment, society and economy from a multidimensional perspective (Liu et al., 2022). The DPSIR model is a tool for detailed analysis that integrates complex systems into an approach (Bidone & Lacerda, 2004). This model can link the time scale and spatial scale and comprehensively reflect the contents of society, economy, environment and policy (Ehara et al., 2018; Liu, Song, & Deng, 2019; Ruan, Li, Zhang, & Liu, 2019). It has compatibility, integrity, hierarchy and logic and can provide a certain basis for ecological security early-warning (Chen & Wang, 2020). In the DPSIR model, driving force (D) indicates potential pressure on ecological security, including the direct drivers of climate and indirect drivers of social and economic development; pressure (P) reflects the direct influence of population, production and resource consumption on ecological security; state (S) means to the

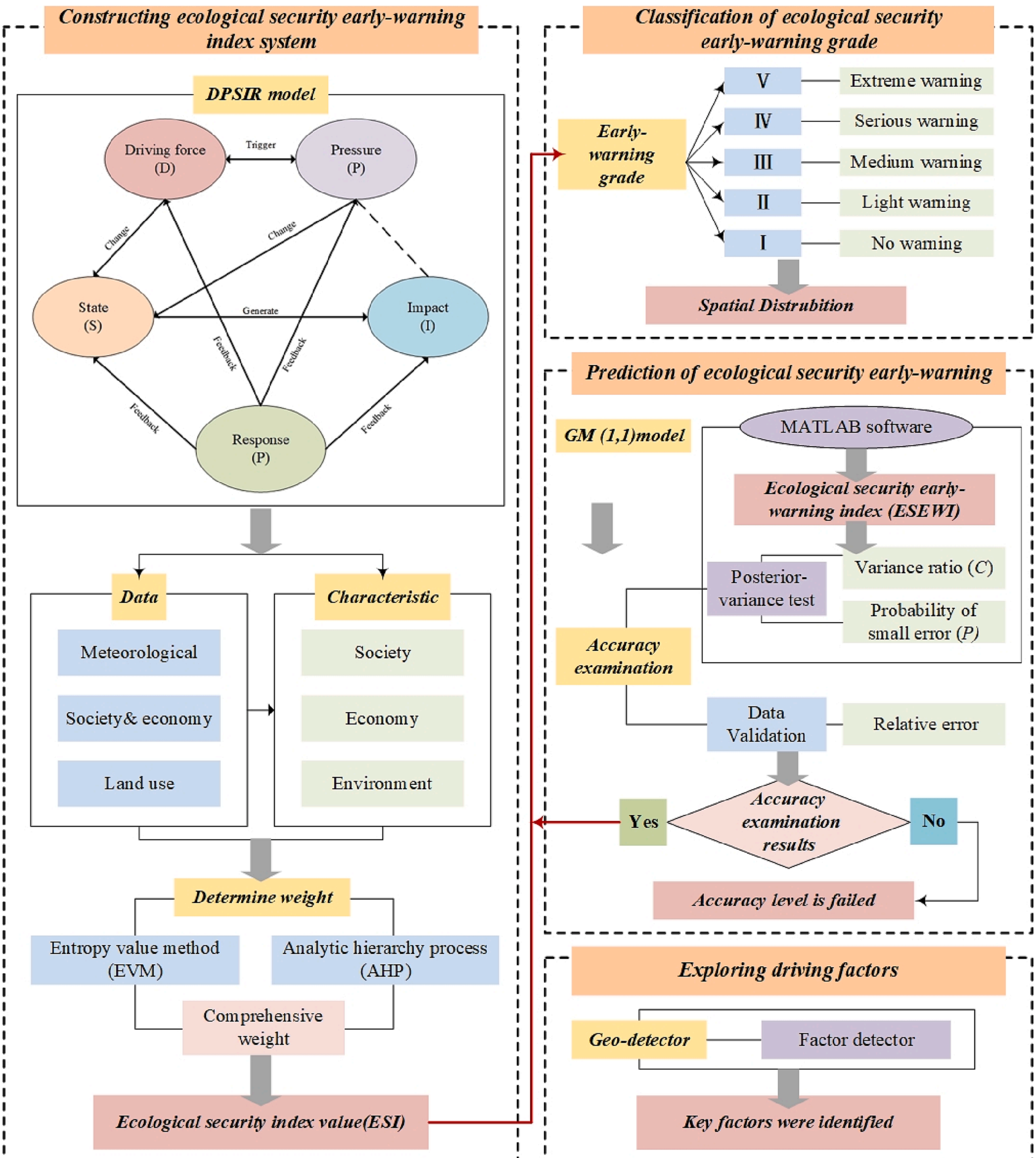

Fig. 2. The analytical framework of ecological security early-warning of the BNNR (Liu et al., 2022; Guo et al., 2020; Peng et al., 2021).

state of society, economy and ecological environment under pressure; impact (I) refers comprehensive impact of society, economy and environment on ecological security when the ecosystem is under shock and pressure; and response (R) reflects the conservation, compensation and improvement measures taken to promote ecological security (Liu et al., 2022; Ruan et al., 2019).

