J. Geogr. Sci. 2019, 29(3): 363-376
DOI: https://doi.org/10.1007/s11442-019-1603-4

Comprehensive evaluation of regional resources and environmental carrying capacity using a PS-DR-DP theoretical model

WANG Liang[1,2,3,4], *LIU Hui[1,2,3]

1. Key Laboratory of Regional Sustainable Development Modeling, CAS, Beijing 100101, China;
2. Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;
3. College of Resource and Environment, University of Chinese Academy of Sciences, Beijing 100049, China;
4. Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

Abstract: The concepts of regional resources and environmental carrying capacity are important aspects of both academic inquiry and government policy. Although notable results have been achieved in terms of evaluating both these variables, most researchers have utilized a traditional analytical method that incorporates the "pressure-state-response" model. A new approach is proposed in this study for the comprehensive evaluation of regional resources and environmental carrying capacity; applying a "pressure-support", "destructiveness-resilience", and "degradation-promotion" ("PS-DR-DP") hexagon interaction theoretical model, we divided carrying capacity into these three pairs of interactive forces which correspond with resource supporting ability, environmental capacity, and risk-disaster resisting ability, respectively. Negative carrying capacity load in this context was defined to include pressure, destructiveness, and degradation, while support, resilience, and promotion comprised positive attributes. The status of regional carrying capacity was then determined via the ratio between positive and negative contribution values, expressed in terms of changes in both hexagonal shape and area that result from interactive forces. In order to test our "PS-DR-DP" theory-based model, we carried out a further empirical study on Beijing over the period between 2010 and 2015. Analytical results also revealed that the city is now close to attaining a perfect state for both resources and environmental carrying capacity; the latter state in Beijing increased from 1.0143 to 1.1411 between 2010 and 2015, an improved carrying capacity despite the fact that population increased by two million. The average contribution value also reached 0.7025 in 2015, indicating that the city approached an optimal loading threshold at this time but still had space for additional carrying capacity. The findings of our analysis provide theoretical support to enable the city of Beijing to control population levels below 23 million by 2020.

Keywords: **resources and environmental carrying capacity; "pressure-support", "destructiveness-resilience" and "degradation-promotion" model; evaluation; Beijing**

Received: 2018-05-21 **Accepted:** 2018-07-15
Foundation: The Specific Project of National Key Research and Development Program of China, No.2016YFC0503506; Strategy Priority Research Program of Chinese Academy of Sciences, No.XDA20010103
Author: Wang Liang (1989–), PhD, specialized in regional sustainable development. E-mail: wangl.17b@igsnrr.ac.cn
***Corresponding author:** Liu Hui, Professor, E-mail: liuh@igsnrr.ac.cn

1 Introduction

Carrying capacity was first defined in the field of ecology as "a limit on the number of a biological population and individuals under specific conditions" (Park *et al*., 1920). The Club of Rome later published "the limits to growth" in which they defined the joint concepts of resources and environmental carrying capacity for the first time. It is clear that "food shortages and environmental destruction will make the Earth's population reach the limit at a certain period along with rapid industrialization, population explosion, private ownership of grain, non-renewable resources depletion and ecological deterioration" (Meadows *et al*., 1972). A series of related definitions, methods, and lots of evaluation index system have all been more recently developed in this field to support research on carrying capacity.

Western scholars prioritized both theory and methods in early research in this area. In one example, however, although the agro-ecological zone project method (FAO, 1996) is widely available, this approach tests carrying capacity by selecting just natural agricultural indexes and so reaches incomplete conclusions. Another approach, system dynamics (Karnopp *et al*., 1990), has also proved popular in forewarning studies that address carrying capacity; this method establishes a dynamic model to explain causality through internal system structure and places particular emphasis on environmental issues. The ecological footprint approach similarly provides a method to calculate the Earth's carrying capacity, the balance between supply and demand that results from human economic activity, and to measure the extent of sustainable development (Rees, 1992; Rees *et al*., 1994). This approach can also be used to perform regional comparisons but cannot fully illustrate the impact of socioeconomic activities on ecological carrying capacity. One further approach, energy analysis, therefore aims to develop an integrated energy value index system by converting different variables into uniform standard values. This method is useful because it can be used to assess the ecological capacity of the Earth on the basis of energy values (Odum, 1996); although this approach is of considerable significance, high parameter demands mean that practical applications have lagged behind theory in this case (Feng *et al*., 2017). Researchers in developed countries have turned their attention to micro-level studies in recent years, including coastal protection and aquaculture (Chadenas *et al*., 2008; Guyondet *et al*., 2015; Reghunathan *et al*., 2016), while some scholars in developing regions have addressed sustainable development (Patil *et al*., 2008; Sarma *et al*., 2016; Irankhahi *et al*., 2017). It is the case that international researchers have tended to be more focused on assessing the micro-carrying capacity of resources and the environment, paying less attention in recent years to comprehensive regional studies.

