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Quantitative assessment of resources and environmental carrying capacity in the northwest temperate continental climate ecotope of China

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Abstract Quantitative assessment of resources and environmental carrying capacity (RECC) is a critical requirement of regional economic development. This paper proposes a new indicator assessment system for RECC that uses the ecological and environmental stress index model (ESI) and state-space method for analysis. A quantitative analysis of the northwest temperate continental climate ecotope of China was performed through a comprehensive evaluation of the present ecological carrying capacity (ECC), resources exploitation and pollution discharge conditions. Regional statistical data from 2010 were used to analyze the RECC distribution trend and explore the relationship between the ECC and socioeconomic pressure. Results indicated that the smallest ECC index was 0.0810, the ecological environment of the western and central parts of this region was particularly fragile. The highest socioeconomic pressure index was 0.0960, reflecting greater development pressure in the central areas. The approximate decoupling index (ADI) indicated that the influence of the ecosystem on RECC was small, within "relative decoupling". RECC and socioeconomic pressure were within "absolute hook", denoting RECC deteriorating faster than the economy grew. Development pressure from net primary productivity, population density, the energy consumption index and the water use index was significant. However, the study area is still developing, and different development strategies must be devised for different regions.

Introduction

The human population and the impacts of human activity on the biosphere continue to increase at an alarming rate, resulting in severe environmental degradation (Monte-Luna et al. 2004). Based on a modified modeling simulation that considered 30 years of data, Meadows concluded that the world had already reached a state of unsafe overloading (Meadows et al. 2004). Schneider defined the environmental carrying capacity as the ability of an ecosystem to sustain the human population without the natural or artificial environment system being severely degraded (Schneider et al. 1978). This topic has become an interdisciplinary academic frontier in the fields of ecology, agriculture, environmental science, and other correlated fields (Wang et al. 2014). In fact, the concept of carrying capacity originates from the field of ecology (Park and Burgess 1921). Subsequently, various concepts and theories of carrying capacity have been introduced to different development stages and resource conditions (Di et al. 2007; Qian et al. 2015; Yang et al. 2015; Zhong et al. 2011), and different research fields have proposed different meanings for the concept (Daily and Ehrlich 1996; Feng et al. 2008; Graefe et al. 1984; Peters et al. 2007; Seidl and Tisdell 1999; Taylor et al. 1990; Wetzel and Wetzel 1995). In 1991, resources and environmental carrying capacity (RECC) was first introduced to China by environmental

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scientists at Peking University in a report titled "The Fujian province Meizhou Bay development zone environmental planning comprehensive research" (Tang and Ye 1998). RECC is defined as the social and economic pressure that can be placed on ecological surroundings on the condition that the ecosystem can maintain a stable structure and complete function. Research performed by various Chinese scholars, such as Guo, has shown that dynamic land use changes impact the regional ecological carrying capacity (ECC) to some extent, and high correlations were obtained for some important indicators (such as natural resource exploitation), thus demonstrating the severe influence of human activities on ECC (Guo et al. 2007).

Methods of calculating carrying capacity have been improved since the end of the twentieth century. The most widely used model for ecological carrying capacity (ECC) is the ecological footprint model (Wackernagel et al. 1997), which has been widely used for the evaluation of regional sustainable development. Gong and Jin applied the fuzzy comprehensive evaluation method to analyze the carrying capacity of regional water resources, and predicted the dynamic trend of water resources capacity after the implementation of a policy (Gong and Jin 2009). Based on the connotation and mechanism of ECC of urban areas, scholars from South Korea developed a GIS-based urban carrying capacity assessment system by integrating seven factors identified beforehand, and evaluated an area in Seoul. The analysis demonstrated the pivotal role of planning and managing urban development (Oh et al. 2005). Although the factors included in this system were limited, this paper provided meaningful information as a quantitative analysis of ECC. Some studies focused on the sustainable development of the Haihe River Basin by considering the water-related carrying capacity assessment system, and found that the current rate of development is not sustainable (Wang et al. 2014). Liu proposed a comprehensive measurement system for the carrying capacity of the environment and calculated the environmental stress in Ningbo (Liu and Borthwick 2011). Such researches have yielded important insights, including shifts in the research: (1) from single studies on water resources or agricultural resources to comprehensive studies on multiple resource and environmental factors, including land resources, water resources, ecology and environmental factors (Li et al. 2008; Oh et al. 2005); (2) from simply considering one spatial or time scale to multi-scale evaluation (Wang et al. 2013); and (3) from considering only population factors to considering human influence factors as well.

However, all of the above researches lack particular quantitative assessment for carrying capacity, especially for RECC, they are also not comprehensive enough on indicators construction. In the last 15 years, western China increased the amount of development and thus led to serious development-related issues. The northwest temperate continental climate ecotope is a typical ecological region of western China. This paper proposed an ecology-based comprehensive quantitative evaluation index system for RECC based on spot investigation and statistical analysis. The feasibility and applicability of regional RECC assessment is then discussed and analyzed, and the relationship between economic development and the sustained capability of ecological systems is explored. In contrast to previous research, the present paper provides a comprehensive and elaborate process for the construction of indicators and focuses on a quantitative description of RECC before proposing feasible countermeasures and suggestions for sustainable development.

Methodology

The RECC evaluation system should be constructed according to the habitat conditions. The indicator system in Table 1 was developed by taking into account the extensive forest and grassland in this region; regional development features and field survey information; and the availability of data. By employing the system analysis method (Zhang 2000), the carrying capacity was divided into two components: the ECC and the socioeconomic pressure index (SEPI). The former comprises 11 natural ecological factors, and the latter comprises nine social ecological-related indices. Values of the 20 indices were calculated from their normalized value and standard value; values equaled the normalized value divided by the standard value. Here, the standard value is indicated by the red line (see "Resource and environment carrying capacity assessment" for more information). All indices are above 0, but without an upper limit value. Since Xu and colleagues first proposed the eco-ESI in 2004 (Xu et al. 2004), the environmental stress index (ESI) has been widely used for ecology-related assessment. Based on ESI theory, the ECC, SEPI and RECC values were first obtained, and then the main control factors analyzed to determine the impact factors. Here, the SEPI is similar to ESI; indeed, SEPI has the same computing method as ESI. The approximate decoupling index (ADI) defined in this paper is a description of the development relationship of each sub-index with the upper layer index, and actually is the same as the decoupling index (DI) (Wang 2010). The value between 0 and 1 is known as relative decoupling, which means that the sub-index shows little influence on the integrated index.

