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Multi-Dimensional Evaluation of Land Comprehensive Carrying Capacity Based on a Normal Cloud Model and Its Interactions: A Case Study of Liaoning Province

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Abstract: Studying land comprehensive carrying capacity (LCCC) is the foundational and key requirement for determining land development planning and urban spatial development patterns of a region. However, the traditional evaluation method discounts the fuzziness and randomness of the evaluation index and its results. The cloud model combines randomness and fuzziness to reveal the correlation between randomness and fuzziness using numerical feature entropy and is used to represent the granularity of a qualitative concept. This study used the Liaoning Province as the study area, and developed a multi-dimensional evaluation index system for LCCC using a normal cloud model. Based on this, the relationship between the different elements of geological condition, resources and environment, economic scale and urban construction were studied using the coupling coordination degree model that reflected not only the system interactions but also the strengths of its degree of coordination. Our results were as follows: (1) numerical feature entropy were evaluated to determine the carrying capacity level of the land, and comprehensive land carrying capacity evaluations were conducted in terms of both quantitative results and the reliability of the results, promoting the scientific application of uncertainty theory in the field of comprehensive land evaluation as well as carrying capacity. (2) Liaoning Province's prefecture-level cities had distinctly different LCCC, demonstrating "low in the west and high in the east" spatial distribution characteristics. Cities with established economies and relatively strong infrastructures had larger comprehensive land carrying capacities. Overall, there was considerable consistency across the region, though the "low in the west and high in the east" spatial distribution characteristics affected the degree of coordination.

Keywords: land spatial planning; comprehensive carrying capacity of land; normal cloud model; coupling coordination degree; Liaoning Province

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1. Introduction

Land comprehensive carrying capacity (LCCC) is the threshold population along with the scale and intensity of various human activities that can be supported by the land resources of a particular area, under specific environmental and resource constraints [1,2]. The influence and interplay of these factors lead to shifts in the area's total carrying capacity (Figure 1).

While specific needs such as conservation and development oriented towards territorial spatial planning are not relative or contradictory, the manner in which territorial spatial planning could be best achieved and the basic position of LCCC within it, still face challenges. Particularly, the qualitative conceptualization and quantitative representation of LCCC reveal the intrinsic relevance of randomness and fuzziness, hence making the need for LCCC evaluation universal [3,4]. Currently, extensive local and global research has been conducted on the total carrying capacity of land [5–10]. Despite the differences in the current framework, index system and evaluation methods, there are obvious common features, acknowledging that LCCC is a complex system; that the past judgment evaluation of overload are no longer applicable, and that the idea of multi-element, multi-indicator and multi-level evaluation has become a basic consensus; however, the representative methods of LCCC evaluation, such as the agro-ecological zone, ecological footprint, and model index methods, are uncertain, subjective, and have other defects [11–15]. Enrichment and diversification trends are seen through research findings, which have gradually shifted from the isolated evaluation of a region's total carrying capacity to the combinatorial evaluation of its temporal and spatial characteristics [16,17], coupling coordination degree analysis [18], index early warning analysis [19], dynamic impact effect, etc.

Randomness and fuzziness of indicators are typically not included in research methodologies, which substantially lower the reliability of the findings. The representation and processing of uncertain knowledge are important challenges faced by artificial intelligence, with randomness and ambiguity being the two most fundamental types of uncertainty [20]. However, research on knowledge representation methods has mainly focused on extracting qualitative concepts from quantitative data, and not on developing cognitive models for the bidirectional transformation of qualitative concepts and quantitative data. Based on normal distribution and normal membership functions, the expectation (Ex), entropy (En), and super-entropy (He) factors were used to address the uncertainty between quantitative and qualitative concepts through a normal cloud generator [21,22]. Normal cloud models have been used in the subject areas of land ecological security, mineral resource sustainability, risk assessment, and carrying capacity [23–27]. Due to human-land relationships being complex territorial systems (containing multiple systems such as populations, resources, environments, social economies, etc.), and the general lack of knowledge on geological and geographical hazards, it is impossible to balance randomness and fuzziness while evaluating LCCC. The normal cloud model that was developed based on normal distributions and fuzzy mathematics is useful for addressing this. The normal cloud model generates quantitative conversion values of qualitative concepts to reflect the uncertainty of the integrated carrying capacity of land through a specific structure generator which includes Ex, En, and He.

