

Evaluation of the land carrying capacity of major grain-producing areas and the identification of risk factors

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Abstract Analyzing the risk factors in the land carrying capacity system of major grain-producing areas is crucial for the optimization of land management by decision makers. For that purpose, the major grain-producing areas (Heilongjiang Province) in China are used as an example, with 17 indicators, such as resource, social, economic, coordinated development of an ecological subsystem, selection of the coordination degree of water and soil, effective irrigation rate, grain yield and environmental protection investment rate. This paper establishes an evaluation index system for the land carrying capacity. In addition, on the basis of the values of each index, the initial values were obtained via multiple interval stochastic weight assignments; the evaluation criteria and the land carrying capacity level were determined using a cloud model, and the major risk factors were determined using the degree of risk for each index. The results indicated that the evaluation criteria for the land carrying capacity can be categorized within level I [0.02, 0.24], level II [0.24, 0.40], level III [0.40, 0.55], level IV [0.55, 0.70] and level V [0.70, 0.91]. The land carrying capacity exhibited a continuous rise at each observation station during representative years. The industrial structure and regional development directly affected the land carrying capacity. Therefore, the evaluation results were concluded to be reliable. The risk factors for the land carrying capacity system were different at different periods of time; they included the effective irrigation rate and net income per capita between 2001 and 2008 and transportation land use, solid waste and fertilizer consumption between 2009 and 2013. In addition, between 2001 and 2013, the risk source for the land carrying capacity system transitioned from economic and social subsystems to ecological and

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social subsystems. The research results provide a decision-making reference for the development, improvement and management of land resources in the study area.

Keywords Land carrying capacity · Major grain-producing area · Cloud model · Evaluation criteria · Degree of risk

1 Introduction

Since the 1970s, as society has been confronted by a dramatic population increase and the rapid expansion of resource demands, global problems associated with population, food, resources and the environment have worsened. Given that land is an irreplaceable resource, its scarcity has become more salient. As a consequence, studies on the carrying capacity that focus on man–land relations have received growing attention.

With regards to these research topics, these studies can be divided into three types. The first type focuses on ecology: Vogot (1949) originated the concept of the land population carrying capacity and its related calculation equation; Allan (1949) proposed the equation for calculating the land population carrying capacity by using food as a marker, and he calculated the upper limit of the population carrying capacity of the land. The second type concerns the dual pressure of rapid population increases and the rapid expanse of resource demands. Using the multi-objective decision analysis method, Millington and Gifford (1973) calculated the land carrying capacity from the viewpoint that the population is restrained by resources. The Food and Agriculture Organization of the United Nations and Slesser (1990) have studied the strategy of carrying capacity via the Agricultural Ecology Zone method and the Evaluation of Capital Creation Options model, respectively. The third type is exemplified by the paper, “Economic Growth, Carrying Capacity and the Environment” by Arrow et al. (1995); research of this type originates primarily in China, and the study by Mao and Yu (2001) is representative. These researchers studied the current status and future trends in the land carrying capacity based on the lack of resources per capita and the rapid regional development in China. Overall, research on the land carrying capacity is increasingly focused on the coordinated development of resources and on environmental, climate-related and economic activities.

In terms of research methods, with the increasing advancement of modern computer technologies, various mathematical models have been adopted to investigate the carrying capacity. Consequently, the study of the carrying capacity has transitioned from statistical analysis to dynamic estimation (Shi et al. 2013), from the linear programming method in the early days (Brown and Ulgiati 1997; Wackernagel and Rees 1996) to the current widely used System Dynamics method (He et al. 2011). Multi-objective programming, fuzzy programming and the analytic hierarchy process subsequently appeared (Ren et al. 2011; Zhou et al. 2014; Jiang et al. 2011; Zhang et al. 2014). These methods employ the relationship between the quantitative index and evaluation criteria to evaluate the land carrying capacity, reflecting land resource development and utilization. However, there are few studies that have analyzed the risk factors associated with the land carrying capacity.

To investigate the fuzziness, the randomness and the relationships among the risk factors, the cloud model was proposed by the Chinese academician Li Deyi, who aimed at the existing insufficiency when using probability theory and fuzzy mathematics to address uncertain problems. Since the cloud model has been proposed, it has been applied successfully to natural language processing, data mining, decision analysis, intelligent control, image processing and many other fields (Parhoudeh et al. 2016; Liu et al. 2013; Zhou et al. 2016; Wang et al. 2014).

Considering that there are many uncertainties in the quantification of evaluation indices in the land carrying capacity and the determination of evaluation criteria and that the cloud model (Li et al. 1998a, b, 2004, 2009) is an effective tool for addressing uncertainty problems, the cloud method was adopted as the theoretical basis for the present paper. Based on the current status of land resource development and utilization, this study uses objective grading criteria to evaluate the land carrying capacity and analyze the primary risk factors to establish new techniques for the objective evaluation of the land carrying capacity.

2 Study area and research methods

2.1 Study area

Heilongjiang Province is the area with the fastest growth, and it makes the largest contribution to China’s grain production (see Fig. 1). The grain production in this area has been increasing since 2003, and the total amount reached 0.6×10^{11} kg in 2013. The plantation area for grain crops has increased from 7.96×10^6 hm² in 2001 to 1.41×10^7 hm² in 2013, and mid-low-yielding lands account for 70% of the total land. With the acceleration of urbanization and industrialization (Fu et al. 2014), the land that was newly allocated for construction in 2013 had an area of 9.57×10^3 hm², accounting for 54.61% of the total land supply. Because of its long-term exploitation, the soil fertility of the farmlands has been decreasing every year. The organic matter content has decreased at an annual rate of 0.13%; the annual reduction rates in the major nutritional elements were 0.008, 0.002 and 0.012% for N, P and K, respectively. The soil nutrition has been depleted (Li et al. 2008). In short, the farmland resources have decreased rapidly, and land problems such as the rapid expansion of construction land and soil depletion have become increasingly apparent, both of which affect regional sustainable development (Cheng et al. 2015).