Evaluation of the main indices

Landscape fragmentation index

The landscape fragmentation index describes the degree of discontinuity and structural complexity of the landscape. It

Table 1 Evaluation index of RECC of northwest temperate continental climate ecotope in China

Target layer	Target layer	Criteria layer	Index layer	Unit	Remark
Resource and environment carrying capacity	Ecological carrying capacity	Natural driving factors	Annual average temperature	°C	China Meteorological Administration. China Meteorological Data Sharing Service System (CMA, 2010)
			Precipitation	mm	China Meteorological Administration. China Meteorological Data Sharing Service System
			Mean altitude	m	Data center of resources and environment science, Chinese Academy of Sciences
		Ecological structure factors	Landscape fragmentation index		Fragstats 3.3 & ArcGIS
			Vegetation coverage	%	More details in following content
			Biological abundance		More details in following content
			Leaf area index		Sum up according to the area ratio of the i-th biome to land cover type in the given region
		Ecological function factors	Net primary productivity	$g\ a^{-1}\ m^{-2}$	Miami Model
			Water retention capacity	$m^3\ a^{-1}$	More details in following content
			Carbon sequestration and oxygen release ability	$kg\ a^{-1}$	More details in following content
			Soil erosion degree		From Model Builder of ArcGIS
	Social and economic pressure	Resource and energy consumption indices	Population density	10^4 persopns km^{-2}	Total population divided by total area
			Energy consumption index	$10^4\ t\ km^{-2}$	Standard coal amount of electricity, gas and coal. If data is not available, it is transferred from GDP
			Water using index	$10^4\ t\ km^{-2}$	Total water consumption divided by total area
			Urbanization rate	%	Nonagricultural population divided by total population
			Cultivated area per capita	$km^2\ person^{-1}$	Cultivated land divided by total population
			Tourism pressure index	person km^{-2}	The county tourists number divided by county area
		Environmental pollution pressure indices	Usage of chemical fertilizer per unit area of farmland	$t\ km^{-2}$	Total agricultural fertilizer application divided by arable land area
			Domestic sewage discharge per unit area	$10^4\ t\ km^{-2}$	When there is no statistical data, it was calculated from the proportion of population
			Industrial three-wastes emissions per unit area	$10^4\ t\ km^{-2}$	The sum of emissions per unit area of waste water, waste gas and solid waste of industry. The waste gas was converted into million tons by atmospheric density

is highly correlated with the degree of natural resources exploitation and is, thus, mainly influenced by human activities. A high fragmentation index value typically indicates excessive human intervention. The value ranges from 0 to 1, where 1 refers to complete discontinuity. This index can be obtained by SPSS, PANS, Excel and Fragstats (Fu 2010). Fragstats is superior to the former tools in many ways. For example, it can provide a more professional calculation model and better data compatibility. Since it was first developed by the Forest Science Department of

Oregon State University (USA), it has shown high operational efficiency and has been adopted by many scholars worldwide. Fragstats 3.3 (Neel et al. 2004) was used to perform the index analysis here.

Vegetation coverage

Vegetation-related indices can be conveniently estimated using remote sensing (RS) technology and geographic information systems (GIS). The normalized difference vegetation index (NDVI), in combination with spectral mixture analysis (SMA), is the most widely used model in linear mixing models. This approach assumes that the pixel is only composed of vegetation and bare soil (Xiao and Moody 2005). Because this topic is not the main focus of this paper, only the basic equation is provided below; for further details, please refer to Xiao and Moody (2005).

$$NDVI = f_c \times NDVI_{veg} + (1 - f_c) \times NDVI_{soil} \quad (1)$$

This equation can also be expressed as:

$$f_c = (NDVI - NDVI_{soil})/(NDVI_{veg} - NDVI_{soil}) \quad (2)$$

where $NDVI_{veg}$ refers to the NDVI value of a pure green vegetation pixel and $NDVI_{soil}$ is the NDVI value of bare soil. $NDVI_{veg}$ and $NDVI_{soil}$ were estimated by assuming that green vegetation and bare soil had 100 and 0 % vegetation coverage, respectively.

Biological abundance

In this study, the biological abundance index (BAI) was based on the calculation method from the technical criterion for ecosystem status evaluation published by the Ministry of Environmental Protection of the People's Republic of China (CESP 2015).

$$BAI = (BI + HQ)/2 \quad (3)$$

$$HQ = A_{bio} \times (0.35 \times A_1 + 0.21 \times A_2 + 0.28 \times A_3 + 0.11 \\ \times A_4 + 0.04 \times A_5 + 0.01 \times A_6)/A \quad (4)$$

The biodiversity index (BI) refers to HJ 623-2011 (CESP 2011), and HQ denotes the habitat quality index. Equation (4) was the method mentioned in HJ 192-2015 (CESP 2015) to get this value, where A_{bio} stands for normalized habitat quality index coefficient, and the reference value was 511.26. A_1 to A_6 denote the area of forest, grass, wetland, cultivated land, construction land and unused land; A is the total area for the target zone. The weights of different kinds of habitat quality are provided in Table 2. When the biological diversity index lacks dynamic data updates, the BAI equal to the habitat quality index changes.

Leaf area index

In the RECC measurement framework, the ecosystem provides primary production materials and basic ecological service functions. The leaf area index (LAI) is a critical index based on the structural characteristics of vegetation and land cover, as leaves have a complex relationship with various biological and physical processes (Scurlock et al. 2001). Because of its significant role in ECC evaluation, the LAI was chosen as the sub-index in the RECC assessment. The average LAIs for different types of biomes/land covers are provided in Table 3 (Costanza et al. 1997).

According to Table 3, the overall LAI for a given region can be estimated as:

$$LAI_t = \sum_{i=1}^{n} w_i L_i \quad (5)$$

where LAI_t refers to the sum of the LAIs of this region ($m^2 \cdot m^{-2}$); L_i is the average LAI for the i-th biome/land cover type in Table 3 ($m^2 \cdot m^{-2}$); the biome/land cover type is identified based on RS or land use/cover maps; and w_i equals the proportion of the area of the i-th biome to the total land cover area for a given region.

Net primary productivity

Net primary productivity (NPP) is the net assimilation of CO_2 into organic matter by vegetation. Terrestrial NPP is a major component of the global C budget. An overall understanding of NPP, as well as its control over and interactions with the physical environment, is helpful for understanding Earth's biogeochemistry (Raich et al. 1991). Here, the Miami model (Lieth 1975) was adopted to compute the NPP for the study area, for this model possesses such advantages as high operability and needing less data input compared with many other famous models, particularly the LPJmL global vegetation model (Bondeau et al. 2007; Krausmann et al. 2013).

$$NPP_t = 3000 \times (1 + e^{1.315 - 0.119t}) \quad (6)$$

$$NPP_r = 3000 \times (1 - e^{-0.000664r}) \quad (7)$$

The NPP ($g\ m^{-2}\ a^{-1}$) in Eqs. (6) and (7) was calculated according to the annual average temperature (t, °C) and annual precipitation (r, mm). According to Liebig's law of the minimum, the lower value was chosen from the above two equations as the vegetation NPP of the target zone.