The thorough assessment of carrying capacity is crucial for meeting the multi-level decision-making requirements of provincial spatial planning, and optimizing sustainable land development [28–30]. Coupling between resources, environmental background conditions, and human socioeconomic activity contributes towards addressing the carrying capacity of a region. This analysis considers the mechanisms of interaction between LCCC subsystems [31], and provides crucial information for assessing the state of land spatial development in order to assess and prevent potential challenges in the future. The concept of bearing capacity is as uncertain as that of complex phenomena and things in nature and human society. This study uses the normal cloud model technology to generate the quantitative conversion value of the qualitative concept of LCCC. Because the specific structure generator formed relaxed the preconditions of normal distribution, and accurately determined that the membership function was relaxed to the expected function of constructing normal membership distribution. It is a universal solution to the uncertainty of the conversion process between qualitative and quantitative analysis of LCCC.

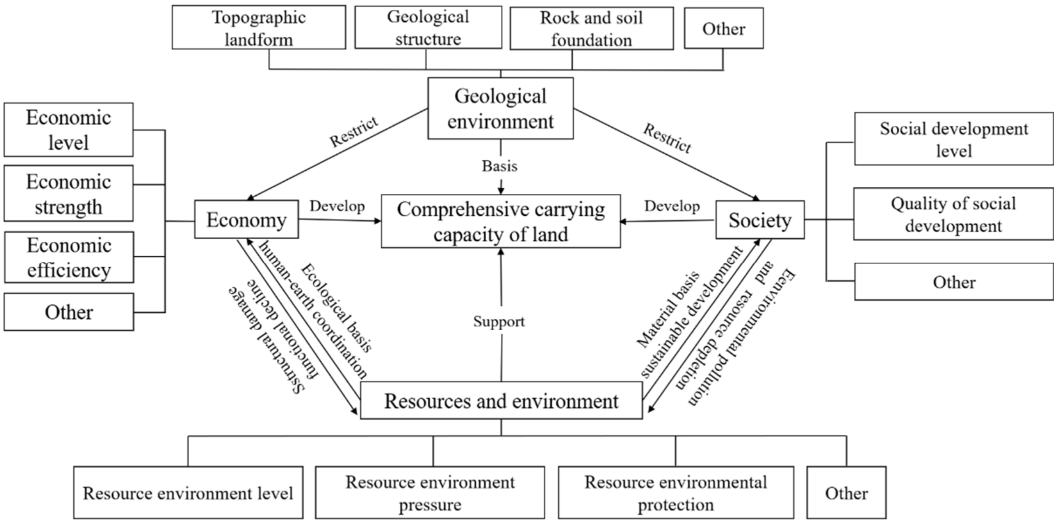

Figure 1. Theoretical framework of LCCC.

2. Materials and Methods

2.1. Study Area

With a geographic area of 148,400 km^2, the Liaoning Province is located between the latitudes 38° and 43° N, and longitudes 118° and 125° E in the northern part of China (Figure 2). The horseshoe-shaped mountains and hills in this region are divided into Eastern and Western sections that fall into the central plain and slope down towards the Bohai Sea. It is an important industrial and agricultural hub of China. However, the low rate of land resource use, uneven regional resource distribution, and tight resource and environmental limitations in this region have prevented sustainable social and economic development. In recent years, Liaoning Province has rapidly established a regional social economy by rejuvenating historic industrial bases in Northeast China. Simultaneously, issues such as the lack of available land resources, and uneven and disorganized regional growth are becoming more prominent. Resolving these issues and ensuring long-term development of a social economy will improve the coordination and order of LCCC in this system.

2.2. Data Sources

This study included 14 prefecture-level cities in the Liaoning Province as basic research units. As shown in Table 1, land use and geological data were mainly obtained from the survey results of land use change in Liaoning Province (2016) and the DEM (Digital Elevation Model) from the Data Center of Resources and Environment Science, Chinese Academy of Sciences. Resource, environmental, economic scale, and urban construction data were obtained from the China City Statistical Yearbook. Calculations were performed using ArcGIS software.

Table 1. Data source and description.