3.3. Constructing an index system of ecological security early-warning

Constructing a scientific and reasonable index system is crucial for ecological security early-warning (Ke et al., 2020). Because of ecological security early-warning was affected by the level of social and economic development and natural environmental conditions (Liao et al., 2021). Therefore, this index system was constructed based on the DPSIR model. The index system was divided into four layers (i.e., the target layer, project layer, indicator layer, and characteristic layer). The target layer is the early-warning index system of ecological security for the BNNR, which consists of five project layers: driving force, pressure, state, impact, and response. Each project layer consisted of different indicators, and each indicator had different characteristics. According to the demands of the DPSIR model, combined with the actual situation, the availability of data, the regional professional opinion and relevant literature of the DPSIR model (Chen & Wang, 2020; Liu et al., 2022), 24 indicators were selected from social, economic and environmental characteristics to construct an ecological security early-warning index system for the BNNR (Table 1).

3.4. Methods

3.4.1. Index weight determination

Standardization of the raw data is the foundation of ecological security evaluation (Zhang & Guo, 2016). In this study, the decimal scaling standardization method was used for all indicators. The formula is as follows:

$$x_i^{'} = \frac{x_i}{(10 \times g)} \tag{1}$$

where $x_i^{'}$ is the standardized value of *ith*, and g is the minimum integer to satisfy the condition.

The multi-level weighted comprehensive index method was selected to evaluate the ecological security index (ESI) (Chen & Wang, 2020; Wei, Zhou, & Wang, 2012).The multi-level comprehensive weights calculated by the EVM and AHP method each accounted for 50% of the comprehensive weight results (Huang et al., 2020). This comprehensive method combines subjective and objective weight methods, making the calculation of weights more accurate and credible. Table 1 presents the results of the weight calculation.

3.4.2. Ecological security index (ESI)

To evaluate the ecological security of the BNNR, the ESI was used. to evaluate ecological security situation. The formula is as follows:

$$\mathrm{ESI} = \sum_{i=1}^{n} x_i^{'} w_i \tag{2}$$

where x_i is the standard value of index i, w_i is the comprehensive weight of index i, and n is the number of index (larger values correspond to higher ecological security).

3.4.3. Ecological security early-warning index (ESEWI)

The GM is a method to measure the degree of correlation between factors according to the development trend among several factors, which analyzes the uncertainty in a system through conditional analysis, prediction, and decision-making (Deng, 1982). It has been widely applied in early-warning research in many fields (Hsu, 2003; Zhang et al., 2020). The GM includes GM (1,1) and GM (1, N). GM (1, 1) is the most commonly used in prediction. Its principle of prediction is to accumulate irregular historical data to obtain a regular sequence with exponential growth. The coefficients of differential equations are then established to obtain a system that contains both known data and unknown information, which can then be used for prediction. The model has a simple operation process and high predictive ability (Wang, Li, & Pei, 2018; Zhong, Hu, Shi, Su, & Yang, 2020). To predict the future situation of ecological security of the BNNR, the GM (1, 1) model was used to calculate the ESEWI of the BNNR from 2018 to 2030. The detailed calculation steps of the GM (1,1) model can be found in a study by Chen and Wang (2020).

3.4.4. Accuracy examination

The accuracy of the GM (1,1) model must be examined to ensure the results of the ecological security early-warning (Guo et al., 2020; Zhu et al., 2014). The P value refers to the small error, and the C value refers to the posterior error ratio. The P value and the C value can be calculated by using MATLAB 2019 software. When $P \geq 0.95$ and $C \leq 0.35$, the model accuracy is excellent; when $0.80 \leq P < 0.95$ and $0.35 < C \leq 0.50$, the model accuracy level is good; when $0.70 \leq P < 0.80$ and $0.50 < C \leq 0.65$, the model accuracy level is acceptable; and when $P < 0.70$ and $C > 0.65$, the model accuracy level fails (Guo et al., 2020). In this study, the data can be divided into two datasets (calibration set and validation set). Data from 2005 to 2013 were used for the calibration set, and the data from 2013 to 2017 were used for the validation set.

3.4.5. Classification of ecological security early-warning grades

To more intuitively reflect the overall ecological security early-warning changes of the BNNR over different years, according to the

Table 1
Ecological security early-warning index system and weight.

Target layer	Project layer	Indicator layer	Characteristic layer	AHP	EVM	Comprehensive weight
Ecological security early-warning of the BNNR	Drive (D)	D1: Annual mean temperature	Environment	0.013	0.04497	0.029
		D2: Annual mean precipitation	Environment	0.027	0.04245	0.035
		D3: Educational level	Society	0.067	0.04501	0.056
		D4: Per capita disposable income	Economy	0.053	0.03879	0.046
		D5: Urbanization level	Society	0.040	0.04501	0.043
	Press (P)	P1: Population density	Society	0.050	0.04501	0.048
		P2: Percentage of total agricultural income	Economy	0.070	0.04501	0.058
		P3: Fertilizer application intensity	Environment	0.027	0.04501	0.036
		P4: Plastic film application intensity	Environment	0.027	0.04501	0.036
		P5: Per capita livestock	Society	0.027	0.04501	0.036
	State (S)	S1: Per capita forest land area	Environment	0.033	0.00653	0.020
		S2: Per capita grassland area	Environment	0.033	0.03308	0.033
		S3: Per capita cultivated area	Environment	0.033	0.04154	0.037
		S4: Per capita water area	Environment	0.033	0.04491	0.039
		S5: Per capita construction land area	Environment	0.033	0.04487	0.039
		S6: Net primary productivity (NPP)	Environment	0.033	0.04300	0.038
	Impact (I)	I1: Per capita agricultural, forestry, animal husbandry and by-fishery output	Economy	0.075	0.04501	0.045
		I2: Shannon's diversity index (SHDI)	Environment	0.050	0.04501	0.056
		I3: Largest patch index (LPI)	Environment	0.050	0.04476	0.056
		I4: Level of disaster	Environment	0.025	0.04501	0.034
	Response (R)	R1: Per capita compensation	Economy	0.100	0.04414	0.072
		R2: Effective irrigation at year-end	Society	0.033	0.04501	0.039
		R3: Grain yield per hectare	Society	0.033	0.04443	0.039
		R4: Terrace field area	Society	0.033	0.03143	0.032

