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Ecosystem Health: Assessment Framework, Spatial Evolution, and Regional Optimization in Southwest China

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Abstract: Regional ecological health, the core of comprehensive ecosystem assessments, is an important foundation for regional exploration, environmental conservation, and sustainable development. The mountainous areas in southwest China are backward in economy, but industrialization and urbanization have been rapid in recent years. This study assessed the ecosystem health of the Sichuan and Yunnan provinces in China using a pressure-state-response (PSR) model. Spatiotemporal patterns of regional ecosystem health were analyzed from 2000 to 2016, including overall characteristics as well as local characteristics. Ecosystem health in most regions was improved over time ($Y = 0.0058X - 11.0132$, $R^2 = 0.95$, $P < 0.001$), and areas with poorer ecosystem health decreased from half to one-third of the total area. Analysis of the primacy ratio and the variation coefficient confirmed that the gap in health scores between regions has gradually expanded since 2007, but there are more high quality regions overall (Z of Moran's index < 1.96, $P > 0.05$). Overall, the regional ecosystems to the east of the Hu line—an imaginary line dividing east and west China into roughly equivalent parts—were healthier than those to the west. The pressure and state scores of ecosystems were determined by physiographic condition, and the response scores by government policies and social concern. The spatiotemporal patterns of ecosystem health were dominated to a greater extent by natural than anthropogenic factors, which explains why the shift in the patterns aligned with the direction of the Hu line. Dividing regions into key management areas based on natural geographical conditions and socioeconomic development could contribute to the formulation of a reasonable ecological and environmental protection policy, guaranteeing ecosystem services in the long run.

Keywords: ecosystem health; spatiotemporal pattern; pressure-state-response (PSR); standard deviational ellipse; mountain area

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1 Introduction

The increased scope and intensity of human activity alongside the rise of industrialization and urbanization has rapidly changed global ecosystems. As such, the survival and development of human society has been confronted with severe challenges (Peng et al., 2017). Urbanization has drastically affected the structure of surface landscapes and the matter cycle and its energy flow, which has caused appreciable changes in regional

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climate, biodiversity, and hydrology, and has deeply affected regional ecological processes (Kalnay and Cai, 2003; Nainggolan et al., 2013; Torres et al., 2014). Furthermore, ecological and environmental problems such as air pollution, forest degradation, soil erosion, and ecosystem degradation limit a region's economic and social development, as well as efforts to promote sustainability (DeFries et al., 2004; Wang et al., 2018). Improving and maintaining healthy ecosystems is essential to realizing social, economic, and sustainable development because the necessary materials and ecological services are provided by the ecosystems themselves (Rapport, 2011). Rational and effective assessments of regional ecosystem health can identify environmental or economic crises, and play a critical role in the management of ecosystems (Sun et al., 2016).

The term ecosystem health was coined in the 1980s. It refers to the stability and sustainability of ecosystems, including their ability to satisfy the requirements of human society and their capacity to self-regulate (Rapport et al., 1985; Lackey, 2001). Exploring better methods to quantify the interaction between ecosystems and human activities has been a long-term objective of sustainable development since the notion of 'ecosystem health analogous to a living organism' was advanced by Odum (Odum et al., 1979). In 1992, the World Health Organization developed the concept of 'Healthy Cities', which emphasized the relationships between the health of urban humanity and the environment, including natural systems, economic systems, and social systems (Liang et al., 2010). In other words, ecosystem health is akin to ecosystem sustainability (Wang et al., 2018).

The notion and research techniques for ecosystem health have evolved over time (Costanza, 2012). Many models have been developed to evaluate ecosystem health for different types of ecosystems, such as urban (Su et al., 2009), wetlands (Sun et al., 2016), forests (Xiao et al., 2004), marine (Xu et al., 2004), and farming ecosystems (Su et al., 2012). Hong et al. (2009) evaluated stream ecosystem health by using binary logistic regression, social accounting matrix and ecosystem condition data. Van Niekerk et al. (2013) evaluated estuary ecosystem health by integrating five indicators associated with ecosystem response and pressure. Peng et al. (2015) used ecosystem health dimensions related to ecosystem vigor, organization, and resilience and added ecosystem services to assess urban ecosystem health. The ideal approach is through the use of integrated research at both the micro and macro levels (Ma et al., 2001). Commonly used methods are indicator taxa (Ogden et al., 2014; Colin et al., 2015) and indices (Bai and Tang, 2010; Sun et al., 2016). The pressure-state-response (PSR) model commonly used in ecosystem health evaluation is a multivariable approach. It focuses not only on the property of ecosystem health but also on the interactions between natural property and human attributes (Yu et al., 2013). The health status of an ecosystem can not be accurately obtained by a single-scale assessment alone (Palmer and Febria, 2012). Currently, single, regional, and global ecosystems are the major scales used in ecosystem health assessments at the macroscopic level (Yan et al., 2016). Although the studies and methods discussed above are of significance in ecosystem health assessment, there are still limitations in their application to some areas where human activities are extensive. For example, at a global scale, developing countries, especially China (the world's largest developing country), have seen dramatic urbanization (Manzoor et al., 2019).

Ecosystem health and its evolution may vary regionally due to distinct natural environments and social development levels. The Hu line, proposed by Hu (1935), is a classical theory in Chinese geography. There are large differences in landform, population, and economy between the two sides of the line (Hu, 1935; Tien, 1981; Li et al., 2009). Yunnan and Sichuan provinces, located at the southern end of the Hu line, are the first and second terrain transition zones of China. The region is a hotspot for economic development, which fully reflects the complex process of coupling nature and humanity and presents an extremely distinctive social development and ecological effect mechanism (Pan et al., 2012; Lu et al., 2016). Regional differences in ecosystem health evolution are rarely discussed, especially in areas where social development varies widely, such as the areas on both sides of the Hu line.

A healthy ecosystem consists of steady internal structures and processes, and maintains its functions at large spatiotemporal scales (Yan et al., 2016). In this study, we evaluated ecosystem health at a city level in two provinces in southwest China from 2000 to 2016 by analyzing the pressures, state, and responses. Further, the spatial evolution of the region's ecosystem health from 2000 to 2016 was analyzed, and the key mechanisms determining these spatial patterns were expounded. Results from this study may help formulate a reasonable ecological and environmental protection policy, and provide scientific supports for regional planning and ecosystem management in mountain areas.