2.2 Methods

2.2.1 Establishment of index system

In using the “Guidelines for land-use planning” issued by the FAO and the “Plan for the sustainable development of resource-based cities (2013–2020)” issued by the General

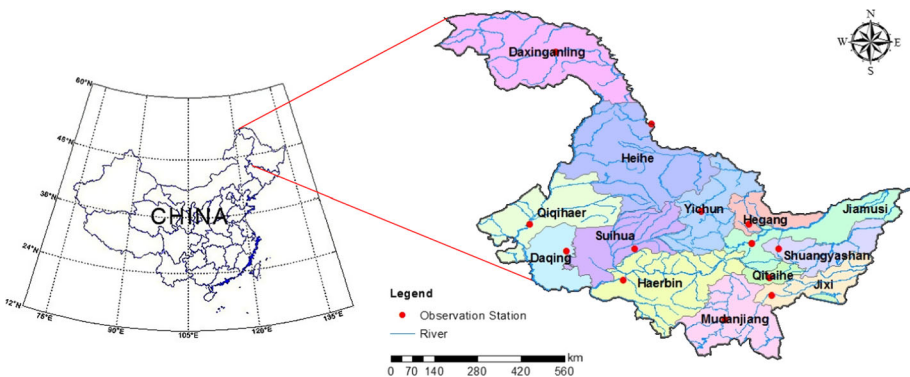


Fig. 1 Geographic location of Heilongjiang province

Office of the State Council of the People's Republic of China as the basic framework and based on the principles of being objective, systematic, dynamic, data-focused and attentive to regional characteristics, an index system was established that employed resource, society, economy and ecology viewpoints (see Table 1). Among the indices, the larger the positive indices are, the stronger the land carrying capacity is; by contrast, the larger the negative indices are, the poorer the land carrying capacity is.

2.2.2 Determination of index weights

The key to objectively evaluating the land carrying capacity is the determination of the weight of the indices. In traditional methods, the weight is determined by assigning an exact value to the indices; a lack of consideration regarding the uncertainty of the indices and the fuzzy relationship between indices can easily affect the evaluation results. Because of these concerns, the present paper accounted for the relative importance of each index; after scoring by experts, the index system was divided into two primary types, namely the primary indices and secondary indices (see Table 1). The weight assignments were the intervals $[0.5, 1]$ and $[0, 0.5]$, and here, the primary indices of the land carrying capacity have a dominant role, with secondary indices in a subordinate position, and they are both interdependent, with mutual influence. In addition, the uncertainty of the indices was also considered, and thus, a multiple stochastic weight assignment was applied to the primary and secondary indices. That is, the multiple interval stochastic weight assignment method was used to simulate the different degrees of contribution by each index to the maximum extent.

2.2.3 Land carrying capacity evaluation model

Here is a brief introduction to the cloud model: Let X be a common set, and $X = \{x\}$ is known as the universe. Regarding the fuzzy set \tilde{A} in universe X , there is a random number with stable tendency $u_{\tilde{A}}(x)$ for any element x' , which is called the degree of membership from x to \tilde{A} . If the elements in the universe are simple and orderly, X can be regarded as the basis of variables, and the membership degree in the X distribution is called the membership cloud. If the elements in the universe are not simple and orderly and according to rule f , X can be mapped to another ordered domain X' , where there is only one x' in X' corresponding to x . Then, X' is regarded as the basic variable, and the membership degree in the X' distribution is called the membership cloud.

(1) Basic concepts

The index system is defined as a cloud space. The evaluation standard C is regarded as the unit of clouds in the evaluation index system, and the actual index value x is regarded as a cloud drop. X falls in C and then obtains a stable tendency of random number $u(x) \in [0, 1]$, which is the membership degree of x for C . The distribution of x on C forms a cloud. The cloud drop is a quantitative expression of the carrying capacity. The overall shape of the cloud reflects the level of the land carrying capacity, which is analyzed by the numerical characteristics of the cloud (expectation Ex and entropy En). Expectation Ex mostly represents the value of C , whereas entropy En represents the random metric in terms of the significance of the index value, which indicates the range of C that can be accepted by C .

The algorithm of the cloud model primarily includes the forward and backward cloud generators (see Fig. 2). In the forward cloud generator, the numerical characteristics

Table 1 Index system for the evaluation of the land carrying capacity

Evaluation index	Equation (units)	Meaning of index
Resource subsystem		
Coordination degree of water and soil (C_1) (+)	Available water resources/total land area ($10^4 \text{ m}^3 \text{ hm}^{-2}$) ★	Degree of match between water and soil resources
Cultivation ratio (C_2) (–)	Arable land area/agricultural land area (%) ★	Degree of arable land use
Rate of land for construction (C_3) (–)	Built-up area/total land area (%) ☆	Degree of non-agricultural land use
Social subsystem		
Urban green space per capita (C_4) (+)	Total area of urban green space/Urban population ($10^{-2} \text{ hm}^2/\text{person}$) ☆	Bearing capacity of land for city environment
Transportation land per capita (C_5) (–)	Total length of road/total population (km/person) ★	Bearing capacity of land resources for travel
Arable land per capita (C_6) (–)	Arable land area/total population ($\text{hm}^2/\text{person}$) ★	Bearing capacity of land to population scale
Urbanization rate (C_7) (–)	Urban population/total population (%) ☆	Level of urban development
Commodity grain per capita (C_8) (+)	Total amount of commodity grain/total population (t/person) ★	Ability to ensure food security
Effective irrigation rate (C_9) (+)	Effective irrigation area/agricultural land area (%) ★	Ability to prevent natural disasters
Economic subsystem		
Grain yield (C_{10}) (+)	Total grain yield/arable land area (t hm^{-2}) ★	Productivity of arable land
Degree of mechanization per unit of arable land (C_{11}) (+)	Total mechanization power/arable land area (kw hm^{-2}) ★	Level of modern agriculture technology
Economic density (C_{12}) (+)	Regional GDP/total land area (10^4 CNY hm^{-2}) ☆	Density of land use
Net income per capita (C_{13}) (+)	Resident’s net income/total population ($10^4 \text{ CNY}/\text{person}$) ☆	Level of economic development
Ecological subsystem		
Solid waste per unit area (C_{14}) (–)	Solid waste/total land area (t hm^{-2}) ☆	Pressure of human activities on land
Fertilizer loading per unit of arable land (C_{15}) (–)	Fertilizer by effective component/arable land area (t hm^{-2}) ★	Pressure of agriculture on soil environment
Wastewater loading per unit land (C_{16}) (–)	Amount of wastewater discharge/total land area ($\text{m}^3 \text{ hm}^{-2}$) ★	Pressure of wastewater on land
Environmental protection investment rate (C_{17}) (+)	Environmental protection capital investment/regional GDP (%) ☆	Ability to control environmental deterioration

(+) positive index, (–) negative index, ★ primary indices, ☆ secondary indices

(Ex , En) of the cloud produce several cloud drops $drop(x_i, u_i)$. By contrast, in the backward cloud generator, the numerical characteristics of the cloud are restored from the numerical value of the cloud.