relevant research and the actual situation of the BNNR (Bahraminejad et al., 2018; Chen & Wang, 2020; Guo et al., 2020; Huang et al., 2020; Ma et al., 2016), the ecological security early-warning grade was obtained by using the natural break point method in ArcGIS 10.2 software, which was divided into five grades: “extreme warning” (V), “serious warning” (IV), “medium warning” (III), “light warning” (II), and “no warning” (I).

3.5. Geo-detector method

The Geo-detector method was used to explore the driving factors of ecological security early-warning. This is a spatial statistical tool for determining factor heterogeneity through spatial variance analysis (Wang, Zhang, & Fu, 2016), which was widely used to analyze the relative importance of various driving factors affecting society, economy, and the environment (Liu et al., 2022; Ruan et al., 2019). The Geo-detector can quantify the driving factors on the dependent variable, which includes factor detector, interactive detector, risk detector and ecological detector. Each detector has a different analytical function. Factor detectors can measure the influence of independent variable × on variable y and explain the spatial differentiation mechanism by the q value. The q value indicates the explanatory power of factors, which ranges from 0 to 1. The greater the q value is, the larger the explanatory power of the factor (Liu et al., 2021). The calculation of the q value can be obtained from Wang et al. (2016). And the Geo-detector can be downloaded for free from the website (http://www.geodetector.cn).

4. Results

4.1. Ecological security index (ESI) and grade of the BNNR

The ESI values were calculated by Eqs. (1) and (2) from 2005 to 2017.The average values of the ESI from 2005 to 2017 ranged from 0.2796 to 0.3171, with an average increase of 11.82%, and the ESI value decreased only in 2010 (Fig. 3). In 2005, BK had the lowest ESI value, while DP had the highest ESI value. Similarly, in 2016, the lowest ESI value appeared in BK and the highest ESI value appeared in DP.

The ESI was divided by the natural break point method from 2005 to 2017 (Table 2). It can be seen from the spatial distribution that there were obvious spatial differences in the ecological security early-warning grades (Fig. 4). The ecological security early-warning grades presented the spatial distribution characteristics of the “M”-type in general. This showed that the marginal and central towns of the BNNR were worse than other towns. From 2005 to 2017, the ecological security early-warning grades of the towns included “extreme warning”, “serious warning”, “medium warning” and “light warning”. Except for TL and BK, which still had a “extreme warning” grade, DP changed from the “medium warning” grade to the “light warning” grade, LJP changed from the “serious warning” grade to the “medium warning” grade, other towns changed from the “serious warning” grade to the “light warning” grade. In regard to the average level, there was one town (16.67% of the total number of towns) with an “extreme warning” grade, two towns (33.33%) with a “serious warning” grade, two towns (33.33%) with a “medium warning” grade and only one town (16.67%) with a “light warning” grade. These results indicated that although the ecological security situation improved year by year, the ecological security is still facing challenges since the poor foundation of the ecological environment in the BNNR.

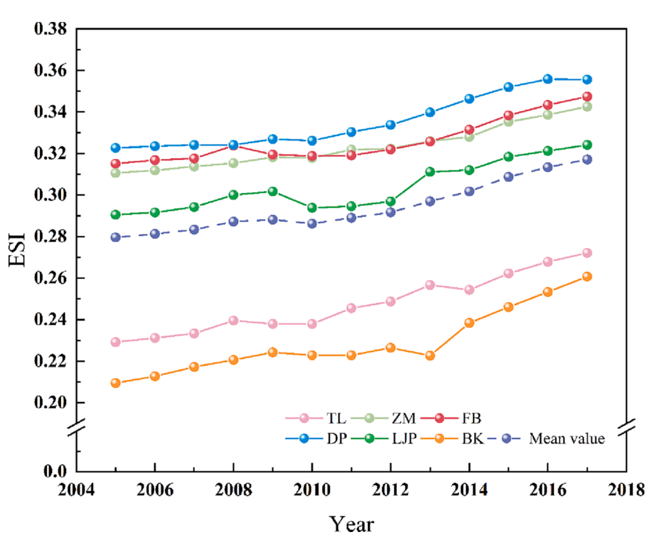

Fig. 3. The changing trend of the ESI in the BNNR.

Table 2
Classification standard of the ecological security early-warning grades in the BNNR.

Grading	Warning situation	ESEI	Security situation	Warning color
V	Extreme warning	≤0.2741	Very bad	
IV	Serious warning	(0.2741, 0.3158]	Bad	
III	Medium warning	(0.3158, 0.3338]	Regular	
II	Light warning	(0.3338, 0.3594]	Good	
I	No warning	> 0.3594	Very good	

4.2. Ecological security early-warning index and grade of the BNNR

The ESEWI values were calculated from 2018 to 2030 by the GM (1,1) model. The ESEWI increased from 0.3171 in 2018 to 0.3622 in 2030, which was an average increased by 12.46% (Fig. 5). These results indicated that the ecological security situation continually improved from 2018 to 2030. BK had the lowest ESEWI value in 2018, while DP had the highest ESEWI value. Similarly, the lowest ESEWI value appeared in BK and the highest ESEWI value appeared in DP in 2030.