2 Materials and Methods

2.1 Study area

Our study area was located at 97°21′E–108°33′E and 21°08′N–34°19′N (Fig. 1) and covered an area of 0.88 million km^2 including two adjacent provinces, Sichuan and Yunnan (consisting 37 city-level administrative units). Sichuan and Yunnan provinces both have complex topography with mountainous areas and abundant biological resources; they also often experience geological disasters (Liu et al., 2016; Peng et al., 2016). This area has not undergone the same rapid process of urbanization as China's eastern part. Sichuan and Yunnan have lagged economically and are subject to slow but notable land-use changes (Yang, 2003; Peng et al., 2008). A large proportion of the Hengduan Mountain Range, which is an important ecological area in China, is located in Sichuan and Yunnan and has been designated as a global biodiversity hotspot (Olson and Dinerstein, 2002; Peng et al., 2019). The highlands and mountains, with average altitudes of 4000 m, are in the northwest and the low basin is in the east with natural and socioeconomic differences between the mountains, highlands, and plains area. The study area has a subtropical monsoon climate with a mean annual precipitation of 1033.7 mm and annual mean temperature of 16.7℃.

2.2 Building assessment framework for regional ecosystem health

The pressure-state-respons model is widely used to simulate the human-environment system, comprising a feedback system of pressures, states, and responses (Burkhard and Müller, 2008). It can provide quantitative or qualitative illustrations of relationships that link environmental and

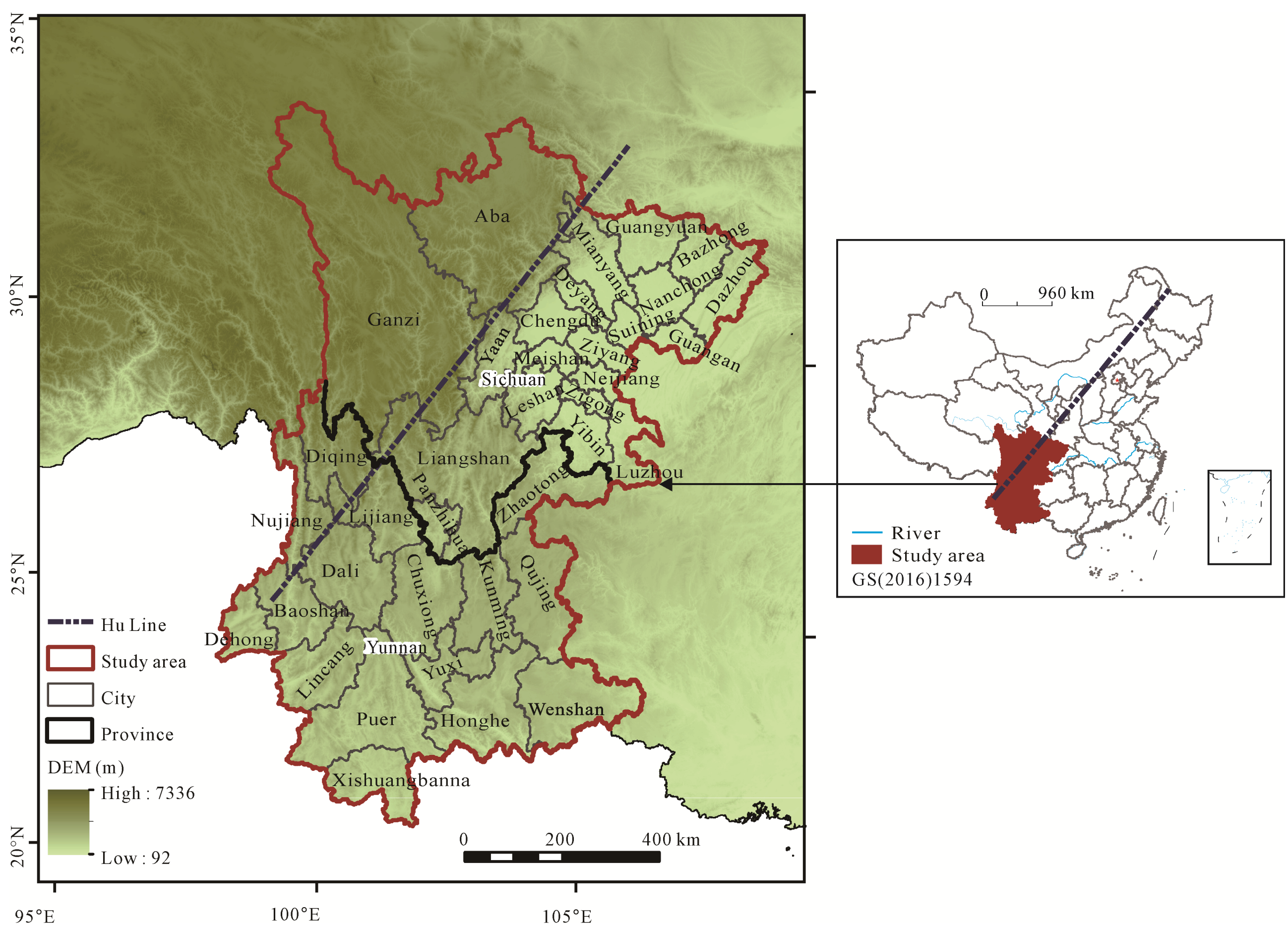

Fig. 1 Location of the study area, Sichuan and Yunnan of China

socioeconomic factors (Sun et al., 2016). The process conducted in this study, 'building an assessment system—assessing regional ecosystem health—examining the spatial evolution pattern—making proposal for key region management', is shown in Fig. 2.

Human activities and excessive resource consumption generate pressures on the environment that can change the quality and quantity of natural resources. Human responses to these changes include organized behaviors such as the implementation of economic and environmental policies to restore or ameliorate environment health, and alleviate or prevent environmental degradation. There are a number of studies of PSR model indices (Bai and Tang, 2010; Liang et al., 2010; Yang et al., 2010; Ye et al., 2011; Yu et al., 2013; Sun et al., 2016). Relevant studies and principles were used to determine the indicator system for this study, and the PSR indicator system applied to the study area is shown in Table 1.