Water retention capacity

The water budget method was used to assess the water retention capacity (Kong and He 1991):

Table 2 Sub-weight for different habitat quality types of habitat quality index

	Weight	Structure types	Sub-weight
Forest	0.35	Forest land	0.06
		Shrub land	0.25
		Open woodland and other woodland	0.15
Grass	0.21	High coverage grassland	0.60
		Moderate coverage grasslands	0.30
		Low coverage grassland	0.10
Wetland	0.28	Rivers (canal)	0.10
		Lakes (reservoir)	0.30
		Tidal flat wetland	0.50
		Permanent ice snow	0.10
Cultivated land	0.11	Paddy field	0.60
		Dry land	0.40
Construction land	0.04	Urban construction land	0.30
		Rural residential area	0.40
		Other construction land	0.30
Unused land	0.01	Sand	0.20
		Saline and alkaline land	0.30
		Bare ground	0.20
		Bare rock pebbles	0.20
		Other unused land	0.10

Table 3 Average LAI of biome/land covers type ($m^2 m^{-2}$)

Biome/Land cover	Farmland	Garden	Woodland	Grassland	Wetland	Water	Construction land	Other land
Average LAI	3.0	3.0	5.0	2.0	6.5	0	0.5	1.0

$$W = (R - E)A = \theta RA \tag{8}$$

where W is the water retention quantity ($m^3 a^{-1}$), R, E and A denote the average precipitation ($mm\ a^{-1}$), mean evapotranspiration ($mm\ a^{-1}$) and total research area (hm^2), respectively, and θ is the runoff coefficient.

Carbon sequestration and oxygen release ability

With regard to carbon sequestration and oxygen release ability, reference was made to the research findings of Yin and Lu (2009), who summarized some representative research achievements abroad and devised the following equations:

$$V_c = 0.27 \times M \times S \times X \times N \tag{9}$$

$$V_O = M \times S \times X' \times N' \tag{10}$$

where V_c is the total value from carbon sequestration and M is the yield per hectare from the given plant, and S and X represent the plant area and carbon sequestration coefficient, respectively. N is the shadow price according to the carbon tax and cost method. V_O is based on the production

per unit (M), vegetation area (S), releasing oxygen coefficient (X'), shadow price of the industrial oxygen generation method and the cost method (N'). Here, only the total quantity was considered; thus, the equations were simplified to:

$$M_c = M \times S \times X \times 1.62 \tag{11}$$

$$M_O = M \times S \times X' \times 1.2 \tag{12}$$

The definitions of the terms are the same as those in Eqs. (9) and (10).

Resource and environment carrying capacity assessment

The state-space method uses Euclidean space geometry to describe the system status. This method can quantitatively measure the load condition by describing the carrying status point of three-dimensional state spaces to express the sustained condition of a region within a certain time scale (Wang 1994; Yu et al. 2003). In this research, the three axes of the state space represent environmental pollution

discharge, resource and energy consumption, and ECC. The RECC value is denoted by a vector model, which from the original point in the state space to the system state point. No specific ecological value has been given to the red line yet, but the government has indicated that the region should retain at least 70 % of original (or healthy) ecological functions. Here, the standard value is typically equal to the value that ensures 70 % of "full" ECC value (it actually refers to the highest value for the whole region). This corresponds to 30 % of SEPI value and 70 % of RECC value for the region. By comparing the present value with the standard value, one can determine whether the region is overloaded, fully loaded or available to support further loading. If, when analyzing the measured results and aiming to identify the key regulatory regions for RECC, the evaluation value surpasses the normal range, then this region belongs to a limited development area. If the evaluation value indicates a fully loaded status, then this region can be regarded as an optimized development ecological region. Finally, a status that indicates further loading can be supported corresponds to a positive development area.

Ecological carrying capacity assessment

The ECC evaluation includes the calculation of the weight and ECC value for each county and analysis of the main control factors, which are most likely to "control" the ultimate result:

Calculation of weight The entropy weight method (Cheng 2010) is a comprehensive objective weighting method in which weights are determined according to the importance degree of each index based on information theory (Shannon 2001; Zou et al. 2006). Assuming that the assessment area includes n counties with m ECC evaluation indices, the matrix is:

$$R' = (r'_{ij})_{m*n} \quad (i = 1, 2, \ldots, m ; j = 1, 2, \ldots, n) \quad (13)$$

where r'_{ij} denotes the statistical value of the j-th county for the i-th index. To eliminate the influence of the different units between different indices, every R' value was normalized and the normalized matrix was obtained. The extremum method was used as the normalized formula in this paper:

$$r_{ij} = \frac{r'_{ij} - \min|r'_{ij}|}{\max|r'_{ij}| - \min|r'_{ij}|} \quad (14)$$

Information entropy was used to normalize the data of the evaluation system. The entropy for the i-th index can be defined as:

$$H_i = -k \sum_{j=1}^{n} f_{ij} \ln f_{ij} \quad (15)$$

In this equation, H_i refers to the entropy value, k is the accommodation coefficient and f_{ij} denotes the normalized value of the j-th county for the i-th index:

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}, \quad k = \frac{1}{\ln n}$$

Here, n is the total number of counties. The entropy weight of the i-th index (W_i) can be determined according to the following equation after determining the index entropy:

$$W_i = \frac{1 - H_i}{m - \sum_{i=1}^{m} H_i} \quad (16)$$

The weight of each index was obtained for the evaluation system according to the entropy weight method given above, as shown in Table 4.

Calculation of the ECC value The weight and standardized values were obtained from the entropy weight method and range analysis method (Wang et al. 2007). This equation was performed according to ESI theory. The equation was simplified as follows:

$$ECC = \sum_{i=1}^{m} W_i \times C_i \quad (17)$$

ECC is a comprehensive evaluation index that consists of the weight of the i-th index (W_i) and the value of the i-th non-dimensional assessment index (C_i), where m indicates the number of the index.

Identification of the main control factors By employing SPSS to perform the correlation analysis and analyzing the correlation between each variable and the ECC value, the main control factors with the highest correlation coefficients were obtained; these factors have the greatest influence on the ECC.