The ESEWI was divided by the natural break point method from 2018 to 2030 (Table 2). The grade results of the ESEWI from 2018 to 2030 indicated that with the ESEWI increasing over time and ecological security early-warning grade presented an obvious downward trend (Fig. 6). The ecological security warning situation had significant spatial differentiation from 2018 to 2028, which was similar to the spatial distribution characteristics of 2005–2017, and still showed the characteristics of the “M” type characteristics. The ecological security early-warning grades manifested the characteristics of the inverted “V” type after 2029. Specifically, from 2018 to 2030, BK and TL with the “extreme warning” grade in 2018 changed to the “medium warning” grade; DP, FB, and ZM changed from the “light warnings” grade to the “no warning” grade, and LJP changed from the “medium warning” grade to the “no warning” grade. TL and BK were the most sensitive towns and LJP was the greatest potential town for development in the BNNR. By 2030, the number of towns with a “no warning” grade increased to four, and the number of town with an “extreme warning” grade was zero. The proportion of areas with early-warnings decreased from 100% to 33% in the prediction period. Most towns changed to the “no waning” grade and the “medium warning” grade on average. These results showed that the current strict ecological protection policy and economic development pattern implemented will greatly improve the future ecological security warning situation in the BNNR.

4.3. Accuracy examination results

The statistical results of the accuracy examination for the GM (1, 1)

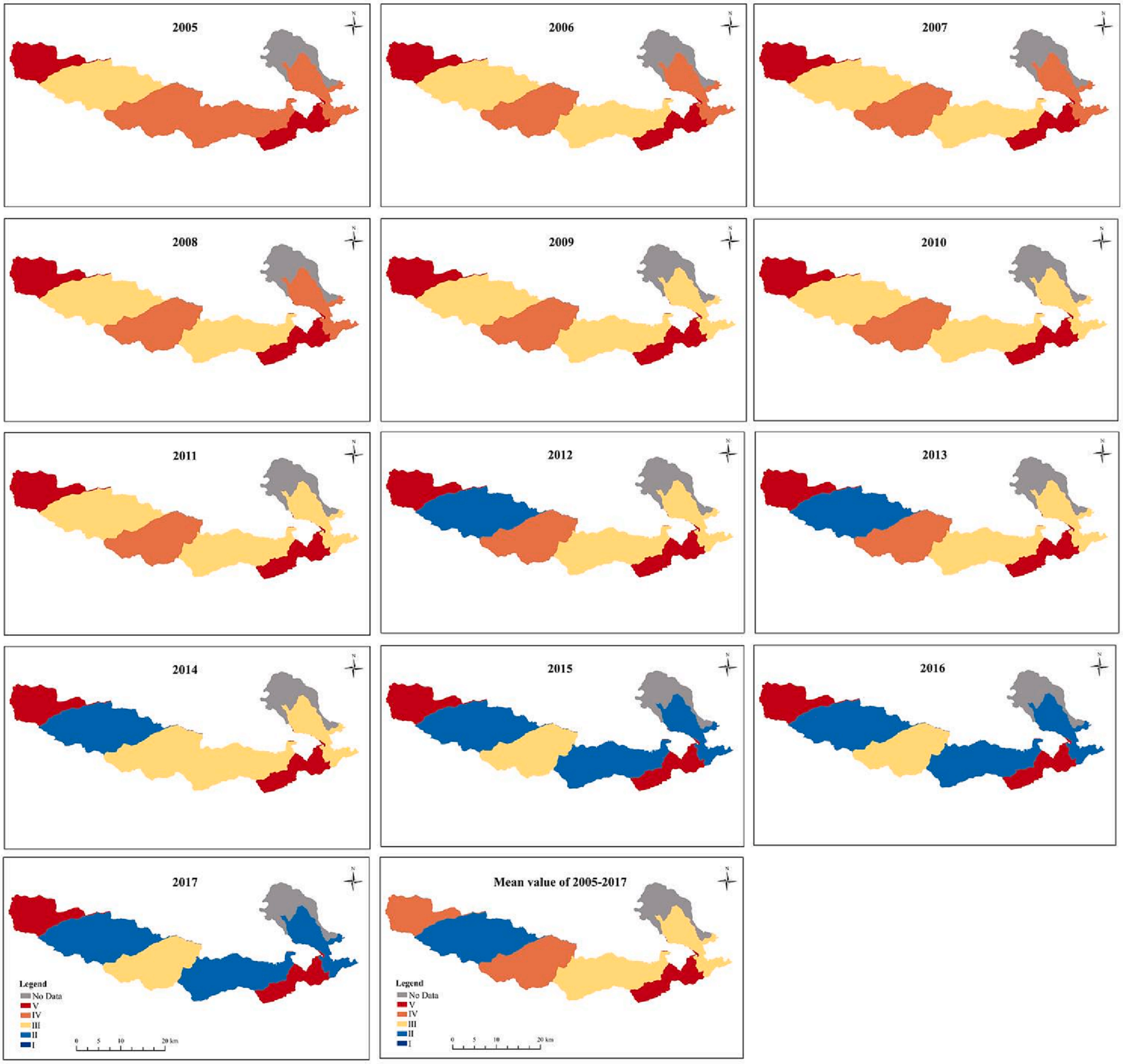

Fig. 4. Spatial distribution of the ecological security grades from 2005 to 2017 in the BNNR.

model are shown in Table 3. The relative errors of the GM (1, 1) model were mainly at 0–2%, and the average relative error was 1.14%. Because the P values were > 0.8 and the C values were <0.5, the P value of the four towns was 1, and the C value of the three towns was <0.35. The results indicated that the ecological security early-warning indices were reliable and could be used to effectively predict the ecological security of the BNNR.