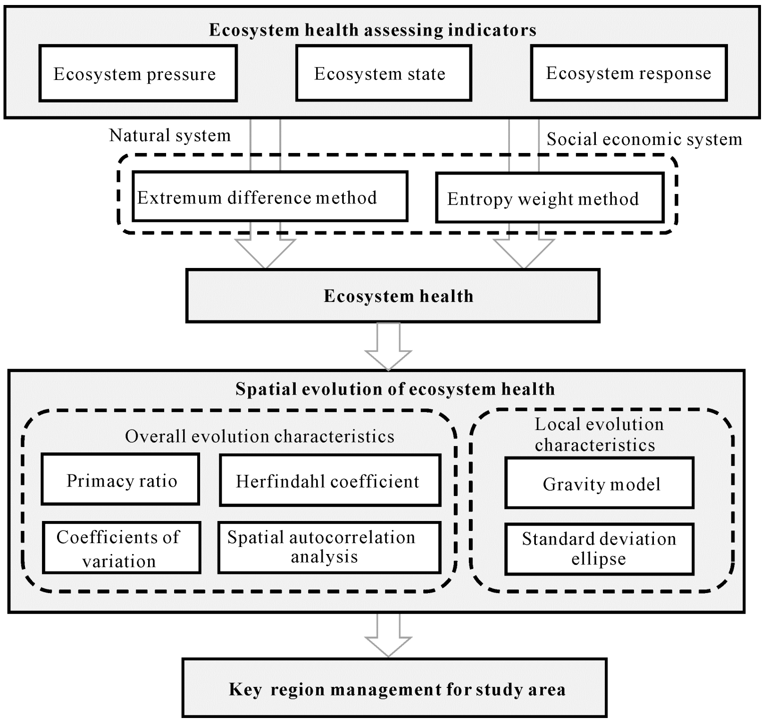

Fig. 2 Flowchart of the health assessment framework for Sichuan and Yunnan

Table 1 Indicator system used to evaluate regional ecosystem health in Sichuan and Yunnan provinces, China

Criterion	Factor	Index	Units
Pressure	Agriculture	Planting area of crops	10^3 ha
		Fertilizer application amount	10^4 t
	Population	Population density	person/km^2
		Natural population growth rate	%
	Climate	Percentage of temperature anomaly	%
		Percentage of precipitation anomaly	%
State	Agriculture	Total output values for agriculture, forestry, animal husbandry, and fisheries	10^4 yuan (RMB)
		Grain yield per unit of cultivated land	t/ha
	Economy	Per capita GDP	yuan/person
		Rural per capita net income	yuan/person
	Ecology	NDVI	
Response	Agriculture	Irrigation area	10^3 ha
		Total power of agricultural machinery	10^4 kW
	Society	Per capita investment in fixed assets	10^4 yuan
		Per capita local government expenditures	10^4 yuan
		Total mileage of highway	km
		Tertiary industry proportion	%

Notes: GDP is gross domestic product, NDVI is normalized difference vegetation index

2.2.1 *Pressure*

Ecosystem health pressures often originate from the combined action of nature and humans. We summarized the pressure indicators into three factors: agriculture, population, and climate. Our study area has a complex topography and limited land resources, with over 90% mountain cover (Peng et al., 2018). The southeastern part of the Tibetan Plateau is located in the study area, which has a fragile environment that is sensitive to climate change (Zhang et al., 2017). Continuous drought also occurs in many places in Yunnan Province. The percentage of precipitation anomaly is commonly used to assess drought events (Yang and Wu, 2010).

After the liberation of New China, the population of the study area nearly doubled, and the permanent population exceeded 130 million in 2016. The study area has the only major grain producing area in the west of China. However, regional differences in land use are very obvious, and cultivated land is distributed centrally in plains or hilly areas. Farmland has been shrinking for various reasons since 1957 (Liu, 2010). In 2013, the per capita cultivated land area of 12 cities, such as Panzhihua, Chengdu, Guangan, and Luzhou, was lower than the average level of Sichuan Province (0.0483 ha/person), and even lower than the critical level issued by the United Nations (per capita cultivated land should be no less than 0.053 ha). Food supplies require continuous soil fertilization, however, the application of chemical fertilizers can cause environmental pollution and soil nutrient imbalance, such as an increase in heavy metals and toxic elements, decrease in soil microbial activity, and soil acidification. To reflect these factors, this study used the planting area of crops, fertilizer application amount, population density, natural population growth rate, percentage of temperature anomaly, and percentage of precipitation anomaly as pressure indicators.

2.2.2 *State*

Ecosystem function and natural environmental status can be described by agricultural production, economic situation, and ecological condition indicators. Agriculture is the most important industry for human survival and development and, globally, the development of agriculture is regarded as an important measure of human well-being and economic prosperity. Therefore, agricultural state, such as total output values for agriculture, forestry, animal husbandry, and fisheries and grain yield per unit of cultivated land, were selected as assessment indicators. Economic state was reflected in the use of per capita GDP and rural per capita net income as assessment indicators. The use of natural resources through social and economic activities can, to a certain extent, improve people's quality of life, increase awareness of environmental protection, and promote coordinated human and land development. Land resource vitality is an important indicator for measuring ecosystem activity and primary productivity (Hong et al., 2015). Healthy ecosystems are more resilient to adverse impacts, such as natural disasters or disturbance from excessive human activities. For example, healthy forests can regulate climate, conserve water sources, and preserve water and soil. In general, the higher the vegetation coverage (the normalized difference vegetation index; NDVI), the better the quality of the regional environment and the ability of the ecosystem to self-regulate.

2.2.3 *Response*

Societal responses to pressures can adjust a system's state and often reflect the degree of social concern about environmental change. For instance, local government expenditure is a crucial means for governments to coordinate regional economic development. In this study, irrigation area, total power of agricultural machinery, per capita investment in fixed assets of the whole society, per capita local government budget expenditures, total mileage of highway, and tertiary industry proportion were selected from agricultural and social responses to measure the responsiveness of the ecosystem.

2.2.4 *Comprehensive assessment*

The selection and classification of indicators took into account the natural and social attributes of the study area and drew on previous research. Positive indicators indicate the scores of ecosystem health improving when indicators values increase; negative denote the score of ecosystem health declining when indicators values increase. In the model, pressure factors were negative indicators, except for the planting area of crops. All state and response factors were positive indicators. Each index was normalized using the extremum difference method (Jin et al., 2015). A weighting for each parameter was determined using the entropy weight method (Sun et al., 2019). And the weight of each index is shown in Table 2.