(2) Evaluation criteria and level of the carrying capacity

Based on the time series formed from quantitative indices, the initial values were obtained through weight assignment. According to the linguistic description, the

evaluation criteria are normally divided into the following five levels: extremely poor, poor, normal, good and extremely good. Therefore, six percentiles of the initial values were selected as the border set to compute the numerical characteristics of the clouds. The cloud drops were generated using the forward cloud generator, and the evaluation criteria were determined according to the “3En” principle using a normal distribution.

Based on the index values at the observation stations, the initial values were obtained via weight assignment; the initial values were entered into the backward cloud generator as the cloud drops to generate the cloud, and the expectation E_x of the cloud was used as the carrying capacity level. To verify the reliability of the evaluation results further, expectation E_x was used to confirm the final membership degree of the carrying capacity (see Fig. 3).

Model steps

Step 1 Normalization of sample data

Assume the sample set is $\{x_{ij}^* | i = 1, 2, \dots, n; j = 1, 2, \dots, p\}$, where c is the j th value of the sample for the i th index and n and p are the number of indices and samples, respectively (see Eq. 1).

$$\begin{aligned} \text{The positive index: } x_{ij} &= \frac{x_{ij}^* - x_{\min}(i)}{x_{\max}(i) - x_{\min}(i)} \\ \text{The negative index: } x_{ij} &= \frac{x_{\max}(i) - x_{ij}^*}{x_{\max}(i) - x_{\min}(i)} \end{aligned} \tag{1}$$

where $x_{\max}(i)$ and $x_{\min}(i)$ are the maximum and minimum of the values of the i th index, respectively, and x_{ij} is the index value after normalization.

Step 2 Determination of the weight of an evaluation index

The random function in MATLAB was used to perform multiple stochastic weight assignments for the primary and secondary indices, synthesizing a $m \times n$ matrix. After