4.4. Driving factors of the BNNR

The factor detector was used to determine the driving factors in the ecological security early-warning. The results revealed that the influencing factors of social, economic and environmental characteristics were different on the ecological security early-warning (Fig. 7). The q value for all influencing factors ranged from 0.13 to 0.93. The primary driving factors affecting ecological security early-warning included per capita forest land area (S1), per capita grassland area (S2) and education level (D3), for which the q values were 0.9334 and 0.9329, respectively. Thus, these were the three main driving factors that affect the ecological security early-warning. The q values of population density (P1), level of disaster (I4), annual mean precipitation (D2), effective irrigation at year-end (R2), urbanization level (D5), and per capita compensation (R1) were all above 0.5, indicating that they were secondary driving factors affecting ecological security early-warning. The q values of per capita agricultural, forestry, animal husbandry and by-fishery output (I1), SHDI (I2), per capita construction land area (S5), annual mean temperature (D1), and fertilizer application intensity (P3) were all below 0.15, indicating that they had little influence on ecological security early-warning. The average q values of social, economic and environmental characteristics were 0.5671, 0.2723 and 0.3329, respectively. These results showed that social characteristic factors had a main effect on the ecological security early-warning of the BNNR.

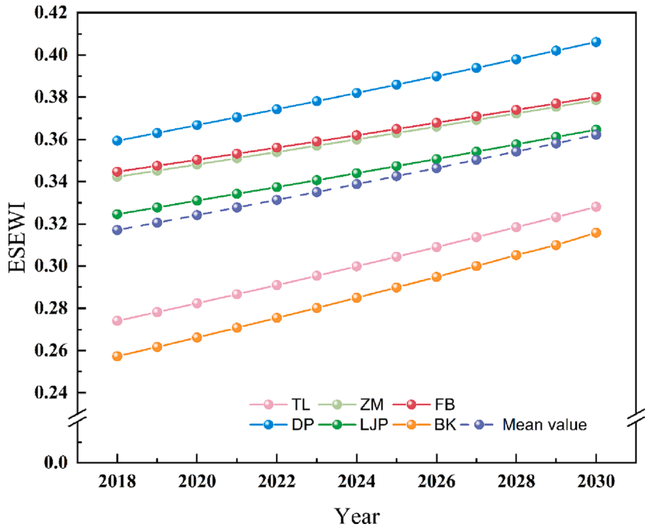

Fig. 5. The changing trend of the ESEWI in the BNNR.

5. Discussion

5.1. Reliability and limitations of the early-warning model for the BNNR

The BNNR is an important giant panda reserve in China (Liu et al., 2022; Wang et al., 2021). It has rich animal and plant resources and a unique traditional culture (Baima Tibetan culture). However, social and economic development is lagging, and the livelihoods of local residents are relative poverty (Han, 2019). To facilitate the protection and restoration of giant panda habitat, China incorporated the BNNR into the national park system in 2017. The pilot stage was from 2017 to 2020. The formal construction stage was initiated after 2020. Thus, study of the ecological security early-warning and prediction of future ecological security early-warning situations will aid the construction of the BNNR. This could also enhance the livelihood level of local residents, achieving a "win–win" between society and economy development and the protection of the ecological environment.

Ecological security early-warning research is still in an incipient stage (Chen & Wang, 2020), and novel methods are currently being explored, especially in NRs. Markov models, multiple logistic regression models, and system dynamics models have been widely used in current studies to evaluate ecological security early-warning situations (Ke et al., 2020; Xia et al., 2020; Xie et al., 2020). The GM has been verified by many researchers to be an effective tool for analyzing ecological security early-warning (Guo et al., 2020; Shaheen et al., 2020). Given that the study area of this paper is small, data were difficult to obtain. Therefore, the GM was used to predict the ecological security early-warning situation from social, economic, and environmental perspectives, which could eliminate the inherent uncertainty of social and economic data and make the prediction results of the GM more accurate and robust. The accuracy examinations of the prediction results also indicate that the GM was reliable. Although our analysis of the ecological security early-warning suggested that the GM was accurate similar to other studies, this study still has certain limitations. First, Chen and Wang (2020) stated that current research on ecological security early-warning methods lacks a unified classification standard of early-warning grades, which precludes comparison among studies. Second, the ecological security early-warning value steadily increased without any fluctuations during the study period. This is likely explained by the fact that the BNNR is too small, and it has strict protection policies. Compared with other districts, such as Beijing city, Yunnan city, and Chongqing city (Chen & Wang, 2020; Ke et al., 2020; Lu et al., 2019), the changes observed for the study area were very small. Thirdly, four towns at the edge of the BNNR (LT, FX SC, and YL) were not located entirely in the study area. In this study, the ecological security early-warning situation was evaluated at the town scale. Therefore, these four towns were not considered in the analysis. However, these four towns occupy a small area and have little influence on the overall ecological security early-warning. Fourth, the ecological security early-warning situation is complex and dynamic, and the data of some indicators are difficult to obtain. In future studies, grid units should be used for early-warning evaluation, and questionnaires should be used to obtain additional data, such as data on animals and plants, to ensure that the results of the ecological security evaluation are more robust. In addition, multi-source data and long-term sequence indicator data should be used to determine the key driving factors in ecological security early-warning.