Table 2 Information entropy and entropy weight of each index for Sichuan and Yunnan provinces, China

Index	Information entropy	Entropy weight
Planting area of crops	0.99797	0.316
Fertilizer application amount	0.99919	0.126
Population density	0.99868	0.205
Natural population growth rate	0.99883	0.181
Percentage of temperature anomaly	0.99964	0.055
Percentage of precipitation anomaly	0.99925	0.116
Total output values for agriculture, forestry, animal husbandry, and fisheries	0.99856	0.196
Grain yield per unit of cultivated land	0.99834	0.226
Per capita GDP	0.99855	0.198
Rural per capita net income	0.99832	0.228
Normalized Difference Vegetation Index (NDVI)	0.99889	0.152
Irrigation area	0.99917	0.107
Total power of agricultural machinery	0.99810	0.245
Per capita investment in fixed assets	0.99851	0.193
Per capita local government expenditures	0.99865	0.174
Total mileage of highway	0.99852	0.191
Tertiary industry proportion	0.99931	0.089

The composite value of regional ecosystem health (H) was calculated using the following formula:

$$H = \left| \sqrt{\frac{\sum_{i=1}^{3} C_i^2}{3}} \right| \quad (1)$$

$$C_i = \left| \sqrt{\sum_{j=1}^{k_i} \left(W_{ij} R_{ij} \right)^2} \right| \quad (2)$$

where C_i is the value of the three criteria i (pressure, state, and response), k_i is the number of assessment indicators in criterion i, W_{ij} is the weight of indicator j in criterion i, R_{ij} is the normalized value of indicator j in criterion i, and factor H is the comprehensive regional ecosystem health score. The higher the scores of all criteria, the healthier the ecosystem. For example, the higher the stress score, the less pressure the ecosystem is facing.

2.3 Data compilation

Relevant data from Sichuan (Sichuan Provincial Bureau of Statistics, 2000–2016), Yunnan (Yunnan Provincial Bureau of Statistics, 2001–2017), and regional economy (National Bureau of Statistics, 2001–2014) statistical yearbooks were collected, including societal, economic, agricultural, and ecological data and an ecosystem health assessment at the city level for the period 2000 to 2016 was performed. Some data were supplemented by the China Statistical Yearbooks (National Bureau of Statistics, 2015–2017) at a county level, and regression equations were used to revise and calculate any partial anomalies or missed data (0.92%). Meteorological data (temperature and precipitation) were downloaded from the China Meteorological Administration. These data were collected from 177 meteorological observatories around, and within, the Sichuan and Yunnan region (China Meteorological Data Sharing Service System, available online: http://data.cma.cn/). The meteorological data were interpolated at 5 km × 5 km resolution via the kriging method, and an average for each region was calculated in ArcGIS (v. 10.4). Averages were then corrected using yearbook data for cities or years that were missing. The NDVI data were compiled from moderate resolution imaging spectroradiometer (MODIS) imagery. To lower the impacts of atmospheric scan angle and cloud contamination, the maximum value composite method was used to compile the monthly NDVI dataset. MODIS data were obtained from the national aeronautics and space administration (NASA) website (http://modis.gsfc.nasa.gov).

2.4 Analysis of overall evolution characteristics

To analyze overall ecosystem health in the Sichuan and Yunnan Provinces from 2000 to 2016, the coefficient of variation, primacy ratio, Herfindahl coefficient, and spatial autocorrelation analysis (Jin et al., 2007; Getis and Ord, 2010; Fang et al., 2013; Zhou et al., 2017) were employed in this study. These models reveal the degree of equilibrium, distribution, degree of agglomeration, and spatial autocorrelation trends of regional ecosystem health, respectively. The coefficient of variation reflects the equilibrium of the whole region, and the smaller the value, the more balanced the region. The primacy ratio reflects the distribution of ecosystem health in prefecture-level cities, calculated by dividing the highest health score by the second highest health score. The Herfindahl coefficient reflects the degree of agglomeration of healthy regions; the larger the value, the more concentrated they are. Global Moran's Index was used to examine the spatial autocorrelation of ecosystem health across the whole research area. Global Moran's I values greater than 0 indicate that regional ecosystem health shows positive spatial autocorrelation; the smaller the value, the stronger the spatial dispersion of the observed values. The calculations were as follows:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{kl}\left(x_k - \bar{x}\right)\left(x_l - \bar{x}\right)}{S^2 \sum_{k=1}^{n}\sum_{l=1}^{n} W_{kl}} \tag{3}$$

$$S = \frac{1}{n}\sum_{k=1}^{n}\left(x_k - \bar{x}\right)^2 \tag{4}$$

where n is the number of regions; x_k and x_l are the health scores (pressure, state, or response scores) for regions k and l respectively; $\bar{x}$ is the average health score for all regions; S is a temporary or intermediate value to calculate Global Moran's I; W is the spatial weight matrix (if k and l are adjacent, then $W = 1$, otherwise, $W = 0$). At the same time, the global Moran's Index was tested for significance:

$$Z(I) = \frac{\left[I - E(I)\right]}{\sqrt{Var(I)}} \tag{5}$$

where $E(I)$ is the expected value of I and $Var(I)$ is the variance of I. At the 0.05 confidence level, $|Z| \geq 1.96$ indicates significant spatial autocorrelation.

2.5 Analysis of local evolution characteristics

The gravity center model enables exploration of the spatial and temporal migrations of ecological or social factors by examining the trajectory of their gravity center (Xiong et al., 2019). The concept of a gravity center originated from physics and the gravity model was used to reveal the migration process of ecosystem health in space (Zhou et al., 2017). Suppose that a large area consists of n small areas, and (X_k, Y_k) is the center coordinate of the small area k, and H_k is an attribute value of the area k, then

$$\bar{X} = \frac{\sum_{k=1}^{n} H_k \times X_k}{\sum_{k=1}^{n} H_k}, \bar{Y} = \frac{\sum_{k=1}^{n} H_k \times Y_k}{\sum_{k=1}^{n} H_k} \tag{6}$$

For a long time, standard deviation ellipse has been used as a general geographic information system tool for measuring bivariate distributed characteristics. If the health condition of each region is represented by a point in space, this tool can be used to determine the trend and direction. The standard deviation ellipse is composed of three elements: the rotation angle, the standard deviation along the long axis, and the standard deviation along the short axis. The long axis of the ellipse dominates the direction of spatial distribution, and the short axis is the direction with no recognition of spatial distribution. The standard deviation ellipse can reflect the spatial distribution of regional ecosystem health identifying the central position change and direction of movement.

3 Results

3.1 Overall features of regional ecosystem health

First, we observed the overall trends of ecosystem health at the city level in Sichuan and Yunnan from 2000 to 2016 (Figs. 3 and 4). In 2000, the health score was 0.710 increasing to 0.780 in 2016 ($Y = 0.0045X - 8.2742$, $R^2 = 0.96$, $P < 0.001$) (Fig. 3). The pressure scores showed a fluctuating trend but overall they gradually increased from 2005 ($Y = 0.0008X - 0.9234$, $R^2 = 0.70$, $P < 0.001$). State and response values in the study area increased rapidly, with slopes of 0.009 ($Y = 0.0089X - 0.1728$, $R^2 = 0.92$, $P < 0.001$) and 0.009 ($Y = 0.0089X - 17.3413$, $R^2 = 0.96$, $P < 0.001$) per year, respectively.