Social and economic pressure assessment

The ESI model was used for the social and economic pressure index evaluation. The principle of the ESI was developed based on a continuous scale for the eco-environmental pressure index from 0 to 100. This was divided into five parts according to value: 0–20, 20–40, 40–60, 60–80 and 80–100; these parts corresponded to very small pressure, small pressure, moderate pressure, high pressure and very high pressure, respectively. Here, each assessment value was divided by 100 to fit within the range of 0–1. This model includes two sub-indices: the resource and

Table 4 Weights and ranks of ECC evaluation indices for northwest temperate continental climate ecotope in China

Index	Precipitation	Annual average temperature	Mean altitude	Landscape fragmentation index	Biological abundance	NPP
Weight	0.0717	0.0423	0.0276	0.0501	0.0820	0.0663
Rank	6	10	11	9	4	7

Index	Leaf area index	Soil erosion degree	Vegetation coverage	Water retention capacity	Carbon sequestration and oxygen release ability	
Weight	0.0763	0.0650	0.1219	0.1955	0.2014	
Rank	5	8	3	2	1	

energy consumption index (RECI) and the environmental pollution pressure index (EPI). The ESI is expressed as:

$$ESI = RECI \times W_1 + EPI \times W_2 \tag{18}$$

where *RECI* and *EPI* are expressed as follows:

$$RECI = \sum_{i=1}^{n} RECI_i \times P_i \tag{19}$$

$$EPI = \sum_{j=1}^{m} EPI_j \times P_j \tag{20}$$

where W_1 and W_2 are the weights of the sub-indices, $RECI_i$ and P_i are the value and weight of the *i*-th resource and energy consumption index, respectively; and EPI_j and P_j denote the value and weight of the *j*-th environmental pollution pressure index value, respectively.

The RECI represents the ecological stress brought about by regional economic development, where a higher RECI value indicates more ecological stress. The EPI represents the environmental pollution pressure originating from economic development, where a higher EPI value indicates greater eco-environmental stress. Through the two-dimensional space represented by the RECI and EPI, the relationship between ecosystem pressure and ecological environment pollution stress resulting from regional development can be established, and one can determine which sub-index contributes more pressure.

Nine indices that were easy to obtain, and which had significant meaning as social and economic pressure assessment indicators, were selected. Additional details are provided in Table 1. Then, using the weights from the entropy weight method, the weights and ranks of the social and economic pressure indices were obtained, as listed in Table 5. The main control factors were obtained from SPSS, and this expresses the degree of correlation between intra-group variables and the SEPI value.

Approximate decoupling index

Since the "factor 4" and "factor 10" theories were first proposed by Weizsäcker and colleagues (Weizsäcker et al. 1997) and Schmidt-Bleek (Friedrich and Klüting 1993), respectively, at the end of the 20th century, there has been a greater focus on the relationship between economic development and eco-environment pressure. Under normal circumstances, resource and energy consumption and waste emissions are associated with economic development (Lu et al. 2011); however, there has been a sustained effort to decouple these two parts. Wang (2010) defined the DI to indicate the relationship between economic growth and energy consumption. According to DI theory (OECD 2002), its value should come from an economic growth and energy consumption-related index. This paper analyzes the relationship between ECC/SEPI and RECC. As the meaning of sub-items in the DI equation were implicitly expressed in ECC/SEPI and RECC, an approximate index named ADI was defined to express their meaning. An ADI analysis (which has the same calculation method as DI) was carried out between RECC, SEPI and ECC:

$$DI_n = EI_n / GI_n \tag{21}$$

where DI_n is the decoupling index for the *n*-th year and EI_n is the energy consumption index or pollution emission index for the *n*-th year. In this paper, ECC and SEPI are used as replacements. GI_n is the GDP growth exponent for the *n*-th year. Here, to ensure all sub-items have the same dimension, the RECC is used, because it includes the meaning of economic growth, and is evaluated in the same system as ECC and SEPI. DI should then be renamed ADI; ADI ≥ 1 indicates increases in resource energy consumption or pollution at a faster rate than the accompanying economic growth (i.e., no decoupling). This situation is called an "absolute hook"; when $0 < ADI < 1$, the

Table 5 Weights and ranks for SEPI assessment system of northwest temperate continental climate ecotope in China

	Resource and energy consumption index						Environmental pollution index		
	Population density	Energy consumption index	Water using index	Urbanization rate	Cultivated area per capita	Tourism pressure index	Usage of chemical fertilizer per unit area of farmland	Domestic sewage discharge per unit area	Industrial three-wastes emissions per unit area
Weight	0.1070	0.0829	0.1084	0.0705	0.1070	0.1210	0.2470	0.1054	0.0509
Ranking	4	7	3	8	5	2	1	6	9
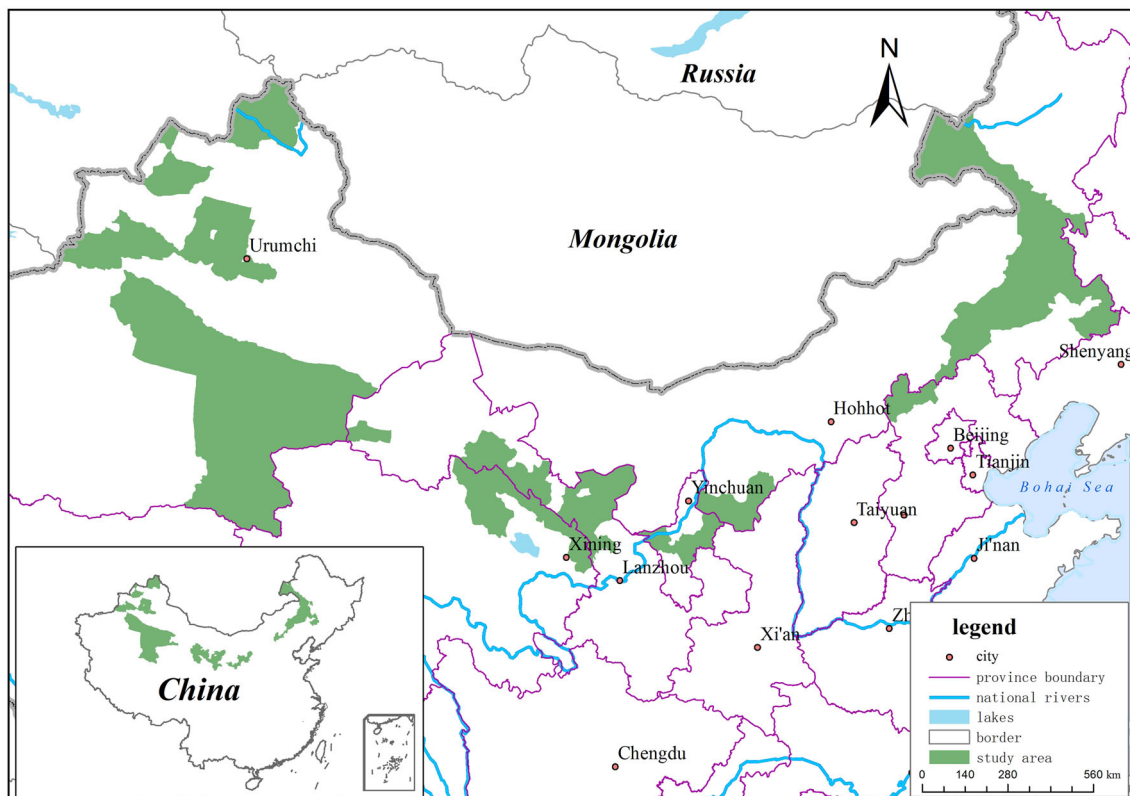
Fig. 1 Location of northwest temperate continental climate ecotope in China

economy is growing at a faster rate than energy consumption or pollution (i.e., relative decoupling). Finally, if ADI = 0, the total energy consumption is constant, which indicates sustainable growth; in other words, pollution will not increase under continuous economic development.