5.2. The ecological security early-warning index system for the BNNR

Constructing a scientifically and reliable ecological security early-warning index system is the key to predicting the ecological security early-warning situation. Previous studies have used a variety of methods to construct ecological security early-warning index systems for different early-warning objectives (Huang et al., 2020; Ma et al., 2016). Urban ecological security early-warning systems use indicators related to urban development, such as GDP, population, and industrial indicators (Ke et al., 2020). Remote sensing or GIS technology is often employed to obtain data on relevant indicators such as the NDVI, land use, and land cover changes for land ecological security early-warning index systems (Wei et al., 2012). Forest ecological security early-warning systems often use the evaluation criteria of the Chinese government to select indicators, focusing on forest damage and the extent of disturbance (Lu et al., 2019). One ecological security early-warning index system previously used for the Darmiyan Protected Area used meteorological data, as well as data on poaching, animal growth rates, and protection policies (Bahraminejad et al., 2018). In this study, data on the social, economic, and environmental characteristics were used to construct the ecological security early-warning index system based on the DPSIR model. Since the DPSIR model can effectively analyze the relationship between social and economic development and the environment and can address the incompatibility between indicators and methods, it can provide a basic framework for comprehensive research on ecological security (Elliott, 2002; Zhang, Zhang, Wu, Ma, & Yang, 2016). The ecological security early-warning situation is determined by social, economic, and environmental characteristics. Because of the implementation of strict control measures in the BNNR, poaching is currently not known to occur. Therefore, data on poaching, animals and plants were not used in this study. This may have some influence on the ecological security warning of the BNNR.

5.3. The driving factors in the ecological security early-warning for the BNNR

The ecological security early-warning was affected by social, economic and environmental characteristics. In terms of social characteristics and economic characteristics, with the implementation of the NFPP, ecological compensation and relevant education policies by the local government, the income and education level of local residents gradually improved, and ecological compensation and education level were key factors in social and economic characteristics. These factors facilitated the conservation of ecological security and decreased the ecological security early-warning grade of the BNNR. In terms of environmental characteristics, the study area is small, and the residents are mostly distributed near the edge towns. No one is permitted to live in the core area. The distribution and change in the population have an important effect on the ecological security early-warning. The local government and management bureau implemented several policies to limit the destruction of forest land and grassland by residents from 2005 to 2017. Forest land and grassland have been gradually restored. Thus, the ecological security early-warning situation has been optimized. The