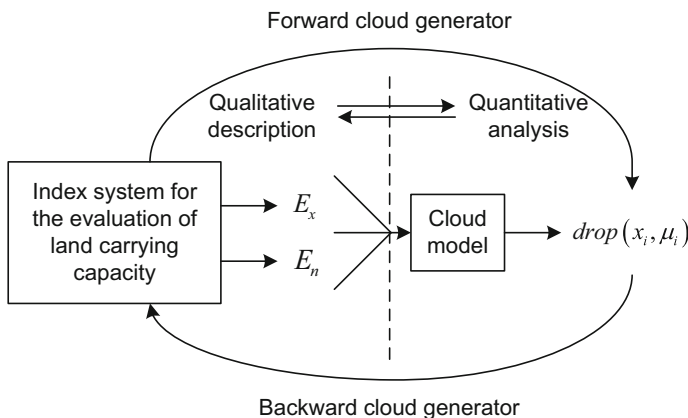


Fig. 2 Algorithm for the cloud model

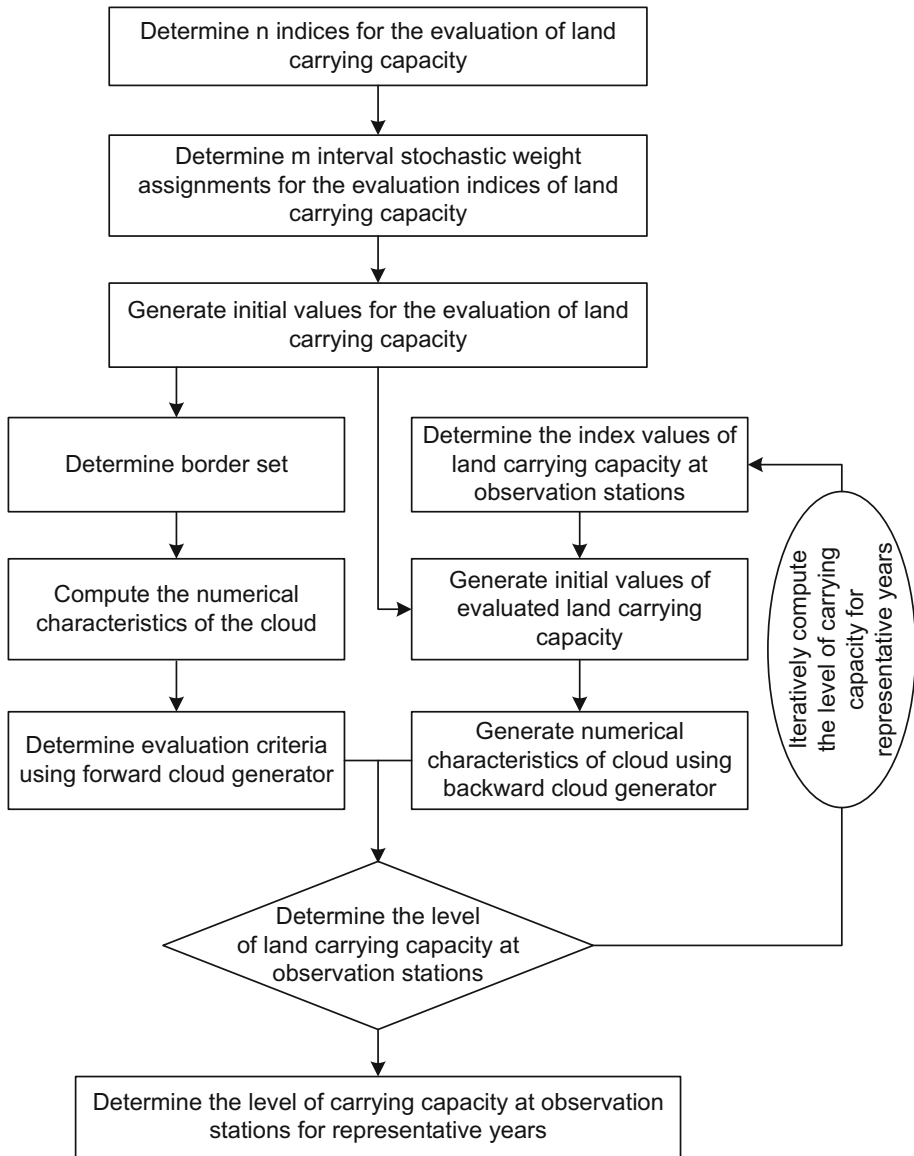


Fig. 3 Flowchart for evaluating the land carrying capacity in the cloud model

normalization, the weighting matrix $w = (w_{mn})$ was obtained, in which m is the number of stochastic weight assignments ($m = 100$).

Step 3 Determination of an initial value

Based on the data (x_{ij}) , an initial value was obtained via Eq. (2).

$$X_{m \times j} = (X_{mj}) = (w_{mn}) \times (x_{ij}) \tag{2}$$

Step 4 Determination of evaluation criteria

Six percentiles of each data in the matrix X were selected as the border set; a, b ($a < b$) were used to represent the mathematical expectation of the adjacent data set in the border set and cloud as generated using the forward cloud generator (see Eq. 3).

$$\begin{cases} Ex = (a + b)/2 \\ En = (b - a)/6 \end{cases} \tag{3}$$

Step 5 Determining the level of the land carrying capacity

The initial values of the indices at the observation stations were obtained via the weighting matrix ($w = (w_{mn})$) and then input into the backward cloud generator (see Eq. 4). The level of the carrying capacity was the grading criterion corresponding to expectation $E'_x(j)$, and the membership degree was determined from Eq. (5).

$$\begin{cases} E'_x(j) = \frac{1}{m} \sum_{m=1}^m R_{mj} \\ E'_n(j) = \sqrt{\frac{\pi}{2}} \times \frac{1}{m} \sum_{m=1}^m |R_{mj} - E'_x(j)| \end{cases} \tag{4}$$

$$\begin{cases} u(j) = \frac{n}{N} \\ n = Ex + 3En - E'_x(j) \\ N = 6En \end{cases} \tag{5}$$

2.2.4 Risk factors of the land carrying capacity system

Each index in the land carrying capacity system impacts the system to a different extent, at different stages of regional development (Pei et al. 2016). Therefore, this paper uses the degree of risk (H_{ij}) to determine the impact of the indicators on the land carrying capacity and to determine the impact of the land carrying capacity of the risk sources.

$$\begin{cases} D_{ij} = 1 - (x_{ij}) \\ H_{ij} = D_{ij} / \sum_{j=1}^p D_{ij} \end{cases} \tag{6}$$

where D_{ij} is the difference between index x_{ij} and the target of system development.

2.2.5 Data source

The evaluation criteria for the land carrying capacity were established on the basis of the index values between 2001 and 2013 in the study area (see Table 2) to evaluate the land carrying capacity of the 13 observation stations in the study area during representative years (see Table 3) and to analyze the risk sources of the land carrying capacity via the degree of risk. These data are from the Heilongjiang Statistical Yearbook (2001–2013), China Statistical Yearbook (2001–2013) and Heilongjiang Agricultural Yearbook (2001–2013).

Table 2 Raw data of the evaluation indices for the years 2001–2013

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
C ₁	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.08	0.08	0.08
C ₂	25.40	25.17	25.64	30.47	32.94	32.50	31.21	33.47	35.11	34.90	37.67	39.39	41.84
C ₃	0.29	0.29	0.30	0.31	0.33	0.32	0.34	0.34	0.34	0.36	0.37	0.38	0.39
C ₄	0.17	0.18	0.19	0.29	0.25	0.18	0.10	0.32	0.30	0.33	0.33	0.34	0.34
C ₅	16.53	16.53	17.07	17.51	17.56	36.45	36.85	39.44	39.59	39.64	40.58	41.49	41.77
C ₆	0.25	0.25	0.25	0.30	0.33	0.32	0.31	0.33	0.35	0.35	0.37	0.39	0.41
C ₇	52.38	53.00	52.59	52.78	53.10	53.50	53.90	55.40	55.50	55.66	56.50	56.90	57.40
C ₈	0.70	0.77	0.66	0.82	0.94	0.99	1.04	1.10	1.14	1.31	1.45	1.50	1.57
C ₉	0.054	0.058	0.056	0.060	0.063	0.068	0.078	0.082	0.090	0.102	0.114	0.129	0.141
C ₁₀	2.76	3.09	2.59	2.72	2.89	3.07	3.35	3.33	3.27	3.79	3.90	3.86	3.78
C ₁₁	1.72	1.83	1.87	1.70	1.80	2.09	2.35	2.38	2.55	2.82	2.87	3.05	3.06
C ₁₂	0.78	0.86	0.98	1.17	1.21	1.36	1.56	1.83	1.83	2.29	2.78	3.03	3.18
C ₁₃	0.39	0.44	0.47	0.54	0.59	0.66	0.74	0.86	0.93	1.05	1.22	1.38	1.54
C ₁₄	0.64	0.66	0.38	0.70	0.71	0.86	0.91	0.99	1.16	1.19	1.33	1.40	1.26
C ₁₅	0.13	0.14	0.13	0.12	0.12	0.13	0.15	0.14	0.15	0.16	0.16	0.16	0.15
C ₁₆	26.21	25.77	26.21	25.11	25.11	25.55	24.01	24.45	24.45	26.27	33.33	33.59	33.83
C ₁₇	0.29	0.39	0.81	0.88	0.85	0.88	0.83	1.19	1.30	1.27	1.21	1.59	1.91