Data Types	Year	Data Descriptions	Coordinate System	Data Sources
Land use data	2016	Vector data	WGS84	The survey results of land use change in Liaoning Province
Geological data	2016	Vector data	WGS84	The survey results of land use change in Liaoning Province
DEM	2000	Grid data	WGS84	http://www.resdc.cn/ (accessed on 8 August 2020)
Resource and Environmental Data	2016	Statistical data		China City Statistical Yearbook
Economic Data	2016	Statistical data	WGS84	China City Statistical Yearbook
Urban Construction Data	2016	Statistical data	WGS84	China City Statistical Yearbook

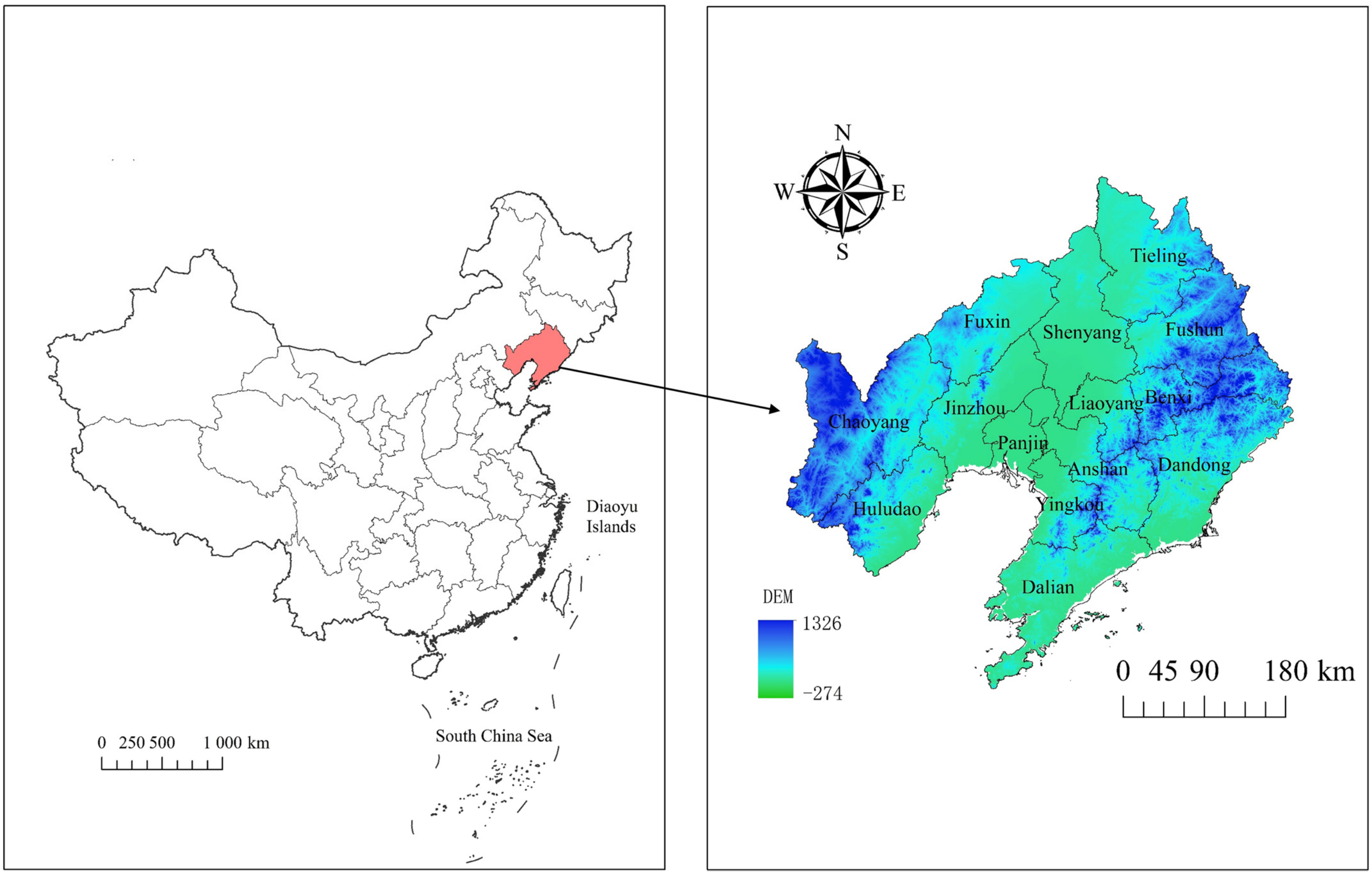

Figure 2. Location of the study area.