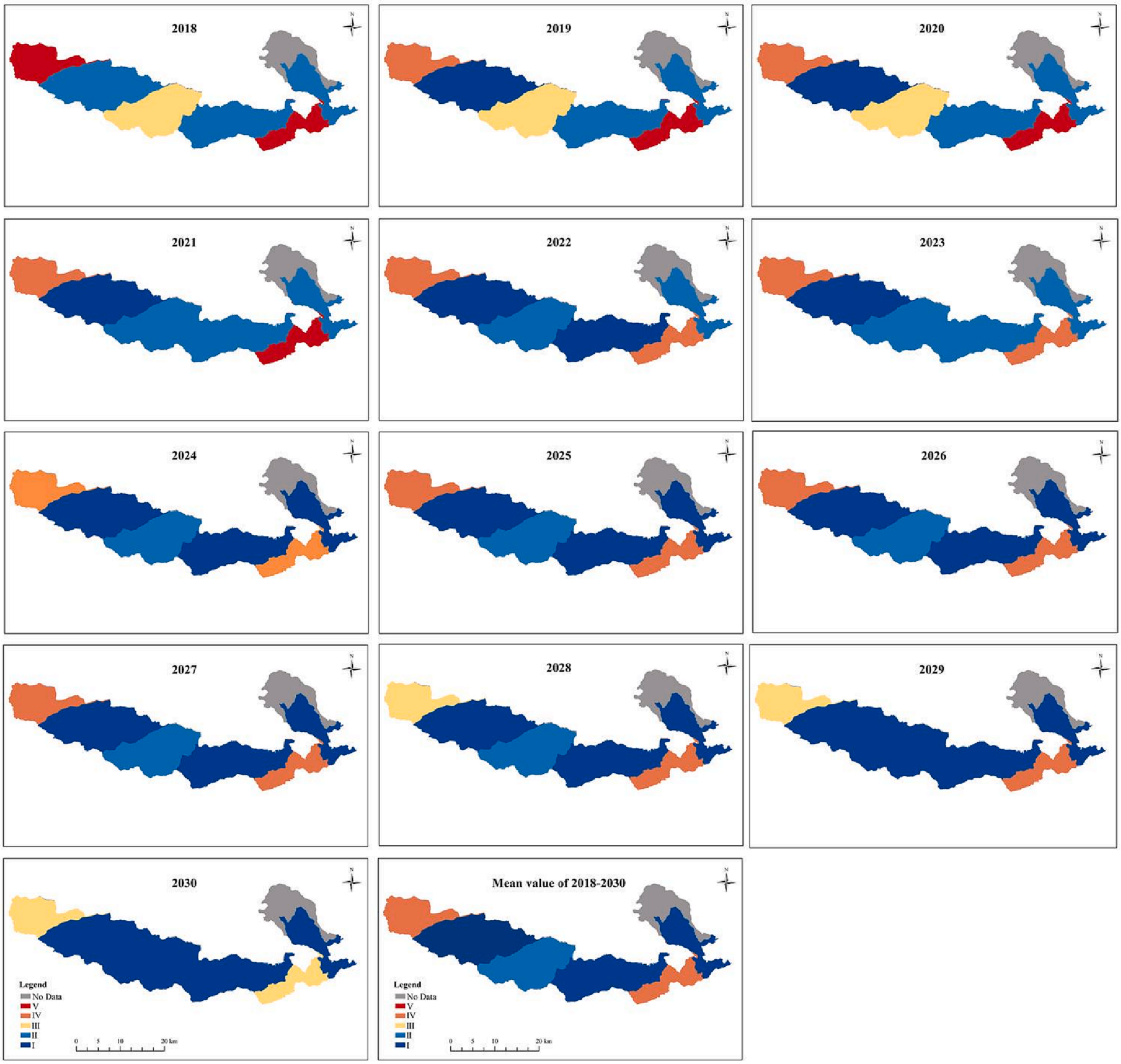

Fig. 6. Spatial distribution of the ecological security early-warning grades from 2018 to 2030 in the BNNR.

Table 3
Error statistics of the early-warning model.

District	Matlab Error Ratio		Percentage of relative error intervals			Average relative error
	P	C	0–1%	1%-2%	> 2%	
Tielou (TL)	1	0.1825	66.67%	23.33%	10%	1.14%
Danpu (DB)	1	0.2582				
Liujiaping (LJP)	0.8462	0.4134				
Fanba (FB)	1	0.4197				
Bikou (BK)	0.9231	0.362				
Zhongmiao (ZM)	1	0.2086				

forest land and grassland areas are closely linked to the livelihoods of residents. Therefore, per capita forest land and per capita grassland areas have a substantial effect on the ecological security early-warning situation. In addition, the effect of precipitation on the ecological security early-warning was higher than that of temperature from 2005 to 2030. The q value of annual precipitation was 0.587. The annual mean precipitation was 42.77 mm higher in 2017 than in 2005. Thus, the important factor affecting the ecological security early-warning was precipitation rather than temperature, which is consistent with a previous study that analyzed the ecological security of the Darmiyan Protected Area (Bahraminejad et al., 2018).

The results of the ecological security early-warning showed that ecological security is predicted to improve in the future. However, the degree of improvement of ecological security varies spatially. The ecological security early-warning of DP, LJP, FB and ZM was good, and that of TL and BK was relatively poor. Although TL and BK have the same