Table 3 Raw data for each index in the study area during the representative years

year	Haerbin	Qiqihaer	Jiamusi	Qitaihe	Shuangyashan	Hegang	Mudanjiang	Yichun	Daqing	Jixi	Heihe	Suihua	Daxinganling
2013													
C ₁	0.36	0.20	0.20	0.16	0.33	0.39	0.34	0.44	0.10	0.29	0.33	0.23	0.42
C ₂	0.37	0.56	0.53	0.32	0.44	0.34	0.14	0.07	0.32	0.42	0.26	0.56	0.03
C ₃	0.74	0.33	0.30	1.14	0.26	0.36	0.20	0.51	1.14	0.35	0.03	0.10	0.02
C ₄	0.33	0.17	0.67	0.20	0.41	0.81	0.10	0.17	0.15	0.51	0.05	0.20	0.20
C ₅	0.36	0.39	0.42	0.39	0.44	0.42	0.39	0.27	0.45	0.40	0.33	0.26	0.50
C ₆	24.25	40.72	55.60	27.74	59.99	55.34	45.51	54.49	30.88	49.05	92.21	37.70	133.77
C ₇	0.20	0.43	0.71	0.21	0.65	0.46	0.21	0.19	0.24	0.50	1.03	0.35	0.33
C ₈	0.48	0.35	0.51	0.59	0.64	0.81	0.59	0.88	0.52	0.63	0.57	0.26	0.86
C ₉	2.67	2.93	3.92	1.71	3.52	2.54	0.73	0.21	2.45	3.00	1.11	3.96	0.04
C ₁₀	7.23	5.19	7.41	5.38	7.95	7.50	5.17	3.00	7.67	7.21	4.21	7.03	1.48
C ₁₁	4.77	3.28	3.18	3.54	3.44	3.51	4.19	3.27	4.66	3.63	2.43	2.65	2.78
C ₁₂	9.44	2.91	2.30	3.89	2.52	2.18	2.81	0.87	19.72	2.54	0.58	3.47	0.25
C ₁₃	2.55	1.62	1.92	2.91	2.09	2.65	2.51	2.36	3.03	2.64	1.87	1.33	2.43
C ₁₄	0.03	0.03	0.02	0.04	0.02	0.03	0.01	0.01	0.02	0.04	0.00	0.01	0.00
C ₁₅	0.25	0.13	0.19	0.18	0.18	0.20	0.16	0.11	0.17	0.15	0.14	0.19	0.05
C ₁₆	75.45	50.39	25.61	87.34	35.19	52.90	23.86	18.17	68.41	39.74	8.03	40.72	5.12
2009													
C ₁	0.28	0.11	0.18	0.15	0.14	0.33	0.28	0.36	0.08	0.18	0.20	0.19	0.25
C ₂	0.36	0.53	0.55	0.30	0.40	0.32	0.13	0.07	0.28	0.37	0.24	0.51	0.03
C ₃	0.65	0.27	0.20	1.01	0.27	0.29	0.17	0.49	0.97	0.35	0.03	0.09	0.02
C ₄	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.92
C ₅	45.12	72.83	119.54	42.77	111.54	85.86	84.58	57.51	59.34	80.23	170.22	68.92	167.15
C ₆	0.19	0.39	0.70	0.20	0.59	0.43	0.19	0.18	0.21	0.44	0.92	0.31	0.32
C ₇	0.48	0.36	0.49	0.57	0.62	0.81	0.55	0.86	0.50	0.63	0.56	0.27	0.87
C ₈	1.35	1.60	3.73	0.90	3.86	2.69	0.85	0.54	1.41	2.64	2.55	2.01	0.67

Table 3 continued

year	Haerbin	Qiqihaer	Jiamusi	Qitaihe	Shuangyashan	Hegang	Mudanjiang	Yichun	Daqing	Jixi	Heihe	Suihua	Daxinganling
C ₉	0.26	0.11	0.39	0.15	0.40	0.47	0.09	0.14	0.10	0.47	0.02	0.16	0.58
C ₁₀	7.06	4.09	5.31	4.50	6.53	6.31	4.55	3.03	6.59	6.04	2.78	6.54	2.13
C ₁₁	3.70	2.65	3.28	3.11	6.09	6.29	3.18	2.24	4.12	5.22	2.91	1.93	1.82
C ₁₂	5.98	1.63	1.33	3.77	1.35	1.38	1.62	0.53	10.00	1.57	0.34	1.74	0.12
C ₁₃	1.73	1.09	1.33	1.65	1.77	2.15	1.67	1.36	2.38	1.69	1.48	0.78	1.77
C ₁₄	6.67	11.76	10.09	27.43	3.96	19.03	7.15	3.45	40.54	5.51	0.24	3.05	1.03
C ₁₅	4.29	0.83	0.62	10.10	2.90	3.51	0.58	0.58	1.47	4.72	0.19	0.23	0.03
C ₁₆	0.23	0.10	0.16	0.10	0.23	0.83	0.15	0.09	0.19	0.39	0.10	0.17	0.05
2005													
C ₁	0.17	0.10	0.12	0.08	0.15	0.20	0.19	0.27	0.09	0.17	0.16	0.12	0.18
C ₂	0.30	0.42	0.46	0.29	0.50	0.43	0.10	0.05	0.21	0.39	0.23	0.45	0.01
C ₃	0.57	0.32	0.18	1.57	0.27	0.29	0.16	0.48	0.80	0.33	0.03	0.08	0.03
C ₄	7.10	5.90	4.70	9.50	7.50	11.70	5.50	15.30	6.80	7.50	3.30	2.50	35.00
C ₅	18.18	25.43	51.46	16.29	50.12	35.03	53.04	30.59	34.83	38.47	62.19	20.34	141.08
C ₆	6.70	5.70	4.10	7.10	5.80	4.20	10.30	6.80	20.00	3.60	6.00	6.50	1.00
C ₇	0.48	0.36	0.50	0.55	0.61	0.81	0.55	0.86	0.48	0.63	0.55	0.27	0.87
C ₈	0.97	1.18	2.22	0.63	2.39	1.88	0.60	0.34	0.89	1.86	1.78	1.28	0.34
C ₉	0.23	0.09	0.27	0.13	0.25	0.23	0.13	0.15	0.08	0.36	0.02	0.15	0.57
C ₁₀	5.89	3.69	3.63	3.10	3.28	3.30	4.14	2.74	5.41	4.03	1.99	4.61	2.12
C ₁₁	2.29	2.21	1.43	2.00	1.39	1.39	2.83	2.40	3.42	1.85	1.96	1.15	2.96
C ₁₂	3.45	1.00	0.74	1.62	0.66	0.77	0.78	0.35	6.61	0.91	0.18	1.01	0.07
C ₁₃	0.97	0.58	0.64	0.83	0.90	1.14	0.84	0.61	1.30	1.04	0.82	0.44	0.85
C ₁₄	9.51	14.46	16.02	28.98	2.23	22.06	23.84	5.22	39.49	4.99	0.35	2.15	2.83
C ₁₅	1.81	0.65	0.37	6.16	0.98	2.09	0.46	0.43	1.01	1.58	0.04	0.08	0.02
C ₁₆	0.47	0.29	0.20	0.31	0.14	0.16	0.35	0.23	0.52	0.15	0.13	0.38	0.10