Study area and data

The study was conducted in the northwest temperate continental climate ecotope in China (36–49.6°N, 81–131.5°E), ranging from Xinjiang Province to Heilongjiang Province (Fig. 1). No specific permissions were required for these locations, and the field studies did not involve endangered or protected species. Division of this region, which has a total area of approximately 801,996.6 km² was based on the Chinese ecological function regionalization database (Xiao 2010). This ecological region is part of the global temperate continental climate zone, and stretches from the most eastern province to the most western province of China. There are several types of landforms, including desert, mountain, grassland and forest. The principal ecological functions include water conservation, wind prevention and sand fixation, and these are promoted by the extensive forest and grass landforms (Xiao 2010).

The temperature and precipitation data for research were downloaded directly from the website of China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do), and data for the total population, the GDP and other socioeconomic factors were obtained from the China Statistical Yearbooks Database (http://tongji.cnki.net/over seas/Dig/Dig.aspx). The Chinese Ecosystem and Ecological Function Regionalization Database (Xiao 2010) includes the majority of the data related to the ecological index. The altitude information, land use data and agrotype used for research were obtained from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences at resolutions of 30 m, 1:100,000 and 1:1,000,000, respectively. In addition to the above indices, some simple calculations were required to obtain the remaining indices.

Results and discussion

The carrying capacity of an ecological system has a subtle indirect relationship with social and economic development patterns, as the ecological system can optimize or restrain the development of socioeconomic development and the latter can influence or alter the load condition. RECC can be influenced by the socioeconomic development pattern and eco-environment (ecology and environment) states.

Results

The ECC value of the study area (shown in Fig. 2) was calculated, and the results divided into five levels using the natural breakpoint method in ArcGIS10.2. The value obtained was based on the 11 ecological indices considered. A higher ECC value indicated a better ecosystem condition. Taking 2010 as an example, the lowest ECC values occurred in Minqin, Wuwei, Tongxin and Jiuquan counties. Their ECC values were all lower than the standard value of the whole region, indicating that the counties contained environmentally unsustainable cities. According to the judgment criteria of meeting a 70 % ECC value across all of the counties, the "full" value should be the highest value of the whole region, not exactly the value of "1", the same below. The region's most environmentally sustainable cities were mainly in the eastern region of the study area—for example, Horqin Youyi Qianqi. The highest and lowest ECC values were approximately 0.3520 and 0.0810, respectively, representing a nearly fivefold difference.

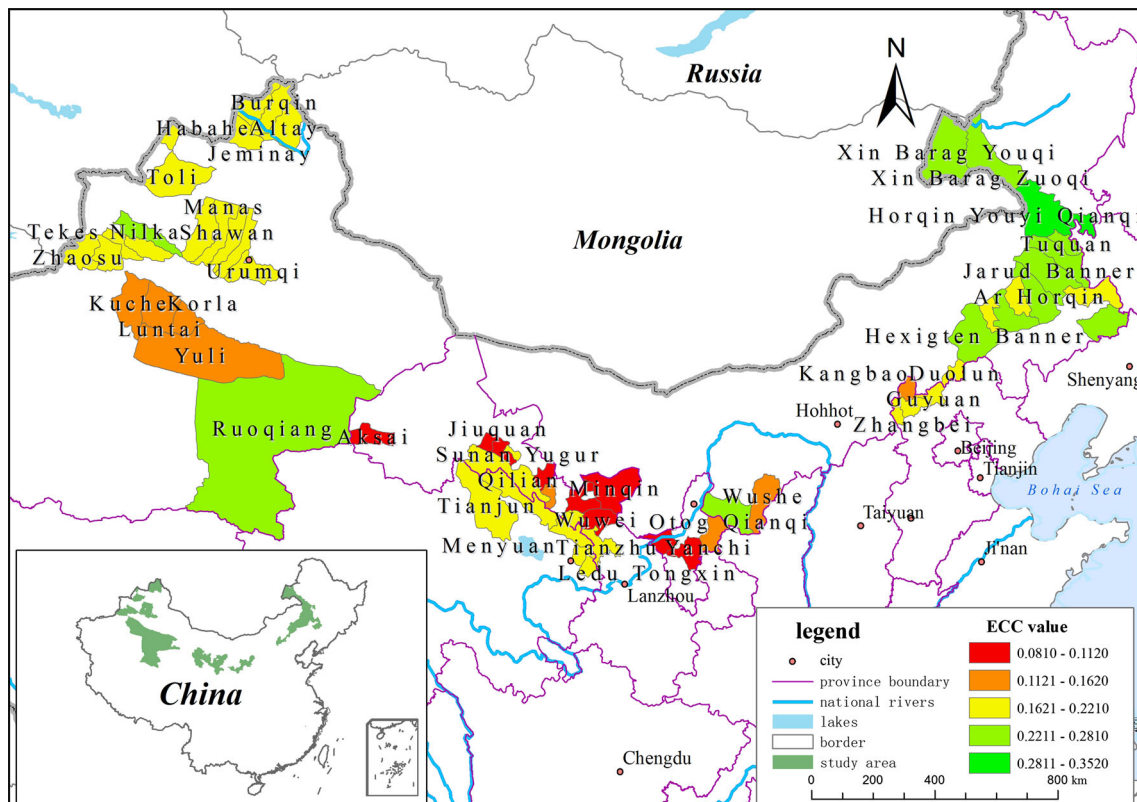Figure 3 illustrates a similar conclusion to the RECC analysis—namely, that the highest SEPI value