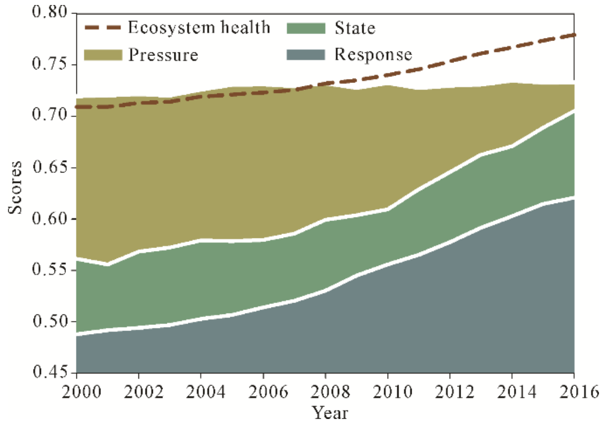

Fig. 3 Comprehensive evaluation of ecosystem health across the study area from 2000 to 2016

Fig. 4 shows that the primacy ratio (after 2004), variation coefficient (after 2007), and the Herfindahl coefficient (after 2007) of ecosystem health revealed rapidly increasing trends in Sichuan and Yunnan; these three values had shown decreasing trends in the previous years (before 2004 or 2007). The *Z* value and *P* value of Moran's Index were less than 1.96 and greater than 0.05, respectively, indicating a random distribution of regional health in space. A dispersed distribution (Fig. 4d) was seen before 2005 ($Z > 1.96$, $P < 0.05$).

3.2 Spatiotemporal pattern evolution of regional ecosystem health

3.2.1 Spatiotemporal pattern evolution

The pressure scores, state scores, response scores, and health scores for each region were calculated and the natural breaks method was used to divide the results into four categories. The spatial distribution of pressure scores over the study area shows higher scores on the east side of the Hu line than that on the west side in Fig. 5a. The highest pressure scores (minimum pressure) emerged in Mianyang City, Nanchong City, Dazhou City, and Yi Autonomous Prefecture of Liangshan in Sichuan Province, and Qujing City and Zhuang-Miao Autonomous Prefecture of Wenshan in Yunnan Province. A negative slope for pressure was found in the Sichuan Basin, while the slope in Yunnan was positive. The state scores on the east side of the Hu line were generally higher than those on the west side (Fig. 5b); the change rate (slope) of state scores is similar to this. There were no visible spatial distribution characteristics in the response scores, and the high values were mainly distributed in Chengdu City, Kunming City and surrounding areas (Fig. 5c). The slope of response scores of regions in Sichuan were higher than those of Yunnan. In

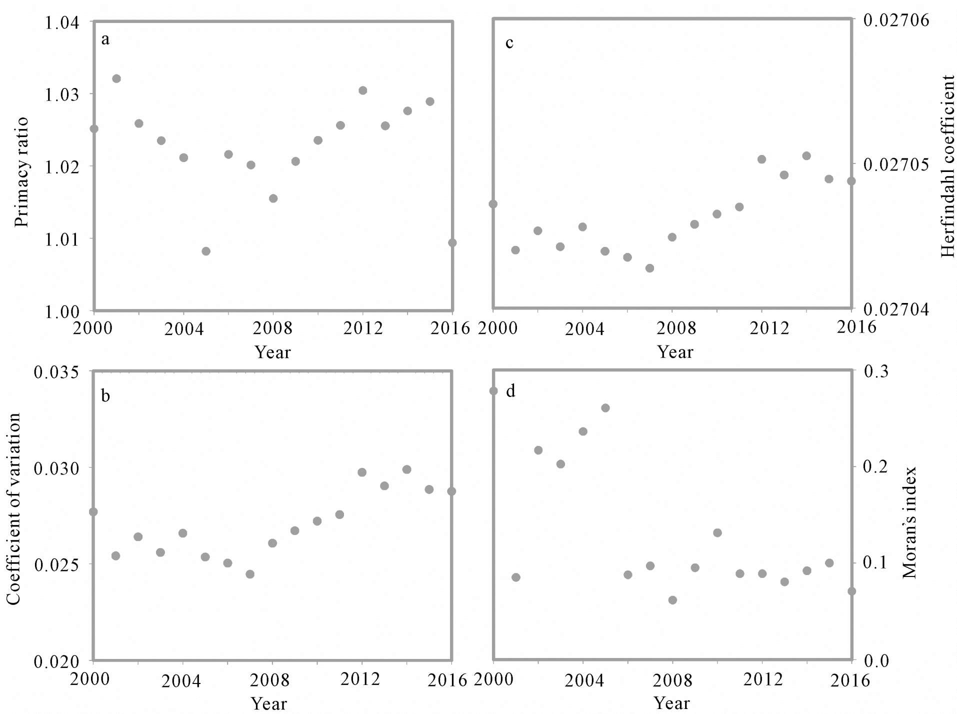

Fig. 4 Overall spatial characteristics of ecosystem health across the study area from 2000 to 2016