2.3. Research Methodology

2.3.1. Construction of LCCC Evaluation Index System for Liaoning Province

Carrying capacity assessments model the potential self-sufficiency of land [17,32,33], and while some existing carrying capacity assessment systems provide important insights, modern urban systems complicate the process by requiring sustainable lifestyles that both limit environmental overdraft and provide the necessary resources for human well-being. This inevitably creates an integrated system design process that encompasses social, economic, resource-environmental and other infrastructural conditions [2,12,34]. Furthermore, the translation of carrying capacity as a vague concept into a functional and quantitative approach is a challenge, especially as the assessment of carrying capacity is even more important with a functional orientation of the land [9,35]. A multi-dimensional LCCC index system including the geological condition, resources, and environment was used to select 19 representative indices based on an analysis of the existing index system, while simultaneously considering the overall actual situation in Liaoning Province (in adherence with the principles of accessible, dominant, and comprehensive index selection). The geographical topography and geological structure were chiefly indicated by the geological condition of the capacity subsystems. The economic scale carrying capacity subsystem primarily indicated the economic level, intensity, and efficiency of the study area. The indicators in the urban construction carrying capacity subsystem primarily indicated city level and infrastructure quality. The resource and environment carrying capacity subsystem primarily indicated the resource and environment level, pressure, and protection status. Therefore, the weight of the LCCC index system based on its geological condition, resources and environment, economic scale, and urban construction was determined using the entropy method and the obtained membership matrix of LCCC for Liaoning Province (Table 2).

Table 2. Evaluation index system of LCCC in Liaoning Province.

Subsystem	Number	Indicator	Attribute	Weight
Geological condition	A1	Slope	Negative	0.03
	A2	The area ratio of settlement area	Negative	0.05
	A3	The area ratio of geological disaster-prone areas	Negative	0.02
Resources and environment	A4	Per capita cultivated land area	Forward	0.07
	A5	Per capita water resources	Forward	0.15
	A6	Discharge of industrial wastewater per 10,000 yuan Gross Domestic Product (GDP)	Negative	0.02
	A7	The application amount of chemical fertilizer	Negative	0.03
	A8	Industrial sulfur dioxide emissions of 100 million yuan GDP	Negative	0.02
	A9	The comprehensive utilization rate of general solid waste (%)	Forward	0.03
Economic scale	A10	Grain yield per unit area	Forward	0.05
	A11	Per capita GDP	Forward	0.10
	A12	Per capita disposable income of urban residents	Forward	0.05
	A13	Average investment in fixed assets	Forward	0.12
	A14	Average GDP	Forward	0.04
Urban construction	A15	Urbanization rate	Forward	0.05
	A16	Urban population density	Negative	0.03
	A17	Per capita urban road area	Forward	0.03
	A18	Per capita construction land area	Forward	0.06
	A19	Per capita park green area	Forward	0.05

2.3.2. Evaluation Model Based on Normal Cloud

The normal cloud model incorporates the ambiguity and randomness of genuine language to investigate its value of uncertainty. Its advantages include the ability to accommodate ambiguity and randomness of quantification and grading of the LCCC assessment index, and its ability to significantly lessen the impact of subjective factors on evaluation outcomes. This study developed an assessment model based on the normal cloud (Figure 3).