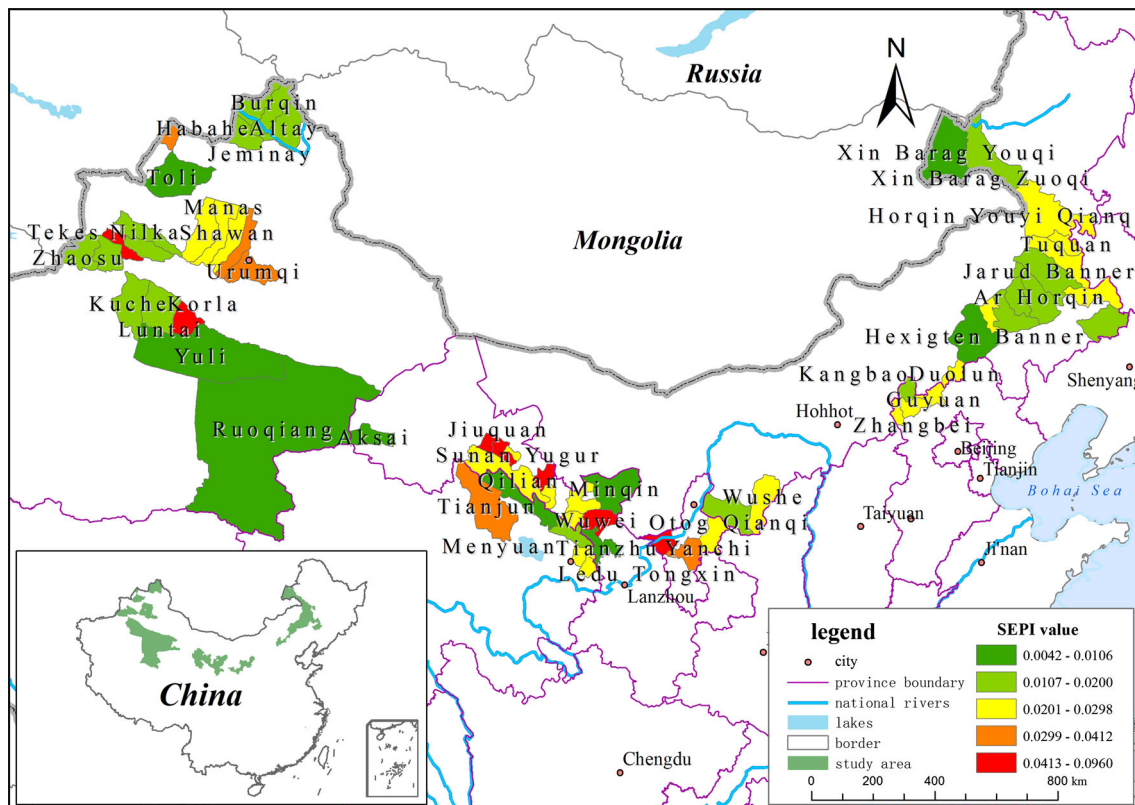Fig. 2 Distribution of ECC of northwest temperate continental climate ecotope in China

Fig. 3 Distribution of SEPI of northwest temperate continental climate ecotope in China

(approaching 0.0960) appeared in the central zone; cities such as Jiuquan, Wuwei and Sunan Yugur were all above the standard value and considered unsustainable. Cities with lower SEPI values were mainly distributed around the region, and Ruoqiang, Toli and Xin Barag Youqi, for example, were environmentally sustainable. The lowest SEPI value was 0.0042, which was considerably smaller than the largest value. Jiuquan and Wuwei, both cities located in the center of this region, had small ECC values and large SEPI values, indicating that these two factors are closely correlated.

The overall evaluation value of the ECC and SEPI is given in Fig. 4. The most serious carrying capacity situations with RECCs almost at 49, such as Wushen County and Aksay County, are shown in red. These high values were obviously larger than the standard value for the whole region, and clearly indicate the unsustainable nature of current development, which can be labeled as 'overload condition'. This needs to be the focus of future research. Most of the surrounding cities have low RECC values, ranging from 0.4123 to 1.3601.

The ADI are an additional way to analyze relationships involved in the rate of development. The ADI value for the SEPI and RECC was 1.42. Based on Sect. 2.3, this result indicated an "absolute hook", demonstrating that resources

and environment deteriorate faster than the economy grows. In contrast, the ADI value between ECC and RECC was only 0.055, which is also located in the 0–1 range, indicating a slower deterioration in the ecological environment than in the entire natural and social environment.

Discussion

The ECC, SEPI and RECC values were calculated to provide useful suggestions for future development. However, further research into the factors influencing the spatial distribution of these values, and which indices have the greatest influence, is still required. An analysis of the main control factors allows one to determine which factors have the largest effect on the final result (Table 6). Biological abundance and vegetation coverage are highly correlated with ECC (correlation factors of 0.83 and 0.81, respectively, which are higher than those of any other factors; $P < 0.001$), and so it is reasonable to treat them as principal control factors for ECC. As the geographical location extends widely over the northern part of China, and is mainly inland, the vegetation coverage or plant distribution is quite important to the target zone. The ECC values are relatively high in the eastern part of the study area, which
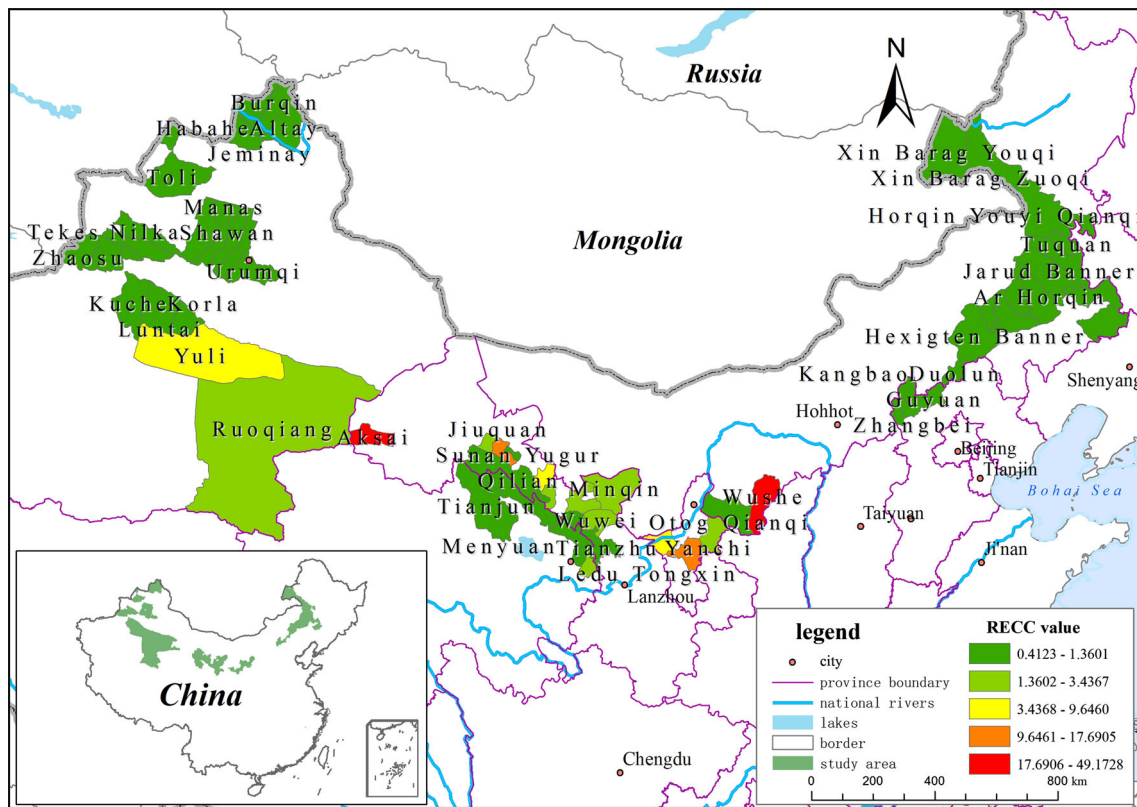
Fig. 4 Distribution of RECC value in northwest temperate continental climate ecotope in China