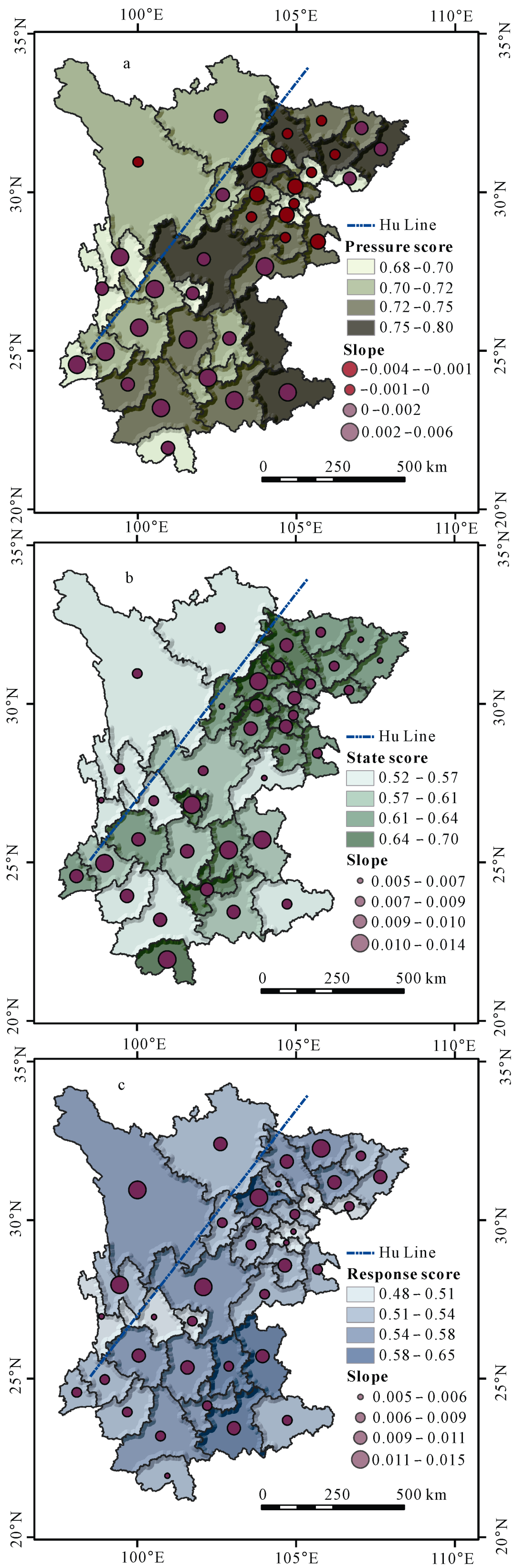

Fig. 5 Regional ecosystem pressure (a), state (b), and response (c) scores and their rate of change (slope) in Sichuan and Yunnan provinces

2000, nearly half of all the regions in the study area were in an unhealthy condition (Fig. 6a). The regions on the west side of the Hu line were in a morbid health condition. The healthiest regions were Chengdu, Deyang, Mianyang, Nanchong, and Dazhou in the Sichuan Basin. In 2016, the number of unhealthy regions dropped to one third (Fig. 6b). The regions on the west side of the Hu line had improved but were still unhealthy, especially Lijiang City and Lisu Autonomous Prefecture of Nujiang.

The pressure, state, and response scores, and health scores of regions on either side of the Hu line differed (Fig. 7). From 2000 to 2016, the difference in the state scores ($Y = 0.0010X + 0.0494$, $R^2 = 0.53$) between the two sides increased continuously. However, the gap between the pressure scores ($Y = –0.0008X + 0.0341$, $R^2 = 0.44$), response scores, and ecosystem health scores ($Y = –0.0004X + 0.6325$, $R^2 = 0.38$) declined.

3.2.2 Local spatial evolution characteristics

The gravity center of regional ecosystem health in the study area was located in the eastern part of the Yi Autonomous Prefecture of Liangshan, and moved 6.65 km to the southwest over the study period (Fig. 8). The gravity center of the pressure scores moved 11.13 km to the southwest along the direction of the Hu line; from 2000 to 2007, the mobile distance reached 8.65 km, which was much greater than for other years. The gravity center of the response scores moved 0.38 km along the direction of the Hu line. The gravity center of the comprehensive ecosystem health scores, including pressure and state scores, moved only slightly in a perpendicular direction to the Hu line.

Fig. 8 shows that the standard deviation ellipse of each year is centered on the center of gravity of that year which is in the middle of the study area, slightly to the east. Standard deviation ellipses varied little and were in a central location in the two provincial capitals of Sichuan (Chengdu) and Yunnan (Kunming).

4 Discussion

4.1 Dynamics of regional ecosystem health

Many human-dominated regional and global ecosystems are under considerable stress (Vitousek, 2008) and it can, therefore, be difficult to acquire benign pressure scores. From 2000 to 2016, the pressure scores of regional ecosystems in the study area experienced

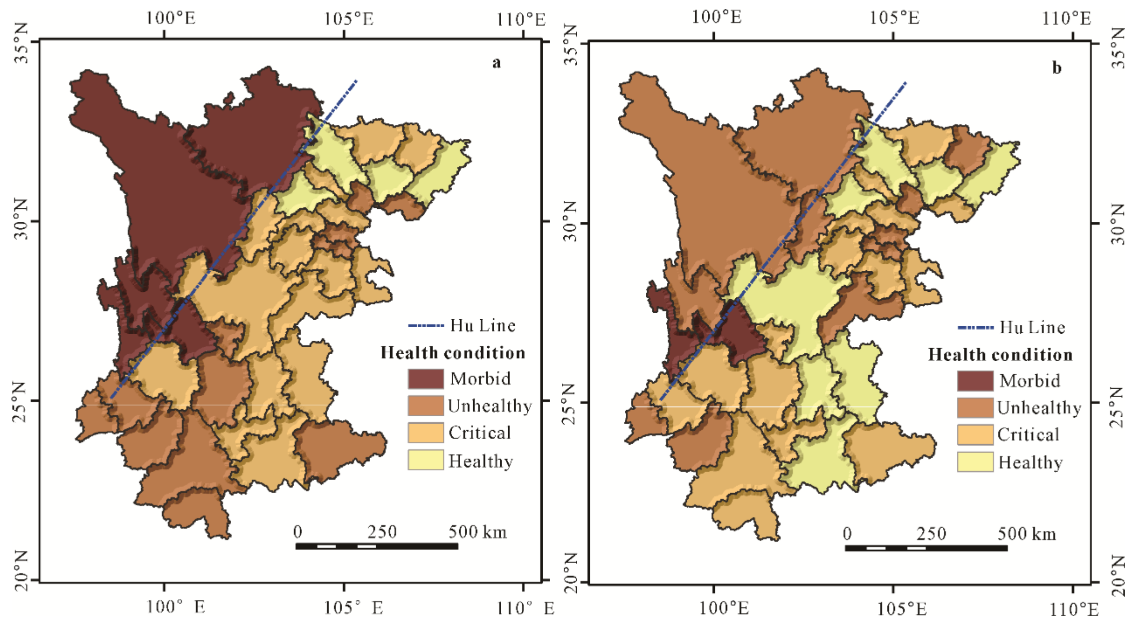

Fig. 6 Comprehensive ecosystem health in 2000 (a) and 2016 (b) in Sichuan and Yunnan provinces