Carrying capacity studies within China were initiated with quantitative research on climate and potential grain production (Zhu, 1964). The Environmental Research Institute of Beijing Normal University initially proposed stipulating a norm concept of "environmental carrying capacity" (Zeng *et al*., 1991), while the Xinjiang Water Resources Research Group of the Chinese Academy of Sciences (CAS) proposed the concept of "water resources carrying capacity" (Shi *et al*., 1992). At the same time, scholars proposed a series of methods to calculate regional carrying capacity; the resources and demand differences method (Wang *et al*., 1999) seems both appropriate and simple in this context but cannot be used to express socioeconomic situations and the living standards of people. The comprehensive evaluation (Gao, 1999) is flexible but requires a huge amount of information while calculation difficulties are inherent to the state space approach (Mao *et al.*, 2001). Numerous researchers within China have emphasized land resources to reveal differences in regional population carrying capacities (Shi, 1992; Feng, 1994; Liao, 1998; Chen *et al.*, 2002; Feng *et al.*, 2008; Yu *et al.*, 2015). A number of studies in this area have also emerged on single elements, including the water environment and resources as well as the atmosphere and soil environment (Cui, 1998; Feng *et al.*, 2003; Luo *et al.*, 2011; Pan, 2016). These studies have all underestimated regional carrying capacities, however; thus, scholars in recent decades have tended to study regional comprehensive carrying capacity in light of functional area (Mao *et al.*, 2001; Fan, 2007) and regional planning studies (Fan, 2009). A consensus of researchers is therefore interested in developing forewarning applications (Gao *et al.*, 2010; Fang *et al.*, 2011; Feng *et al.*, 2016).

Numerous researchers have more-or-less ignored both the openness and dynamic nature of systems without incorporating the stability of the human-Earth relationship system. These approaches have therefore led to underestimates for the actual capacity of specific regions. In an attempt to remedy this issue, the Institute of Geographic Sciences and Natural Resources Research Team at the CAS initially developed a comprehensive evaluation system and theoretical framework for monitoring and forewarning about resources and environmental carrying capacity at the national level based on the dual concepts of “short board” and “growth limit” (Fan *et al.*, 2015; Fan *et al.*, 2017). Although this led to the development of a technological process that was issued by the National Development and Reform Commission and is now being implemented domestically, practical issues remain because this system does not include a specific critical threshold value or an early warning index standard for overloading.

The aim of this study is to develop a novel method to comprehensively evaluate regional resources and environmental carrying capacity. We therefore initially created a “pressure-support”, “destructiveness-resilience”, and “degradation-promotion” “PS-DR-DP” hexagonal interaction theoretical model based on the concept of “growth limit” and the human-earth relationship stability system. We then developed a comprehensive evaluation index system and standard on the basis of this theoretical model and then applied it to determine its validity and practicability to empirical studies in Beijing. This approach has enabled us to develop a series of new results that are informative with regard to the carrying capacity of this city.

2 Methodology

2.1 Theoretical model

It is clear that the dual concepts of “growth limit” and “short board” can be used to define stability in the context of the human-earth system as a research prerequisite. Thus, utilizing mechanics-bearing and “growth limit” ecological principles, we define regional resources and environmental carrying capacity as the point at which “the regional population will reach its limit in a specific condition when the resource use is ‘fulfilling’ and ‘most efficiency’ under a stable human-earth relationship system”. Carrying capacity in this context includes resource support, environmental capacity, and risk-disaster resistance. The first of these refers to the largest population supported by total available resources depending on current technology and economy, while environmental capacity refers to the ability of water, soil, and atmosphere to accommodate pollutants generated by humans. This concept reveals the largest population a region can accommodate when regional water, soil, or atmospheric quality meet the minimum standards for agricultural production and human health. The concept of risk resistance refers to the ability to protect the largest number of people when a given region suffers from a major natural disaster. It is clear that the concepts of both resources and environmental carrying capacity comprise open and hierarchical systems; thus, different regional ranks will encompass basic carrying capacities and load limit ranges. Regional carrying capacity is therefore dynamic and related to both technological advances and economic development.