Table 3 continued

year	Haerbin	Qiqihaer	Jiamusi	Qitaihe	Shuangyashan	Hegang	Mudanjiang	Yichun	Daqing	Jixi	Heihe	Suihua	Daxinganling
2001													
C ₁	0.13	0.05	0.12	0.07	0.12	0.19	0.25	0.15	0.04	0.15	0.10	0.06	0.20
C ₂	0.26	0.43	0.29	0.23	0.32	0.26	0.11	0.04	0.24	0.25	0.14	0.44	0.02
C ₃	0.40	0.28	0.17	1.08	0.27	0.40	0.15	0.48	0.68	0.33	0.03	0.07	0.01
C ₄	0.08	0.12	0.11	0.09	0.15	0.19	0.11	0.26	0.30	0.12	0.03	0.02	0.50
C ₅	1.77	2.17	4.23	12.73	7.35	9.34	5.71	9.03	10.77	7.06	5.94	1.36	23.24
C ₆	0.14	0.33	0.40	0.16	0.46	0.35	0.15	0.09	0.20	0.29	0.55	0.28	0.19
C ₇	0.72	0.63	0.73	0.80	0.71	0.76	0.84	0.92	0.73	0.74	0.39	0.48	0.80
C ₈	0.73	0.65	1.84	0.48	1.69	1.46	0.51	0.25	0.48	1.52	1.17	0.91	0.32
C ₉	0.19	0.08	0.33	0.13	0.36	0.36	0.09	0.16	0.09	0.46	0.02	0.12	0.51
C ₁₀	1.30	0.86	1.37	0.67	1.15	1.11	0.36	0.10	0.57	1.33	0.30	1.42	0.03
C ₁₁	2.20	1.40	1.75	2.18	1.58	1.74	2.42	2.26	1.92	1.86	1.67	1.30	2.09
C ₁₂	2.11	0.71	0.51	0.99	0.42	0.48	0.59	0.24	5.08	0.61	0.12	0.97	0.07
C ₁₃	0.75	0.57	0.58	0.60	0.61	0.62	0.71	0.50	1.18	0.63	0.45	0.41	0.61
C ₁₄	11.54	29.42	16.29	11.61	3.46	17.89	13.69	4.54	32.04	4.36	1.13	1.85	3.98
C ₁₅	1.56	0.68	0.31	5.32	0.56	2.49	0.41	0.36	0.78	1.60	0.05	0.12	0.02
C ₁₆	0.18	0.10	0.12	0.13	0.11	0.13	0.14	0.07	0.13	0.13	0.10	0.16	0.06

3 Results and discussion

3.1 Evaluation criteria for the land carrying capacity

The six percentiles required for the evaluation criteria were generated according to the “General Land-use Planning in Heilongjiang Province (2006–2020)” as sanctioned by the State Council of the People’s Republic of China and “The 12th Five-Year Plan of Land and Resources of Heilongjiang Province” issued by The Provincial Department of Land and Resources of Heilongjiang. Combined with the method for establishing the evaluation criteria, the evaluation criteria were determined as follows (see Fig. 4): Level I [0.02, 0.24] is the lowest and indicates that the impact to the land resources is minimal, thus showing excellent development potential to support regional development; Level III [0.40, 0.55] is the normal level for which the development of land resources has a certain benefit and is coordinated with regional social and economic development; Level V [0.70, 0.91] is the highest and indicates that the impact to the land resources is maximal, that land development has reached its limit and is thus incapable of satisfying the demands of regional development; and Levels II [0.24, 0.40] and IV [0.55, 0.70] are the transition levels of the land carrying capacity for which different management modes and utilization levels will result in the transition of these two levels to other levels.

3.2 Evaluation of the land carrying capacity

By using the years 2001, 2005, 2009 and 2013 as the representative years to verify the evaluation criteria, the level and membership degree of the land carrying capacity were determined and used to evaluate the land development and utilization at each observation station (see Fig. 5).

Figure 5 shows that the land carrying capacity at each observation station continuously increased; this finding is consistent with the trend in land development and utilization in