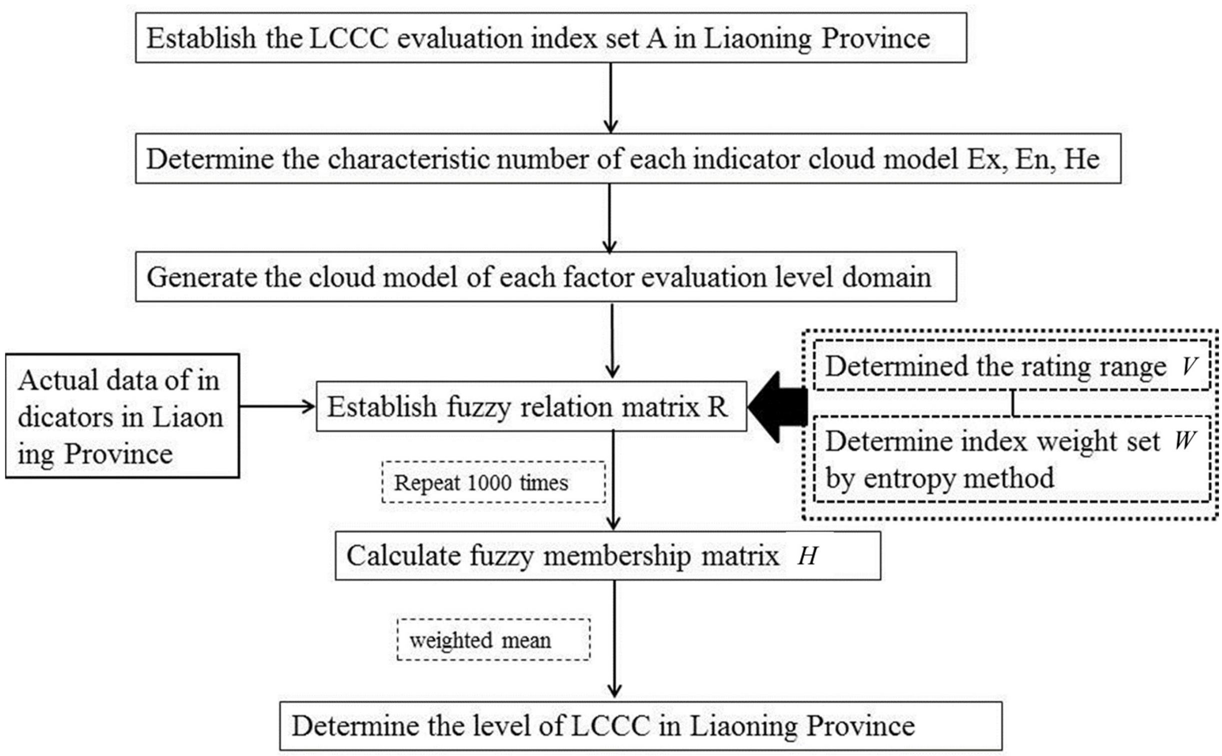

Figure 3. Flow chart of LCCC evaluation method based on normal cloud model.

The normal cloud model is characterized by three values of Ex, En, and He [20,36,37]. Ex is the expectation of the distribution of cloud droplets in the universe space, and En is the uncertainty measure of the qualitative concept, which is determined by the randomness and fuzziness of the concept. It not only reflects the degree of dispersion of cloud droplets that can represent the qualitative concept, but also reflects the range of cloud droplets that can be accepted by the concept in the universe space. He is the uncertainty measure of entropy, that is, the entropy of entropy, which is determined by the randomness and fuzziness of entropy, and reflects the cohesion of the uncertainty of all points representing the linguistic value in the number field space, that is, the cohesion of cloud droplets. The greater the He, the greater the dispersion of cloud droplets, the greater the randomness of membership, and the greater the "thickness" of cloud. The cloud generator is used to generate the affiliation distribution of this particular point x belonging to the concept according to the determination of the point x in the set A [20,38,39].

The normal cloud model can expand the normal distribution to pan-normal distribution, and measure the degree of deviation from the normal distribution with He. This processing method is more relaxed than using the normal conditional distribution alone, and is simpler than the joint distribution, which is easy to express and operate [20,38]. The precise operation stages were as follows:

(1) Established the LCCC evaluation index set *A*, where *A* = {*A1*, *A2*, *A3*, . . . , *A19*}.

(2) Determined the rating range *V*, where *V* = {*V1*, *V2*, *V3*, . . . , *V19*}. The fuzzy relation matrix *R*, where *R* = {*R1*, *R2*, *R3*, . . . , *R19*}, was constructed, which was the membership degree of evaluation index set *A* in evaluation grade domain *V*. In this study, the normal cloud model was used to calculate the expected value of membership degree, and index I corresponding to grade J.