The "pressure-state-response" and "driving force-pressure-state-impact-response" models have both become a mainstream in regional carrying capacity studies. Although the former can be used to adequately characterize causal relationships, it nevertheless depends on subjective judgments and empirical models for index development. This approach cannot therefore be used to grasp the structure and decision-making processes of the system and does not work well in the context of complex feedback systems (Li *et al*., 2012). Indeed, the latter can be utilized to improve the former via comprehensive human-earth relationships, emphasizes the "limit of growth", and just expresses a traditional "responsive" environmental protection concept (Cao, 2005). It is clear that both these approaches do not encapsulate urgently needed early warning-oriented evaluation processes.

We therefore advance a new hexagonal interaction force model in this study to remedy these shortcomings that is founded on "pressure-support", "destructiveness-resilience", and "degradation-promotion" ("PS-DR-DP"). This model is founded on the original carrying capacity concept and incorporates both the "limit of growth" and "structural stability" of the human-earth system. We utilize a hexagonal filling degree to simulate dynamic changes in resources and environmental carrying capacity in order to create an "early warning-oriented" evaluation system (Figure 1).

Pressure in this "PS-DR-DP" model refers to total resource consumption, while support denotes the entirety of potential resources available given current technology. The resultant force of these variables therefore characterizes resource use status, while destructiveness refers to the habitat damage caused by human activities, including environmental pollution, epidemics, and major natural disasters. Resilience therefore refers to the abilities of humans to mitigate environmental pollution as well as the power to predict, resist, and repair major natural disasters, while the concepts of destructive force and resilience together characterize ability to mitigate risk. Degradation refers to the degenerative state of resources and ecology while promotion denotes the ability to use advanced technologies, to improve resource use, or to delay or repair

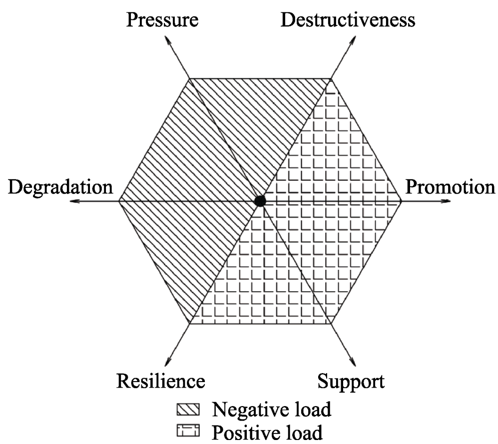

Figure 1 The warning model used in this analysis, comprising a fully loaded resource state and environmental carrying capacity

degradation. Taken together, pressure, destructiveness, and degradation therefore encapsulate negative resource load and environmental carrying capacity; in this context, positive load includes support, resilience, and promotion such that the ideal regional resource state and environmental carrying capacity requires that the limit is avoided and the system is held stable (Figure 2).

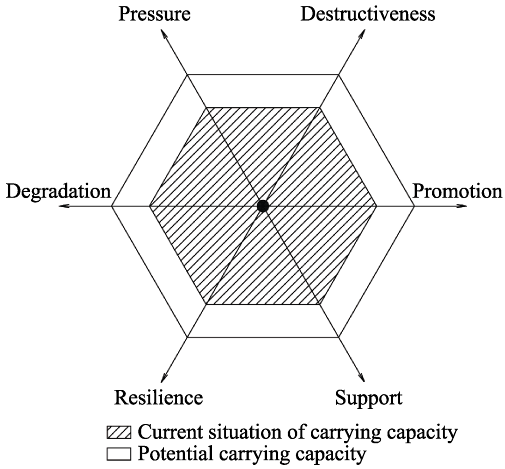

Figure 2 The perfect state model used in this analysis encompassing resources and environmental carrying capacity

2.2 Research methods

2.2.1 Reliability index analysis

We performed a reliability analysis in order to completely avoid (where possible) and mitigate reductions in subjective influence when selecting indicators for inclusion in our index system. Reliability in this context refers to the degree of consistency of results when this index system is used as a measurement tool. We therefore used the Cronbach Alpha coefficient to test the internal consistency of our standardized index system (Mangi *et al*., 2007); this approach reveals high reliability if a coefficient is not less than 0.9, while a value between 0.9 and 0.7 is also acceptable. However, if the coefficient falls to between 0.7 and 0.5 then certain items are in need of revision, and some might need to be abandoned entirely if the value is lower than 0.5. The equations used for this calculation are as follows:

$$\alpha = \left(n/n-1\right)\left(1-\sum s_i^2/s_t^2\right) \tag{1}$$

$$\sum s_i^2 = \sum\left(k_i^m - k_m\right)^2 \tag{2}$$

where α is the reliability coefficient and n denotes the number of variables, while $\sum s_i^2$ is equal to the sum of subentry variances, s_t^2 is the total variances, k_i^m stands for the variable values of the m index system, and k_m is the mean value of the variables in this system.