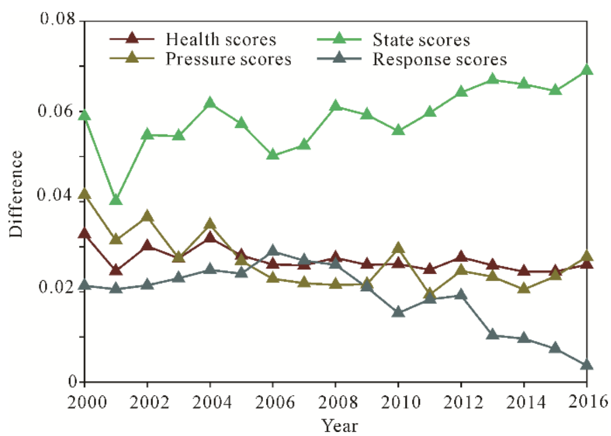

Fig. 7 Difference in ecosystem health between regions on the east and west sides of the Hu line from 2000 to 2016

extremely slow growth (Fig. 3). Development of the West Region began in 2000 through a large investment of state capital. Both state scores and response scores showed significant progress from that point, both of which are very sensitive to administrative polices as macroscopic development is regulated and controlled by the state (Tang et al., 2017). Consequently, the comprehensive health scores in Sichuan and Yunnan increased gradually even though the pressure scores were not high. Figs. 4a, 4b and 4c reveal that the degree of imbalance in regional development has been reinforced over time, and the regions with the highest health scores have expanded their relative advantages since 2006; Moran's index of comprehensive health scores (Fig. 4d) shows that spatial distribution has become more random in the study area since this time. Due to its prosperity, the Chengdu economic circle region has taken the lead in achieving rapid economic development by taking advantage of historic opportunities (Deng and Zhang, 2010). The economic growth of mountain areas, involving traditional industries, was largely dependent on the exploitation and utilization of resources (Wang et al., 2009). Those regions with rapid economic development were under huge pressure, resulting in an increase in the balance of regional health in the study area before 2006. Moran's index indicated that more and more regions became well developed, but still not as developed as the core region, and thus failed to reduce regional imbalances.

The pressure, state, response, and comprehensive health scores showed that regions on the east side of the Hu line were better off than those on the west (Figs. 5 and 6). The unique topography and weather on the left side result in a harsh and fragile natural environment (Zhang et al., 2017). The arable land resources on the west side of Hu line are scarce, which has a fragile environment that is and sensitive to climate change. The ecosystem here is inherently under enormous demographic and climate change pressures. Meanwhile, land fertility is insufficient, productivity is low, vegetation status is

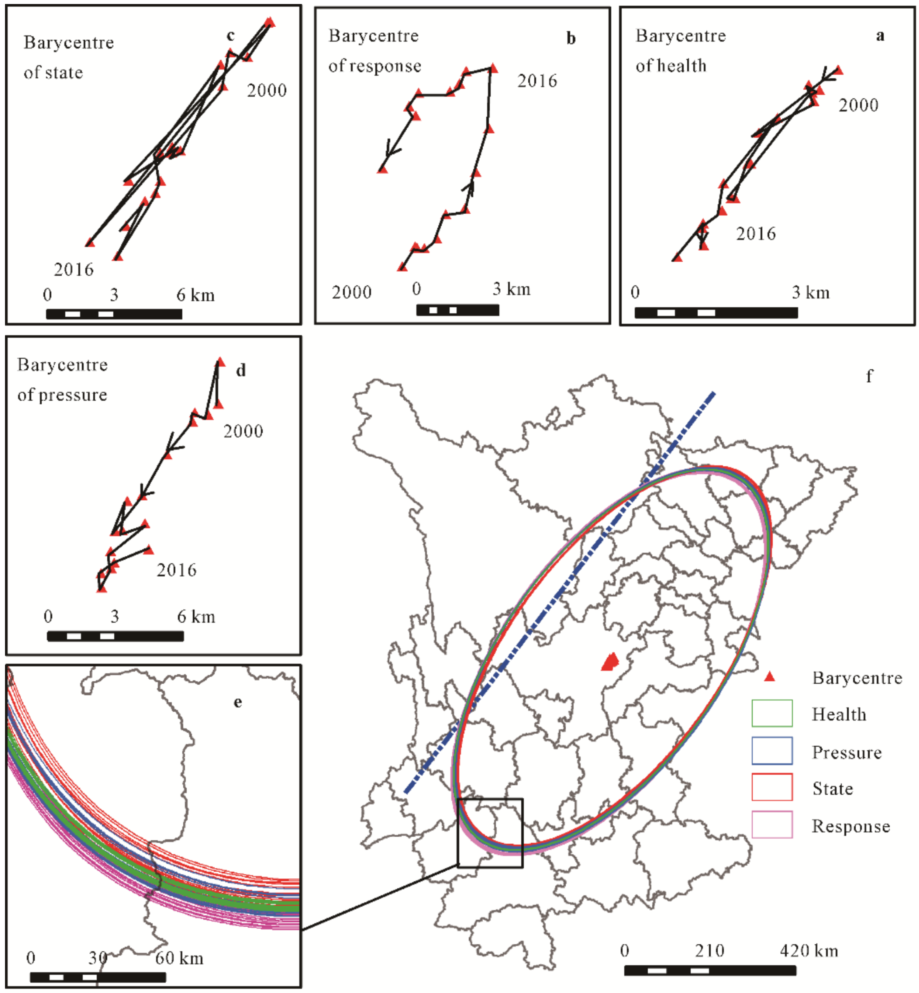

Fig. 8 Moving track of the gravity centers and standard deviation ellipse of ecosystem health from 2000 to 2016

poor, agricultural output value and GDP are far lower than the eastern region of Hu line (Deng and Bai, 2014). These natural determinants are the main reasons for the poor pressure and state scores. The excellent natural conditions in the Sichuan Basin are more suitable for social and economic development, but areas in that region have also faced challenges, including intensive reclamation of farmland, over-exploitation of resources, water pollution, and habitat destruction. Consequently, pressure scores in these areas decreased (Fig. 5a). Response scores were mainly influenced by anthropogenic determinants, dominated by the degree of society response and concerns about environmental changes (Yu et al., 2013). Some core regions receive more policy support, which improved their response scores. The ecosystem health of most regions improved over time, but the situation in Lijiang appears to be very serious (Fig. 6). The evaluation at the county level also concluded that ecosystem health was deteriorating in most parts of the region (Peng et al., 2017). The gap in regional ecosystem response scores between the east and west side of the Hu line remained nearly constant over time (Fig. 7), suggesting that ecologically fragile areas are regions of concern (Zhang and Cai, 2010). A decreased gap in the pressure scores indicates that the area to the east of the Hu line may be developing too fast. The long-term existence of the Hu line depends on geographical conditions that can not change in the near future (Chen et al., 2016). Similarly, the barycenter and spatial patterns of ecosystem health can only move alongside the Hu line (Fig. 8). Unlike pressure and state, the gravity center of the response scores tended to move northwest. After Wenchuan Earthquake, the State Council implemented a plan arranging over a total of 31.8

billion dollars for reconstruction, and pairing poor localities with better-off regions of China to assist with recovery and development (Xin, 2012). Successive promulgation and implementation of the Development of the West Region, The Main Functional Area Planning, and National New Urbanization Plan have made the northwest of the study area to be valued by the society and supported by the national policy (Deng and Bai, 2014).