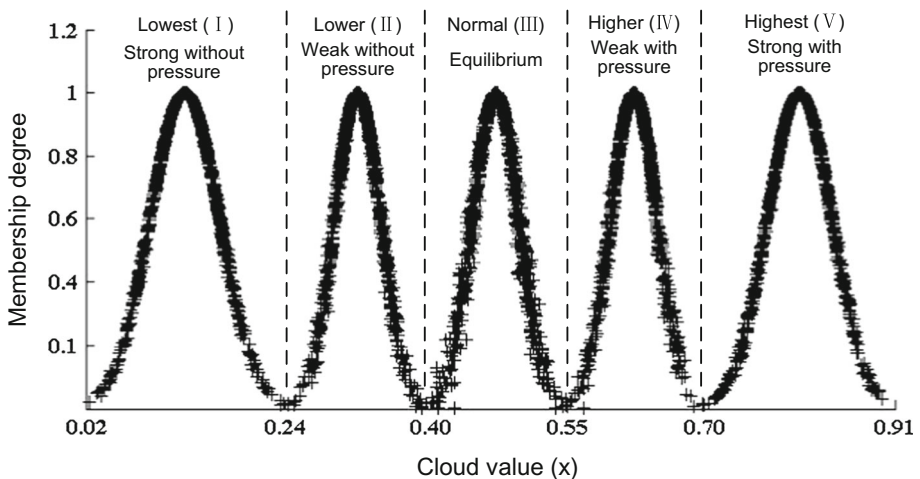


Fig. 4 Evaluation criteria for the land carrying capacity

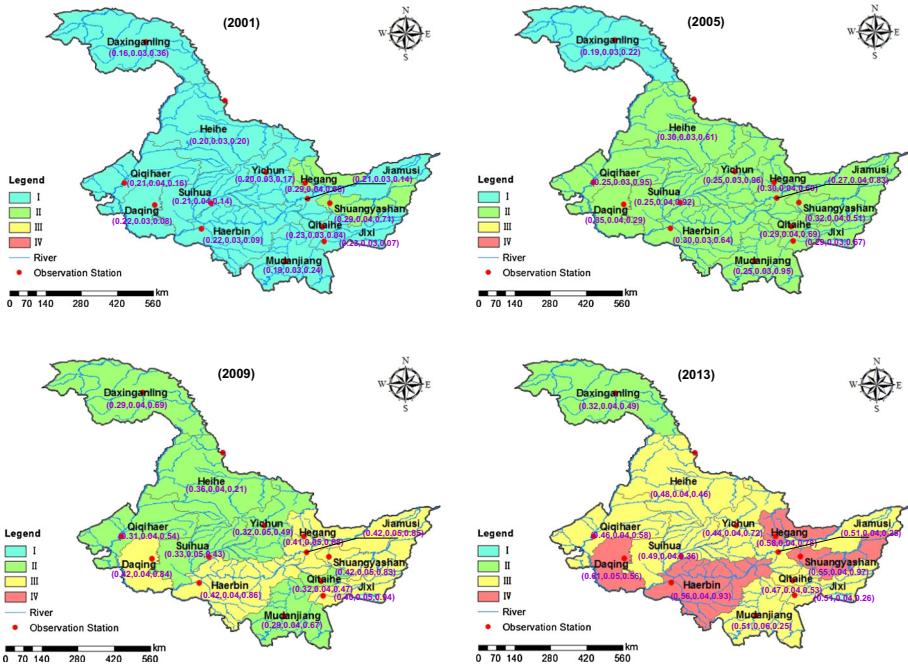


Fig. 5 Spatial variation of land development and utilization in the study area during representative years

Table 2, indicating that the evaluation criteria determined in this paper are reliable and feasible. In addition, when the carrying capacity level changed at each observation station, more than 85% of the membership degree values were high. By contrast, when the carrying capacity level did not change, the membership degree values all exhibited a decreasing trend; this trend is consistent with the trends in land development and utilization, further verifying the reliability of the carrying capacity level.

In the last 12 years, as the centers of regional politics, economy and culture, Haerbin and Daqing have been the areas that have witnessed the biggest changes and fastest increases in the land carrying capacity from levels I to IV (the amplitudes of the changes in *Ex* were 0.34 and 0.39, respectively). The observation stations at which agriculture, mining and tourism were the primary industries witnessed a rapid rise in the land carrying capacity. For example, the level increased from II to IV in Shuangyashan and Hegang, whereas it increased from I to III in Qiqihaer, Jiamusi, Qitaihe, Mudanjiang, Yichun, Jixi, Heihe and Suihua; the rising amplitude of *Ex* was 0.24–0.32. For Daxinganling, which has excellent forest coverage and other natural features, the change in the land carrying capacity level was the lowest. The amplitude of the change for *Ex* was only 0.16.

It is thus known that regional development and industrial structures directly affect the land carrying capacity. With the exception of Daxinganling, the land carrying capacity at other observation stations all reached level III or beyond in 2013. Therefore, it is imperative to scientifically plan and manage land resources to ensure the sustainable supply of land for regional development.

3.3 Identification and evolution of the risk factors of the land carrying capacity system

According to the method for calculating the degree of risk, the top five degrees of risk were summed and used as the degree of risk for the land carrying capacity system. The sum of all the degrees of risk for the subsystem was used as the degree of risk for the subsystem; the change in the degree of risk for the land carrying capacity system and subsystem was thus obtained for the years 2001–2013 (see Fig. 6).

3.3.1 Land carrying capacity system

Figure 6a shows that the evolution of the degree of risk for the system can be divided into two stages, i.e., a fluctuating decrease (2001–2008) and a rapid rise (2009–2013), with a minimum of 39.61% in 2008 and a maximum of 64.44% in 2013.

The indices that stayed in the top five from 2001 to 2008 were the effective irrigation rate (C_9) and net income per capita. The degree of risk decreased from 11.29 to 7.89% and 6.96% with an annual average decrease of 1.27 and 1.23%, respectively. According to Pearson’s correlation analysis, the correlation coefficients of the two indices with this system’s degree of risk are 0.967 and 0.981. Thus, these two indices are the important factors that impact the land carrying capacity. During this period, the mechanization degree per unit area of arable land and the economic density appeared five times as the primary risk factors. Combined with the fact that the income per capita is the index of the economic subsystem, it can be concluded that the economic situation determines the carrying capacity level. This finding is related to the emphasis on industry and urban development and the ignorance or even sacrifice of the economy in the major grain-producing areas. In addition, the coordination degree for water and soil became a primary risk factor in 2002–2005. The likely reason is the impact of financial pressure, which resulted in the decrease in water use on agricultural irrigation, drainage and hydraulic engineering. Notably, the transportation land per capita in 2006–2008 among the primary risk factors and the associated degree of risk increased from 8.35 to 10.66%. This is the opposite of the trend in the changing degree of risk for the system. The likely reason is that the lagging transportation conditions caused the crops not to enter the market effectively, thus hindering the land carrying capacity level. In short, the regional economy and agricultural infrastructure are the primary factors that cause the fluctuating decrease in the degree of risk for the system.