2.2.2 Contribution of carrying capacity

We revised the entire-array-polygon method as proposed by Wu *et al*. (2005) to render our mathematical expression more exact (equation 3). This approach supposes the presence of N standardization indexes, sets the zero point as the origin, and takes one (the largest standardized value) as the radius to form a central N polygon. This means that each variable value is distributed between the zero point and vertex such that value points link up and form an irregular N polygon. Thus, N indexes can generate (N–1)!/2 irregular N polygons according to the multiplication principle of classified arrangement, and the ratio between the irregular N polygonal average area and the central N polygonal area is the contribution value of each component of carrying capacity.

As influencing factors interact with one another in a complex fashion, the "short board" principle cannot be the sole criterion applied. Thus, in order to supplement this feature, we defined carrying capacity status is the ratio between positive and negative contribution values (equation 4). This means that if the ratio is bigger than one, a region is in good condition, while a larger overall number denotes enhanced carrying capacity. Other values can be used as warnings of danger; thus:

$$C = \frac{\sum_{i<j}^{i,j} \left(k_i^m + 1\right)\left(k_j^m + 1\right)}{N\left(N-1\right)} \tag{3}$$

$$S = \frac{\sum_{i=1}^{i} C_i^p}{\sum_{j=1}^{j} C_j^n} \tag{4}$$

where C is the carrying capacity contribution value of the subentry, N is the index number, k_i^m and k_j^m stand for the i and the j variable value in the m index system, respectively, S is the state of the carrying capacity, C_i^p is the i positive contribution value, and C_j^n is its negative counterpart.

2.2.3 Carrying capacity status classification

Although resources and environmental carrying capacity are limited by natural factors, both economic growth and technological progress exert significant influence. At the same time, the urbanization process provides the fundamental impetus for changes in regional carrying capacity; a generally higher urbanization level is therefore reflected in a stronger carrying capacity. If the urbanization level is too high, however, to exert negative impacts on regional carrying capacity, changes in the latter will impede the former. We therefore refer to the "threshold value of three stage urbanization" developed in the *China Modernization Report* (*2013*): *Urban Modernization Study* (He, 2014) while also taking the turning point of counter urbanization in developed countries into account. These stages enabled us to finally determine resources and environmental carrying capacity rating standard (Table 1).

Table 1 Classification of resources and environmental carrying capacity

Rank	Mean contribution value	Carrying capacity state
I	⩽ 0.30	Balance load at lower level with an approximate stable state
II	0.30–0.70	Unstable state developing at high speed
III	0.70–0.85	An ideal carrying capacity close to the stable state
IV	⩾ 0.85	A fully loaded state with the system collapsing

Note: Mean contribution value denotes the average subentry contribution sum.

3 Evaluation index system

An index system provides the key to judge whether, or not, an evaluation result is credible because resources and environmental carrying capacity are comprehensive, uncertain, open, and dynamic. The hugely variable and complex indicators in different regions also make it hard to build a unified quantitative index system. Existing research suggests that land (pressure index) and water resources (usage amount), as well as the environment (exceeding pollutants) and ecology (eco-health) should be the primary contents of such an index (Fan *et al*., 2015, 2017). Thus, by applying the "PS-DR-DP" theoretical model and literature, we present a scientific and workable evaluation index system that is based on three pairs of interaction forces. The consumption and stock of water, soil and energy comprise the "fulfilling" state, while 'energy consumption per unit of gross domestic product (GDP)' and 'whole-society productivity' comprise the degree of "efficiency" (Table 2). Indexes presented in Tables 3 and 4 were used to assess whether, or not, regional ecology and the environment were stable.