(3) ${x_{ij}}^1$ and ${x_{ij}}^2$ represented the upper and lower boundary values of grade *j*, respectively, and the entropy of index *i* corresponded to grade *j*. The value of super entropy He was determined according to previous studies [40].

$$Ex_{ij} = \left(x_{ij}^1 + x_{ij}^2\right)/2 \tag{1}$$

$$En_{ij} = \left|x_{ij}^1 + x_{ij}^2\right|/2.355 \tag{2}$$

(4) Calculated fuzzy membership matrix *H*: In MATLAB, used the forward cloud generator to obtain the membership degree H_{ij} of each evaluation index at different grades. To ensure the accuracy and reliability of the evaluation results, the forward cloud generator was run *N* times, and the average value of the results was used for subsequent analyses.

(5) Due to the complexity, ambiguity and uncertainty of the index system, and to incorporate several subjective factors while determining weights, the entropy weight method was adopted to determine the weight coefficient set *W*, where *W* = {*W1*, *W2*, *W3*, . . . , *W19*} of 19 indices.

(6) To facilitate the comparison and coordination analysis of LCCC, the membership matrix *H* was weighted and averaged as [40]:

$$Y_l = \sum_{p=1}^{q} pH_{lp} / \sum_{p=1}^{q} H_{lp} \tag{3}$$

where H_{lp} is the membership degree of the corresponding grade of the Lth-row and Pth-column element in *H*, and Y_l is the evaluation index of this index.

(7) Calculated the LCCC index *Z* [40]:

$$Z = \sum_{\mathrm{l}=1}^{\mathrm{s}} \mathrm{Y_l} \times \mathrm{W_l} \tag{4}$$

2.3.3. Coupling Coordination Degree Model

This study used the concept and model of capacity coupling from physics and the multi-system coupling degree formula [41], and constructed a LCCC coupling degree model system. Its functional expression is as follows [42]:

$$C = \left[\frac{U_{geo} \times U_{ecos} \times U_{econ} \times U_{soc}}{\left(\frac{U_{geo}+U_{ecos}+U_{econ}+U_{soc}}{4} \right)^4} \right]^{\frac{1}{4}} \tag{5}$$

where U_{geo}, U_{ecos}, U_{econ}, and U_{urb} represent the carrying capacity index of four subsystems (geological condition, resources and environment, economic scale, and urban construction), respectively, and C is the coupling degree of the LCCC system, with values between 0 and 1. When C is 1, the coupling degree of the LCCC system is maximized, and the system reaches a benign interactive state and tends to be orderly. When C is 0, the coupling degree of the LCCC system is the lowest, and the system is disorderly and chaotic.

To further explore coordination of the overall LCCC system based on the coupling degree model, which only reflects the correlation degree among the subsystems, this study used the coordination degree model. Its formula is as follows [43,44]:

$$O = \sqrt{C \times T} \tag{6}$$

$$T = \alpha U_{geo} + \beta U_{ecos} + \theta U_{econ} + \lambda U_{urb} \tag{7}$$

where O is the degree of coordination, T is the evaluation index of LCCC, and α, β, θ, and λ are the weights of the four subsystems (geological condition, resources and environment, economic scale, and urban construction), respectively. These weights are different from those determined by the above entropy method, and were determined subjectively because of their compensatory effect on the LCCC system. This study emphasized the equal importance of the four subsystems, therefore, $\alpha = \beta = \theta = \lambda = 1/4$.

2.4. Normal Cloud Membership Degree of Different Grades

To determine the evaluation standard for each index in ArcGIS 10.2, the natural discontinuity classification method was used. The evaluation standard for the LCCC evaluation index for the Liaoning Province was established in accordance with the normal cloud model's principles, and the digital characteristics of the model corresponding to each evaluation index were calculated (Table 3), where "Ex" reflects the average level of the evaluation results (i.e., the current level of the evaluation object) and "En" reflects the dispersion of the cloud image (i.e., the reliability of the current evaluation results). Larger "En" values indicate lower result reliability, while "He" reflects the condition of the cloud drops [45].

The evaluation index value and its accompanying digital characteristics were run 1000 times using the normal cloud generator, establishing the evaluation index's normal cloud membership function. Finally, the average value was used to determine each index's membership level.

Table 3. Normal cloud membership degree of different grades of LCCC in Liaoning Province.