Table 6 Correlation analysis between ECC and evaluation indices of northwest temperate continental climate ecotope in China ($\alpha = 0.05$)

Index	Precipitation	Annual average temperature	Mean altitude	Landscape fragmentation index	Biological abundance	NPP
Coefficient	0.52	−0.55	0.22	−0.35	0.83	0.52

Index	Leaf area index	Soil erosion degree	Vegetation coverage	Water retention capacity	Carbon sequestration and oxygen release ability	
Coefficient	0.64	0.49	0.81	0.62	0.59	

has a high proportion of forest and grassland area. The negative index value in Table 6 indicates a negative correlation between a factor and ECC. The linear correlation models between ECC and the main control factors are shown in Fig. 5. The R^2 for these factors are 0.68 and 0.66, respectively, indicating the strong contribution of these two factors.

Several conclusions can be drawn from Table 7 and Fig. 6 about the main control factors for SEPI: (1) the energy consumption index and domestic sewage discharge per unit area index exhibit the highest correlation coefficients with the SEPI series (0.87 and 0.82, respectively; $P < 0.001$), which means that energy consumption and pollution exert the largest pressure on social and economic carrying capacity. Both of their R^2 values were above 0.60 (0.75 and 0.68 for the energy consumption index and

domestic sewage discharge per unit area index, respectively), which were high enough to prove their significance.

(2) Inter-relationships between the RECI and EPI were considered. The sub-index of the RECI characterizes the ecological pressure from the development of the regional economy. A high RECI value corresponds to high ecological pressure. In contrast, the EPI index represents pressure from environmental pollution due to regional economic growth. A high EPI value typically indicates serious environmental pollution. Thus, the two-dimensional space constructed by the RECI and EPI can be used to illustrate the relationship between ecosystem pressure and environmental pollution pressure, derived from regional economic development, to estimate the main source of eco-environmental pressure. The RECI and EPI were designed as having closed interval values between 0 and
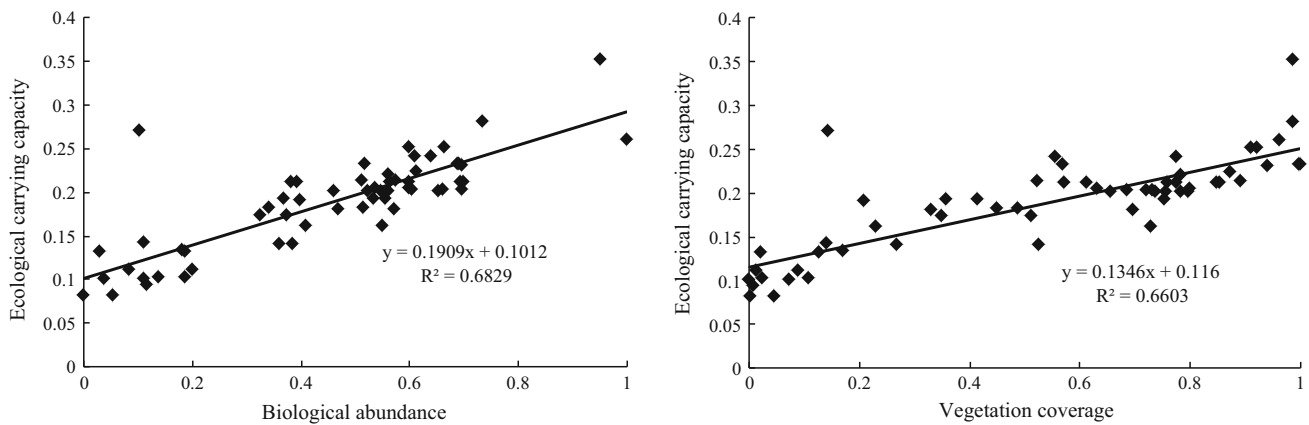
Fig. 5 Linear correlation models between ECC and main controlling factors of northwest temperate continental climate ecotope in China (α = 0.05)

Table 7 Correlation analysis between social & economic pressures and evaluation indexes in northwest temperate continental climate ecotope in China (α = 0.05)

Index	Population density	Energy consumption index	Water using index	Urbanization rate	Per cultivated area
Coefficient	0.74	0.87	0.76	0.61	0.09

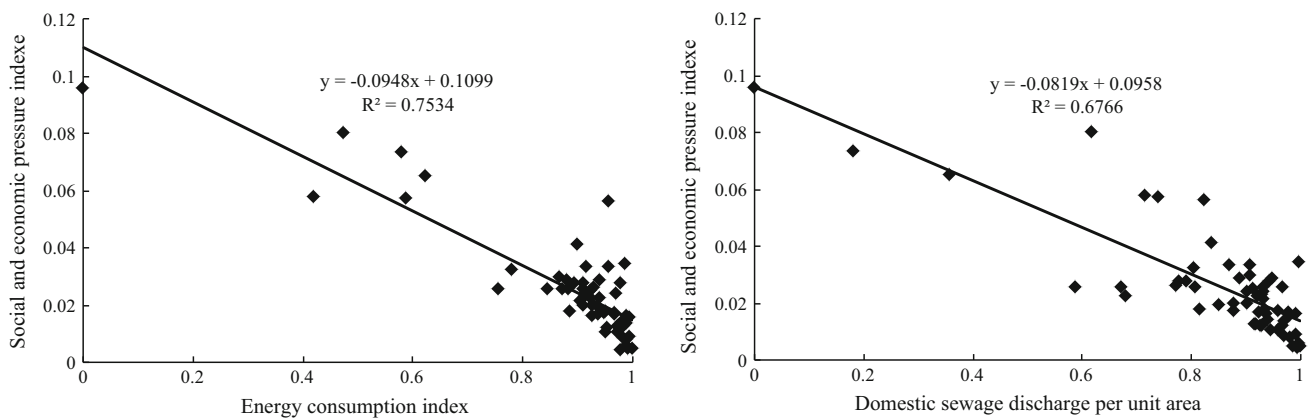| Index	Tourism pressure index	Usage of fertilizer in agriculture per unit area	Domestic sewage discharge per unit area	Industrial "three-wastes" emissions per unit area
Coefficient	0.43	0.04	0.82	0.04

Fig. 6 Linear correlation model between social & economic pressure and main controlling factors of northwest temperate continental climate ecotope in China (α = 0.05)