Table 2 The evaluation index system for pressure and support used in this analysis

Force	Influencing factor	Index	No.
Pressure	Water	Average water consumption (m^3)	K^1_1
		Total water consumption (10^8 m^3)	K^1_2
	Land	Requisition of cultivated area (km^2)	K^1_3
		Requisition of industrial and mining land (km^2)	K^1_4
	Energy	Coal consumption (10^8 ton)	K^1_5
		Oil consumption (10^4 ton)	K^1_6
		Gas consumption (10^8 m^3)	K^1_7
		Electricity consumption (10^8 kw·h)	K^1_8
		Energy consumption per unit of GDP (ton of standard coal/10^4 yuan)	K^1_9
	Population	Population density (person/km^2)	K^1_{10}
		Total population at year-end (10^4)	K^1_{11}
		Population growth rate (‰)	K^1_{12}
		Urban unemployment rate (%)	K^1_{13}
		GDP (10^4 yuan)	K^1_{14}
Support	Resources	Water resource per capita (m^3/per capita)	K^1_{15}
		Total water resources (10^8 m^3)	K^1_{16}
		Total land area (km^2)	K^1_{17}
		Cultivated land increments of a year (km^2)	K^1_{18}
		Cultivated land area (km^2)	K^1_{19}
		Per capita food production (kg)	K^1_{20}
		Hydropower generation (10^8 kw·h)	K^1_{21}
		Coal reserves (10^8 ton)	K^1_{22}
		Crude oil production (10^4 ton)	K^1_{23}
		Gas production (10^8 m^3)	K^1_{24}
		Electrical energy production (10^8 kw·h)	K^1_{25}
	Socioeconomy	Whole-society productivity (10^4 yuan/per capita)	K^1_{26}
		Disposable income per capita for urban citizens (10^4 yuan)	K^1_{27}
		Rural per capita net income (10^4 yuan)	K^1_{28}

Note: k_i^1 is the pressure and support variable in this evaluation index system.

4 An empirical study in Beijing

4.1 Data

The data used in this analysis were mostly extracted from the *China Statistical Yearbook*, the *China Statistics Yearbook of Environment*, the *China Statistical Yearbook of Land & Resources*, the *China Rural Statistical Yearbook*, the *China Forestry Statistical Year*

Table 3 The evaluation index system for destructiveness and resilience used in this analysis

Force	Influencing factor	Index	No.
Destructiveness	Atmospheric environment	Sulfur dioxide emission (10^4 ton)	K^2_1
		Flue dust emission (ton)	K^2_2
	Water environment	Wastewater discharge (10^4 ton)	K^2_3
		Chemical oxygen demand (10^4 ton)	K^2_4
	Soil environment	Dangerous industrial solid waste output (10^4 ton)	K^2_5
		General industrial solid waste output (10^4 ton)	K^2_6
	Major disaster	Fatality rate of class A and class B infectious diseases ($1/10^5$)	K^2_7
		Number of geological disasters	K^2_8
		Number of sudden environmental accidents	K^2_9
Resilience	Pollutant treatment	Proportion of environmental pollution control costs in GDP (%)	K^2_{10}
		Amount of industrial sulfur dioxide removal (10^4 ton)	K^2_{11}
		Disposal of general industrial solid waste (10^4 ton)	K^2_{12}
		Disposal of dangerous industrial solid waste (10^4 ton)	K^2_{13}
		City sewage treatment rate (%)	K^2_{14}
	Disaster prevention	Number of disease control centers	K^2_{15}
		Number of automatic meteorological stations	K^2_{16}
		Number of seismological stations	K^2_{17}
		Number of emergency shelters	K^2_{18}

Note: k_i^2 is the destructiveness and resilience variable in this evaluation index system.

Table 4 The evaluation index system for degradation and promotion used in this analysis

Force	Influencing factor	Index	No.
Degradation	Desertification	Desertification land area (hm^2)	K^3_1
	Forest degradation	Area of plantation forestry (hm^2)	K^3_2
		Forest disease and insect pest and rodent disaster area (hm^2)	K^3_3
	Water and soil erosion	Increased area of water and soil erosion (hm^2)	K^3_4
		Scope of responsibility for soil erosion control (hm^2)	K^3_5
Promotion	Protection and governance	Forest area (hm^2)	K^3_6
		Wetland area (hm^2)	K^3_7
		Afforestation area (hm^2)	K^3_8
		Small watershed management area (hm^2)	K^3_9
		Control rate of forest disease and insect pest and rodent disaster (%)	K^3_{10}
		Control area of water and soil erosion (hm^2)	K^3_{11}
		Natural reserve area (hm^2)	K^3_{12}

Note: k_i^3 is the degradation and promotion variable in this evaluation index system.

book, and the *Bulletin of Soil and Water Conservation in China*, and encompass the period between 2008 and 2016. A component of the data used here were also extracted from the *Beijing Statistical Yearbook* (2008–2016), as well as various public information and annual reports released by concerned departments of Beijing Municipal Government.