In the years 2009–2013, the degree of risk for the system rapidly increased from 48.72 to 64.44% with an annual growth rate of 1.99%. As mentioned above, the transportation land use per capita (C_5) was the primary risk factor in the system, and it increased from 8.35% in 2006 to 12.89% in 2013 with an annual growth rate of 6.4%. This increase also indicates that

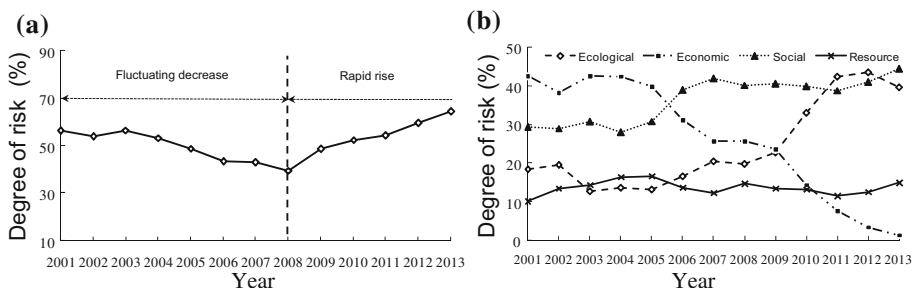


Fig. 6 Evolution of the risk factors in the land carrying capacity system and subsystem

improving the transportation conditions is an effective measure of improvements in the degree of the land carrying capacity. During this period, the solid waste per unit area and the fertilizer loading per unit area of arable land of the ecological subsystem became the primary risk factors continuously for 4 years, with annual average increases of 11.68 and 14.8%, respectively. Wastewater loading per unit land has also emerged as a primary risk factor between 2011 and 2013. Thus, the ecological environment is the primary risk source associated with the regional land carrying capacity. Furthermore, the role of construction land increased with the modernization of the study area. The annual growth rate of the built-up area was 2.94% between 2009 and 2013 or 0.78% greater than it was between 2001 and 2008. Consequently, the rate of construction land use became the primary risk factor between 2010 and 2013. In summary, the ecological environment and urban development at this stage were the primary factors responsible for the rapid rise of the system's degree of risk.

3.3.2 Subsystems

Figure 6b shows that the primary risk factors that affected the land carrying capacity between 2001 and 2009 were concentrated in the social and economic subsystems. The average degrees of risk were 34.29 and 34.55%, respectively (17.32 and 13.84% for the ecological and resource subsystems, respectively). However, the trends for the two subsystems were opposites of one another. Before 2005, the economic subsystem was the primary risk source for the land carrying capacity system. However, after 2005, the degree of risk for the economic subsystem markedly decreased; the amplitude decreased to 16.22% from 2005 to 2009. Therefore, the effect of the economic subsystem on the land carrying capacity lagged behind that of the social subsystem. The primary risk factors that affected the land carrying capacity between 2010 and 2013 were concentrated in the social and ecological subsystems, with average degrees of risk of 40.94 and 39.48%, respectively (6.61 and 12.97% for the economic and resource subsystems, respectively), and there was an increasing trend. Among these factors, the rising amplitude of the degree of risk for the ecological subsystem was as high as 6.7% from 2010 to 2013 or 2.08% higher than that for the social subsystem; this increase is particularly obvious for 2011 and 2012.

In 2001, the sum of the degree of risk for the two primary subsystems that affect the land carrying capacity was 71.68%, whereas the sum of the degree of risk for the other subsystems was 28.32%; the difference was 43.36%. However, in 2013, the sum of the degree of risk for the two primary subsystems that affected the land carrying capacity was 83.91%, whereas the sum of the degree of risk for the other subsystems was 16.09%; the difference between the two widened to 67.81%. Thus, the primary factors that affect the land carrying capacity have become increasingly concentrated in the social and ecological subsystems (the sum of the degree of risk for the two subsystems increased by 36.38% in 12 years).

3.4 Suggestions and measures

(1) The industrial structure is the direct cause of the land carrying capacity level, and it is necessary to plan the regional development strategy and the resource utilization plan scientifically and rationally. For example, we can solve the problem of adverse effects and hazards pertaining to land use by increasing our investment in the protection and management of land in a region with a better economic base. For a good agricultural foundation, in view of the fact that the decreasing benefits of the northeast region were brought on by the increase in the quantity of cultivated land (Zhang and Jiao 2015), it is necessary to expand the extension of regional industry and promote the rational allocation of land

resources in the areas with a good agricultural foundation. For a good industrial foundation, the emission of pollutants can be controlled through a land ecological compensation mechanism. In other words, the development, improvement and management of land resources should stand on the characteristics of the regional industrial structure, which is the primary measure for improving the land carrying capacity.

(2) The degree of risk associated with the land carrying capacity system has significant gradual effects, and it is necessary to grasp the different stages of regional social and economic development accurately and to effectively identify the risk sources of the land carrying capacity. It is concluded that the primary source of the impact of the land carrying capacity is the process of regional agricultural production and urbanization in the analysis of the risk degree from individual indicators. It is necessary to improve agricultural production with all types of policies and to increase the financial support of agricultural production to improve the carrying capacity of the land because the urbanization process is the inevitable trend in social development. This support includes measures such as increasing farmer income, improving agricultural infrastructure, and accelerating the promotion of science and technology.

4 Conclusions

Based on the current situation of regional land development and utilization and the selection of 17 indices from the viewpoints of factors such as the resources, society, economy and ecology, an index system for the evaluation of the land carrying capacity has been established. Based on a rigorous data survey and using a cloud model, the evaluation criteria and the level of the land carrying capacity were determined. In addition, the primary risk sources of the land carrying capacity were also analyzed.

1. A forward cloud generator was used to determine the evaluation criteria of the land carrying capacity as follows: level I [0.02, 0.24], level II [0.24, 0.40], level III [0.40, 0.55], level IV [0.55, 0.70] and Level V [0.70, 0.91].
2. A backward cloud generator was used to evaluate the land carrying capacity at each observation station during representative years; the stations all exhibited a continuously increasing trend. Furthermore, the regional development and industrial structure are the primary factors that affect the carrying capacity level.
3. The primary risk factors for the land carrying capacity were determined via the degree of risk. The primary risk factors were an efficient irrigation rate and the net income per capita between 2001 and 2008 as well as transportation land use, solid waste and fertilizer consumption between 2009 and 2013. The risk source for the land carrying capacity system was converted from economic and social subsystems to ecological and social subsystems between 2001 and 2013.

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