0.1; and very small pressure, small pressure, medium pressure, large pressure and very large pressure were defined as values in the ranges of 0–0.02, 0.02–0.04, 0.04–0.06, 0.06–0.08 and 0.08–0.1, respectively. Using the two-dimensional figure, the relation between the RECI and EPI can be divided into 25 micro-regions, with 25 composition relationships (Fig. 7). The values along the diagonal line correspond to the equation RECI/EPI = 1, which

indicates that environmental pollution and resource and energy consumption exert the same degree of pressure on the ecology and environment. The points above the diagonal line correspond to RECI/EPI <1, which indicates that pressure on the ecology and environment mainly originates from environmental pollution. In contrast, the points below the diagonal line correspond to RECI/EPI >1, which indicates that pressure on the eco-environment mainly
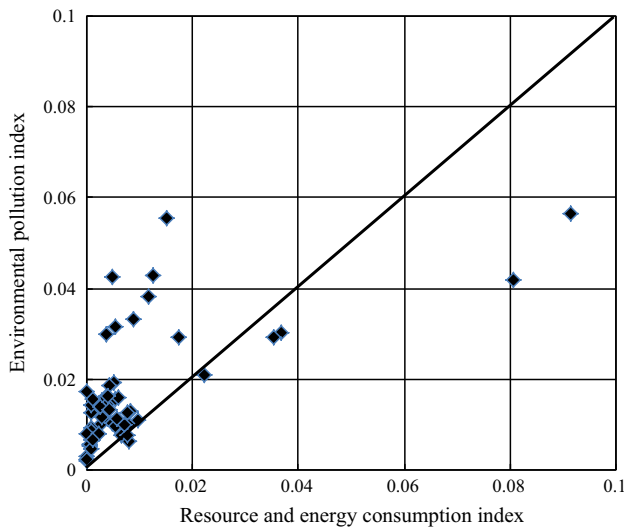
Fig. 7 Relationship between energy consumption and environment pollution for northwest temperate continental climate ecotope in China

Table 8 Canonical correlation coefficients between RECC value and evaluation indices for northwest temperate continental climate ecotope in China (Sig = 0.003)

Evaluation index	Canonical loadings
Annual average temperature	0.067
Precipitation	0.125
Mean altitude	0.145
Landscape fragmentation index	0.487
Biological abundance	0.363
Leaf area index	0.169
Net primary productivity	0.649
Water retention capacity	0.521
Soil erosion degree	0.485
Population density	0.799
Energy consumption index	0.739
Water using index	0.652
Urbanization rate	0.489
Cultivated area per capita	0.386
Tourism pressure index	0.451
Usage of chemical fertilizer per unit area of farmland	0.386
Industrial three-wastes emissions per unit area	0.026
Canonical correlation coefficient	0.745

originates from resource and energy consumption. Points further away from the diagonal line indicate a larger pressure differential between environmental pollution and resource and energy consumption.

It can be concluded from the analysis above that the social and economic pressure from the study area is strongly related to environmental pollution.

RECC assessment involving the societal system, economic system and eco-environmental system can be used to determine which system contributes most to the RECC, as well as the correlation between them. In this paper, canonical correlation analysis (Thompson 2005) was used to measure such relationships: (1) canonical elements from the ecosystem and socioeconomic system indices were identified, and the dimension was reduced; (2) using the correlational analysis method, the degree of correlation between the two indices was determined, and the single limiting factors were confirmed; (3) analysis of variance was used to determine the relationship between the limiting factors; and (4) the limiting factor of RECC was determined.

Canonical correlation analysis adopts a cell group whose significant value is smaller than 0.01 as the variable group; in this study, there was only one group that satisfied this requirement (Table 8). Statistical requirements typically call for a correlation coefficient that is higher than a threshold value; considering the canonical correlation coefficient, this paper employed 0.6 as the threshold value. Thus, the population density, energy consumption index and water use index from the socioeconomic system, and NPP from the ecosystem, were considered the most important factors affecting the RECC. This means that

photosynthesis, as the basic driving force for natural productivity, was important to the ecosystem and also affected the RECC. The socioeconomic system, population density, water usage and energy consumption were critical to the RECC, illustrating the effect of the population size.

In the foreseeable future, human activity will remain the main stress for sustainable development in the extensive northwest temperate continental climate ecotope in China: destruction of the ecosystem (indirect influence) and heavy loading from socioeconomic development (direct influence). To maintain sustainable development, a rational strategy of developing, using and protecting the regional resources and environment is needed. Specific suggestions and measures include: (1) establishing and optimizing a healthy modern economic structure; (2) restricting the development of high-consumption and high-polluting industries, and transitioning to cleaner production. Local government should adopt policies to control the discharge of pollution and allocate limited resources more effectively in the next Five-Year Plan (2016–2020); (3) strengthening the construction of an information network of ecosystem management and establishing a resources and environmental monitoring system (Liu et al. 2010); (4) establishing an information platform with the central economic office as its main body to ensure that the exploitation of nature resources (e.g., grass, forests and water resources) follows

clear government standards and that harm to human beings and local ecosystems is avoided; and (5) strengthening technological research and popularizing the use of energy conservation and environmental protection products. In the absence of strong development pressure from the population, the ecosystem will improve and the RECC will increase.

Conclusions

1. A quantified resource and environmental carrying capacity index evaluation system is introduced that considers the influence of ECC and socioeconomic growth pressure and uses the ESI model to obtain comprehensive assessment values. The ADI is used to verify the impact of ecological factors and economic aspects to explore the accompanying relationships between individual factors and the ultimate result. The following conclusions can be drawn:

2. The ECC, SEPI and comprehensive evaluation results yield the same conclusion: the central zone of the study area has a low ECC and high economic developing pressure; thus, efforts should be made to prevent this region from entering an inferior carrying capacity situation. The western part of the study area ranked second, while the eastern part was in the best condition.

3. The ADI provides helpful information about whether the variations in RECC are accompanied by a synchronous change in ecosystem conditions and socioeconomic system. The results showed that each individual effect does not have a clear effect on the RECC in the short term but, as no conclusion has been reached regarding their combined influence, this topic requires further research.

4. The analytical results from the canonical correlation analysis illustrate that the main factors affecting the target area are population density, energy consumption index and water usage index from the socioeconomic system, as well as the NPP of the ecosystem. Those factors are the most meaningful indicators for the ultimate RECC value. Oh and colleagues (Oh et al. 2005) reached a similar conclusion. The results illustrate the importance of natural factors and human activities on the ultimate evaluation results.

5. The most sustainable ecological condition of the study area is in the eastern part. Future development should focus on the central and western parts of the region. Although the evaluation system proposed in this paper was not specific to a particular ecological region, it is useful for different types of areas, and additional local information should be considered when selecting

indices. Future research should consider the development of predictive functions to provide more suitable suggestions for regional development.

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