4.2 Reliability analysis

We selected original data encompassing the period between 2008 and 2010 for Beijing and standardized records using the min-max method (Table 5). We then used the software SPSS to analyze data reliability; our results (Table 6) show that all three index systems are credible because their coefficients are all greater than 0.9.

Table 5 Evaluation index standardization values for Beijing between 2008 and 2010

Index	2008	2009	2010	Index	2008	2009	2010	Index	2008	2009	2010
K^1_1	1.0000	1.0000	0.8629	K^1_{20}	0.3577	0.3513	0.2838	K^2_{11}	0.0605	0.0511	0.0613
K^1_2	0.1665	0.1725	0.1604	K^1_{21}	0.0002	0.0002	0.0020	K^2_{12}	0.0402	0.0341	0.0368
K^1_3	0.0527	0.1440	0.0679	K^1_{22}	0.3173	0.3401	0.1727	K^2_{13}	0.0366	0.0258	0.0307
K^1_4	0.2323	0.4116	1.0000	K^1_{23}	0.0000	0.0000	0.0000	K^2_{14}	0.4243	0.3633	0.3873
K^1_5	0.0130	0.0129	0.0120	K^1_{24}	0.0000	0.0000	0.0000	K^2_{15}	0.1667	0.1403	0.1462
K^1_6	0.0530	0.0565	0.0509	K^1_{25}	0.1172	0.1200	0.1230	K^2_{16}	1.0000	1.0000	1.0000
K^1_7	0.2877	0.3372	0.3407	K^1_{26}	0.0548	0.0597	0.0634	K^2_{17}	0.5591	0.4570	0.4387
K^1_8	0.3272	0.3592	0.3690	K^1_{27}	0.0124	0.0137	0.0140	K^2_{18}	0.1774	0.1493	0.1557
K^1_9	0.0031	0.0029	0.0026	K^1_{28}	0.0051	0.0057	0.0060	K^3_1	0.1202	0.1049	0.0965
K^1_{10}	0.0376	0.0369	0.0544	K^2_1	0.0661	0.0538	0.0542	K^3_2	0.5959	0.6849	0.6568
K^1_{11}	0.0840	0.0904	0.0894	K^2_2	0.0190	0.0165	0.0181	K^3_3	0.0858	0.0754	0.0730
K^1_{12}	0.0162	0.0170	0.0140	K^2_3	0.6089	0.6372	0.5308	K^3_4	0.0706	0.1105	0.0571
K^1_{13}	0.0863	0.0680	0.0638	K^2_4	0.0543	0.0448	0.0434	K^3_5	0.0098	0.0142	0.0276
K^1_{14}	0.0527	0.0591	0.0643	K^2_5	0.0645	0.0507	0.0538	K^3_6	0.0198	0.0346	0.0258
K^1_{15}	0.9749	0.6152	0.5658	K^2_6	0.0622	0.0562	0.0599	K^3_7	0.8336	1.0000	0.9589
K^1_{16}	0.1622	0.1059	0.1052	K^2_7	0.1115	0.0500	0.0725	K^3_8	0.0757	0.0661	0.0634
K^1_{17}	0.0778	0.0797	0.0748	K^2_8	0.0860	0.0543	0.0519	K^3_9	0.0610	0.0164	0.0146
K^1_{18}	0.0094	0.0096	0.0090	K^2_9	0.1989	0.1403	0.1415	K^3_{10}	0.0219	0.0191	0.0183
K^1_{19}	0.0110	0.0113	0.0106	K^2_{10}	0.0785	0.0778	0.0774	K^3_{11}	1.0000	0.9833	1.0000
								K^3_{12}	0.2991	0.2611	0.2504

Table 6 Reliability index analysis results

Evaluation index system	Cronbachs Alpha	Sample size	Elimination
Pressure and support	0.949	28	0
Destructiveness and resilience	0.998	18	0
Degradation and promotion	0.999	12	0