4.2 Suggestions and implications

As important ecological and resource-enriched areas in China, Yunnan and Sichuan provinces have high ecological value for soil and water conservation, water resource conservation, and biodiversity protection. Their ecosystem health is of great significance to the development of the western region and even the country as a whole. However, there is a huge disparity in population density and GDP between the southeast and northwest regions of China. In 2014, Premier Li Keqiang questioned whether the Hu line can be broken (http://www.gov.cn/guowuyuan/2014-11/28/content_2784332.htm). Simultaneously, the National New Urbanization Plan (2014–2020) was promulgated. New urbanization in mountain areas is an important driving force for adjusting the distribution of the Hu line. A key questions is how to apply sustainable development in Sichuan and Yunnan and areas on both sides of the Hu line. To design an 'ecological development model' suitable for Sichuan and Yunnan, it is essential to establish links between physiographic condition and economic development and seek the best development path for each region. According to the results of this ecosystem health assessment and temporal and spatial changes in the study area, three key management regions were identified (Fig. 9).

Region I is provincial capitals (Chengdu in Sichuan Province and Kunming in Yunnan Province) and surrounding areas, which should maintain its current ecosystem health. At present, this region has the best ecosystem health in Yunnan and Sichuan, which is mainly a benefit of its superior geography and the improvements in ecological state and ecological response scores. Under increasing pressure, it should restrict the speed of economic development. Emissions of polluting gases within the basin should be reduced, especially in winter. Meanwhile, this area should strengthen cooperation and provide assistance to the west side of the Hu line and surrounding areas of slower development.

Region II is the area on the west side of the Hu line with relatively harsh natural conditions. Agricultural resources in this region are inherently inadequate, and management should focus on reversing the deterioration of ecosystem health as a result of the over-harvesting of forest resources and overgrazing of grassland. Connections between financial assistance and economic development must be established to increase self-sufficiency. Simultaneously, more investment should be made in tertiary industry, especially tourism, which can be environmentally friendly and sustainable. Relying on the unique cultural advantages of the plateau, the industrial structure should be further transformed and upgraded to a public service type, and ecological tourism and professional services should be developed.

Region III includes Lijiang and Diqing (Shangri-La) in Yunnan Province, areas where tourism is over-developed. The exploitation of tourism resources beyond the ecological carrying capacity cause environmental pollution and ecological damage. The government and tourism administrative departments should attach greater importance to the tourism carrying capacity concept and the sustainable development of the tourism industry. On this basis, corresponding management laws and regulations should be formulated and promulgated to actively support, encourage, and guide visitors and residents to participate in the protection and management of the ecological environment.

Our study focused on the impact of nature and humanity on ecosystem health and its spatial evolution. In addition to the traditional evaluation framework reflecting ecosystem quality, such as pressure, state and response, health assessment is also related to biophysical processes and human ecological services. The ownership determination for each index of ecosystem pressure, ecosystem state and ecosystem response should be highlighted. The ownership of each index is clear and understandable, whereas related areas are prone to confusion, especially ecosystem state and ecosystem response. Future assessments of regional ecosystem health require an integrated system based on different information scales of ecology and biology that also take human health and cultural factors into account.

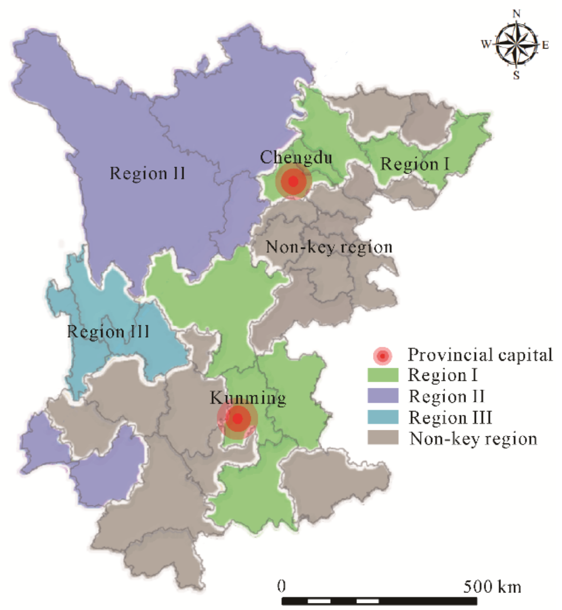

Fig. 9 Zoning of key management regions for Sichuan and Yunnan

5 Conclusions

Ecosystem health is needed to provide sustainable social and economic development and maintain ecosystem services. In this study, the PSR model was used to analyze the ecosystem health of Sichuan and Yunnan provinces in China from 2000 to 2016. Coefficients of variation, the primacy ratio, the Herfindahl coefficient, Moran's Index model, the gravity center model, and the standard deviation ellipse model were used to further analyze regional spatial and temporal patterns of ecosystem health.

The ecosystem health of most regions was improved over time and areas with poorer ecosystem health decreased from half to one-third of the total area, however it seems that the situation in Lijiang City, Yunan Province is very serious. In general, the gap in health scores between regions appears to be gradually expanding (as the primacy ratio and variation coefficient are increasing), but more high quality areas appeared over the study period (although the results of the Moran's index were not significant). The ecosystem pressure, state, response, and comprehensive health scores east of the Hu line were slightly better than those on west. The pressure and state scores of regional ecosystems are largely determined by physical geography, and response scores by policy and social concerns. Successive implementation of the Development of the West Region, The Main Functional Area Planning, and National New Urbanization Plan have made the northwest of the study area to be valued by the society and supported by the national policy. The long-term existence of the Hu line can not change in the near future and the move of the gravity center and spatial pattern of ecosystem health aligned with the direction of the Hu line.

Provincial capitals (Chengdu in Sichuan Province and Kunming in Yunnan Province) and surrounding areas, the area on the west side of the Hu line, and Lijiang and Diqing (Shangri-La) in Yunnan Province are three key management regions. All regions should strengthen cooperation and develop the characteristics and competitive industries, and better-off regions should provide assistance to the west side of the Hu line and surrounding areas of slower development. In the future, it is necessary to monitor the state and sources of risks in each key management area, as well as enforce timely regulation of probable sources of stress.

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