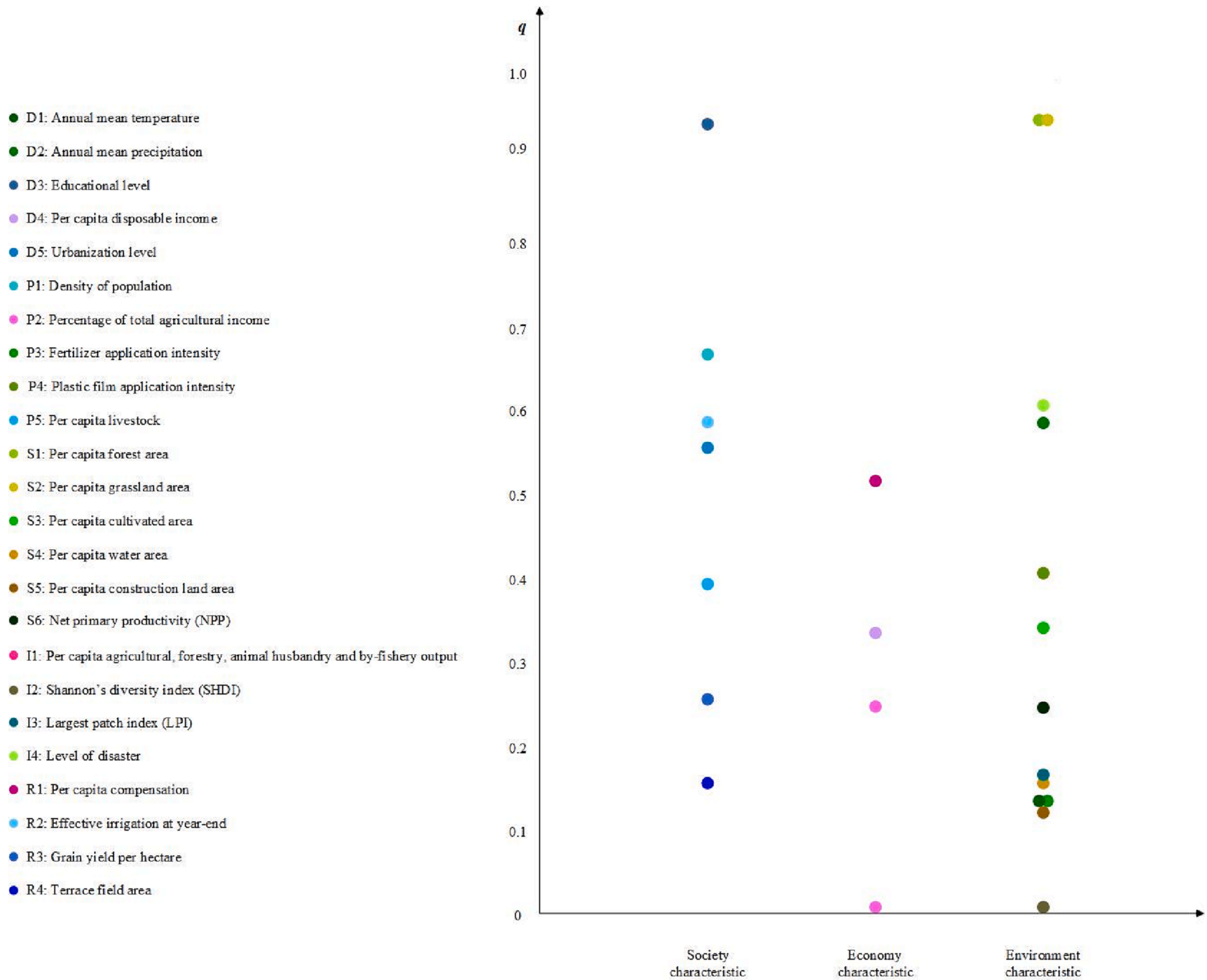

Fig. 7. The *q* value of driving factors on the ecological security early-warning in the BNNR.

ecological security early-warning grade, they face different threats. TL, once the poorest area in the BNNR, is frequently affected by natural disasters, such as the 2008 Wenchuan earthquake. This town is also characterized by poor infrastructure, an inadequate supply of public services, and a lack of social and economic development. However, the forest resources are rich in TL. Before the implementation of the strict forest protection policy, timber was the main source of the livelihoods of local residents. TL is also a site occupied by the Baima people; the education level of the residents is low, and the awareness of ecological protection is poor. The unique Baima Tibetan culture in this town has attracted many tourists, and some residents have begun to engage in agritainment activities, which have negatively affected local ecological security. Compared with other towns in the BNNR, the ecological security early-warning of TL is poor; however, the continual strengthening of national measures to alleviate poverty has helped ameliorate the ecological security of TL. BK shows the highest degree of economic development. It also has a large population with a high frequency of economic and industrial activities. Excavation activities are commonly conducted in BK because of its abundant underground mineral resources. The per capita forest land and per capita grassland areas are lower in this town. As a result, the ecological compensation is less compared with other towns. Consequently, the ecological security early-warning situation of BK is poor, and the gradual improvement in the ecological security situation is slow.

5.4. Policy implications for the BNNR

The ESI and ESEWI have gradually improved from 2005 to 2030, which is closely related to the strict protection and compensation policies. The NFPP was launched in 2002 in the study area. The first stage of the NFPP focused on the restoration of forest and animal resources from 2002 to 2010. The second stage of the NFPP from 2011 to 2020 was focused on ecological compensation and non-commercial forest construction (Wei et al., 2008). The property rights reform of collective forests in 2003 clarified the property rights of forest land, the forestry system was continuously improved, ecological compensation was increased gradually, and the interests of residents were maintained. As a result, the ecological security early-warning situation greatly improved after 2012. In addition, giant panda protection policies were also important. For example, the giant panda monitoring program was implemented in 2003. The improved monitoring efforts and policies have steadily enhanced ecological security early-warning levels. The regulations of the NRs were revised in 2011, new forest management and protection approaches were implemented, and these have promoted the transformation of the ecological security situation in a good direction (Manual, 2017). Targeted poverty alleviation efforts have enhanced the livelihood level of residents while improving the ecological security situation. Therefore, constructing and applying the ecological security early-warning framework and index system can contribute to forest restoration and the protection of giant pandas and their habitat to realize the sustainable development of ecological protection, society and economy in the BNNR.

6. Conclusion

Ecological security early-warning is an important measure to maintain coordinated and sustainable development of ecological environmental protection, society and economy development in NRs. Therefore, according to the unique social, economic and ecological environment characteristics of NRs, the development of robust ecological security early-warning systems is critically important. This study proposes a framework and index system of ecological security early-warning based on the DPSIR model. The ecological security early-warning situation of the BNNR was evaluated, and the Geo-detector was used to analyze the driving factors of the ecological security early-warning situation. The main conclusions were as follows: (1) The ecological security index (ESI) average value of the BNNR increased from 0.2796 in 2005 to 0.3171 in 2017, with an average increase of 11.82%, which showed that the ecological security situation presented a fluctuating upward trend from 2005 to 2017. (2) The ecological security early-warning index (ESEWI) average increased from 0.3171 in 2018 to 0.3622 in 2030, which was an average increase of 12.46%. These results showed that the ecological security situation will continually improve in the BNNR. By 2030, the number of towns with a “no warning” grade should increase to four, the number of towns with an “extreme warning” grade should be zero, and the proportion of areas with early-warnings should decrease from 100% to 33%. (3) The ecological security early-warning situation was affected by the level of social and economic development and the natural environmental condition. The per capita forest land area, per capita grassland area, and education level were the primary driving factors in the ecological security early-warning of the BNNR. The results of this study demonstrate that the ecological security early-warning index system based on the DPSIR model and grey model can effectively prediction ecological security situations, which can also be applied to other NRs with different protection objectives and will provide scientific support for the ecological protection and management of NRs.

CRediT authorship contribution statement

Youyan Liu: Conceptualization, Formal analysis, Methodology, Visualization, Funding acquisition, Writing – original draft. **Chuan Wang:** Data curation, Visualization. **Hong Wang:** Data curation, Methodology. **Yapeng Chang:** Data curation. **Xiaogao Yang:** . **Fei Zang:** Writing – review & editing. **Xingming Liu:** Funding acquisition, Project administration, Resources, Supervision. **Chuanyan Zhao:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

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

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