4.3 Results and analysis

Researchers from across various fields have shown a great deal of interest since the turn of the 21st century in predicting the likely upper population limit for Beijing. Indeed, most workers have argued that both the resources and environmental carrying capacity of this city are already overloaded (Fan *et al*., 2005; Feng *et al*., 2005; Qiang *et al*., 2007; Tong, 2010; Tong *et al*., 2011); one early study even suggested that the population of Beijing should not exceed 18 million (Wang *et al*., 2005), and the *Beijing Urban Master Plan* (2016–2035) (Beijing Municipal Planning and Land Resources Management Commission, 2017) states that the resident population should be less than 23 million by 2020. It is therefore important to evaluate the loadable population of this city by calculating the overall carrying capacity state. Incorporating China's national five-year plans, we selected 2010 and 2015 as dates for a comparative analysis and to explore the carrying capacity status of Beijing; results are presented in Figure 3 as well as in Table 7.

According to the classification standards of resources and environmental carrying capacity applied in this paper (Table 1) and our results, it is clear that the city of Beijing did not overload in either 2010 or 2015. In the first of these two years, the carrying capacity state reached 1.0143 and the mean contribution value was 0.6908; these values are both indicative of a good state and an ideal development trend. Indeed, both values were larger in 2015 than their counterparts in 2010, which shows that the city actually had a better carrying capacity

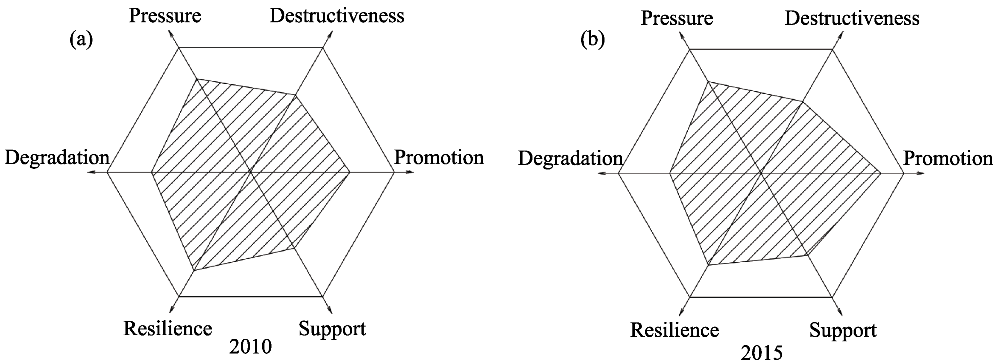

Figure 3 The resources and environmental carrying capacity state of Beijing in 2010 (a) and 2015 (b)

Table 7 The carrying capacity of Beijing between 2010 and 2015

Contribution value	Pressure	Support	Destructiveness	Resilience	Degeneration	Promotion	Carrying state	Mean contribution
2010	0.7468	0.6065	0.6191	0.7874	0.6917	0.6931	1.0143	0.6908
2015	0.7428	0.6627	0.5827	0.7443	0.6432	0.8394	1.1411	0.7025

Note: The internal data holds to four decimal places based on the original data.

in the later year than the earlier one. Secondly, data show that negative forces had weakened and positive ones had strengthened in 2015 compared to 2010; we show that two sets of forces were characteristic that if the negative one increased (or reduced) and its corresponding positive counterpart also trended in the same direction, with the exception of pressure and support. Third, data show that both destructiveness and degradation declined sharply between 2010 and 2015; this result means that environmental management and ecological protection are well controlled within the city and its ability to resist risks has enhanced. The contribution value of degradation also decreased while promotion increased between 2010 and 2015; this result suggests that humans have transitioned from a passive model of "driving force-pressure-state-response" and have developed a positive attitude towards warning and prevention. In contrast to the widespread belief that the carrying pressure of Beijing is increasing, our research results show instead that pressure on the city actually decreased in 2015 compared to 2010, even though population increased by 2.09 million and GDP increased by 890.1 billion yuan.

It is clear that local natural resources within the city are scarce and thus Beijing is subject to a high level of external dependence (Table 8); at the same time, however, the concept of regional carrying capacity will reveal the largest population that can be supported under such global and regional conditions. This ability also embodies the openness of regional

Table 8 The degree to which the energy and resources of Beijing were externally dependent between 2010 and 2015

Net input	Crude oil (10^4 tons)	Gas (10^8 m^3)	Water resource (10^8 m^3)
2010	1,116.29	74.79	12.1
2015	1,165.18	130	11.4
External dependence in 2010 (%)	100	100	34.375
External dependence in 2015 (%)	100	88.51	29.84

Note: External dependence is equal to the ratio of net input to total consumption in a given year.

carrying capacity; obviously, Beijing could support a much smaller population than is the current case if just local resources were employed. Although pressure on the city is greater than support at present, we can nevertheless look forward to a better carrying potential given the emergence and progress of new technologies.

One previous study in this area utilized the possible-satisfaction method to predict the carrying capacity of Beijing; this research estimated that a total level between 22.5 million people and 25 million people would be acceptable, a size around 23.5 million would be optimal, and that a level of 25 million people would be problematic (Wang *et al*., 2016). Our data reveal an average 2015 contribution value within Beijing of 0.7025, compared with an upper value of 0.85; this result indicates that there is still room for a larger population even though almost 22 million people currently live within this agglomeration. Indeed, given the level of human satisfaction within Beijing, our result is actually consistent with that of Wang *et al*. (2016). The problematic nature of previous research is also illustrated by the most commonly cited paper in this field in the context of resource capacity research (Xia *et al*., 2006) which suggested that water resources are the most critical limiting factor influencing the future development of Beijing. This study used Tongzhou District as an example and concluded that the population of this area can only rise to 1.119 million people by 2020 yet 1.184 million were living in this zone in 2010. A further study in this area also predicted that the population of Haidian District would be 3.0733 million by 2020 (Zhang *et al*., 2008) yet some 3.2 million people were living in this region in 2010. Several researchers have addressed these discrepancies by arguing that the actual population of Beijing has consistently been larger than its corresponding capacity since at least 1995 (Wang *et al*., 2005); we note that previous researchers have only focused on local resources and have ignored the extrinsic capacities of this region to acquire resources. Earlier predictions have thus been underestimated and therefore have limited practical application.

We argue in this study that natural resources represent both absolute variables for development and are important restrictions. It is clear that as regional carrying capacity will change along with economic development, the city of Beijing will be able to maintain a perfect level of the former by enhancing comprehensive carrying capacity and controlling population size.

5 Discussion and conclusions

The concepts of resources and environmental carrying capacity from the point of "growth limit" and the stable structure of the human-earth system are defined in this study. This enabled us to determine "PS-DR-DP" hexagonal interaction theoretical model and divide carrying capacity into three pairs of interacting forces, "pressure-support", "destructiveness-resilience", and "degradation-promotion", corresponding to resource supporting ability, environmental capacity, and risk-disaster resisting ability, respectively. The carrying capacity state can therefore be calculated via the value length between the origin and the vertex of an equilateral-hexagon; differences in hexagon shape can therefore also be used to simulate dynamic changes in carrying capacity.

In order to apply our "PS-DR-DP" theoretical model, we built a comprehensive evaluation index system that was certified via Cronbachs Alpha reliability analysis. We modified the entire-array-polygon method as a classified-array polygonal approach in order to avoid the influence of subjective assignment on results. This new method is easier to visualize and use as it reduces complicated calculations and avoid the impacts of imprecise weighting.

Our results reveal that the city of Beijing has attained to close to perfect carrying capacity state. Indeed, the state value of carrying capacity increased from 1.0143 to 1.1411 over the period between 2010 and 2015; the city has therefore more recently attained enhanced resource and environmental carrying capacity status levels. As the average contribution value reached 0.7025 in 2015, Beijing attained an optimal loading threshold while maintaining additional space for further carrying. This result differs from previous research in this area that has converged on the opinion that Beijing is overloaded and that population should restricted to less than 23 million people by 2020. Despite this significant result, we nevertheless cannot ignore competition in land resource between ecological protection and urban construction going forward.

We show that the "PS-DR-DP" model represents a marked improvement on traditional approaches for the study of regional resources and environmental carrying capacity. However, as the key issue faced by research in this area is to determine the underlying mechanisms controlling the factors influencing resources, environmental carrying capacity, and population limits under specific conditions, our model is able to only test the relative status of these two variables. It will be necessary to continue with research in this area to determine methods that can be applied to calculate approximately optimal solution given maximum population levels or those of optimal size.

Previous researchers have argued that increases in population will mean a concomitant pressure on regional resources. Our results show, however, that this pressure on Beijing was actually reduced as population expanded. We hypothesize that perhaps technical progress has enhanced both regional resources and environmental carrying capacity. A number of questions remain to be addressed, including how to adequately express this offset effect between technological progress and negative forces. In addition, can this pressure continue to decline under the premise of technological progress? Will this mean more room for a larger population? How can this threshold be determined? These issues are all key areas for future research.

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