Number	Different Evaluation Grades Ex, En, He				
	Low	Lower	Medium	Higher	High
A1	(10.79, 2.84, 0.10)	(6.20, 1.07, 0.01)	(3.88, 0.90, 0.01)	(1.95, 0.73, 0.01)	(0.74, 0.29, 0.01)
A2	(91.13, 7.01, 0.10)	(52.88, 25.47, 1.00)	(14.58, 7.05, 0.10)	(3.85, 2.06, 0.10)	(0.71, 0.60, 0.01)
A3	(19.63, 3.46, 0.10)	(13.23, 1.97, 0.10)	(8.50, 2.04, 0.10)	(3.90, 1.87, 0.10)	(0.85, 0.72, 0.01)
A4	(0.06, 0.01, 0.001)	(0.08, 0.01, 0.001)	(0.10, 0.01, 0.001)	(0.14, 0.02, 0.001)	(0.22, 0.05, 0.001)
A5	(304.08, 13.30, 1.00)	(381.17, 52.17, 1.00)	(857.95, 352.74, 1.00)	(1648.39, 318.54, 1.00)	(2624.87, 510.7, 1.00)
A6	(5.44, 1.16, 0.01)	(3.54, 0.45, 0.01)	(2.61, 0.33, 0.01)	(1.61, 0.52, 0.01)	(0.84, 0.14, 0.01)
A7	(59.15, 5.48, 0.10)	(39.15, 11.51, 0.10)	(22.80, 2.38, 0.10)	(14.50, 4.67, 0.10)	(6.70, 1.95, 0.10)
A8	(530.7, 182.5, 10)	(221.04, 80.39, 5.00)	(104.08, 18.94, 1.00)	(58.16, 20.05, 1.00)	(31.80, 2.34, 0.10)
A9	(14.21, 6.97, 0.50)	(33.72, 9.59, 0.50)	(54.65, 8.18, 0.50)	(75.39, 9.44, 0.50)	(90.91, 3.74, 0.10)
A10	(50488, 166.1, 10)	(5793, 466.8, 10)	(6584, 204.99, 10)	(7075,212.02,10)	(8121.67, 676.58, 30.00)
A11	(23,785.00, 1326.54, 100.00)	(30,746.00, 4585.14, 400.00)	(38,943.00, 2376.22, 200.00)	(44,549.55, 2385.18, 200.00)	(72,413.85, 21,278.77, 2000.00)
A12	(22,884.00, 930.79, 50.00)	(25,159.00, 1001.27, 50.00)	(27,737.50, 1188.54, 50.00)	(31,729.50, 2201.70, 100.00)	(36,728.50, 2043.74, 100.00)
A13	(112.66, 22.70, 1.00)	(209.38, 59.44, 3.00)	(395.60, 98.70, 5.00)	(647.17, 114.94, 5.00)	(1131.01, 295.97, 10.00)
A14	(492.69, 109.50, 10.00)	(824.80, 172.55, 10.00)	(1303.82, 234.26, 10.00)	(2035.26, 386.92, 20.00)	(3953.48, 1242.14, 80.00)
A15	(46.65, 1.81, 0.10)	(53.59, 4.08, 0.10)	(62.14, 3.18, 0.10)	(70.68, 4.08, 0.10)	(78.02, 2.15, 0.10)
A16	(2622.50, 249.26, 15.00)	(2026.00, 257.32, 15.00)	(1418.50, 258.60, 15.00)	(858.00, 217.41, 10.00)	(564.00, 32.27, 3.00)
A17	(6.51, 0.43, 0.01)	(9.36, 1.99, 0.01)	(12.29, 0.50, 0.01)	(13.58, 0.60, 0.01)	(16.79, 2.13, 0.01)
A18	(353.35, 5.72, 0.10)	(405.57, 38.63, 1.00)	(455.92, 4.13, 0.10)	(471.43, 9.04, 0.10)	(533.90, 44.00, 1.00)
A19	(9.41, 0.35, 0.01)	(10.29, 0.39, 0.01)	(10.92, 0.14, 0.01)	(11.53, 0.37, 0.01)	(13.35, 1.17, 0.01)

3. Results

3.1. Evaluation of LCCC

There were distinct differences in the LCCC of each prefecture-level city in the Liaoning Province, as shown by their LCCC evaluation indices (Table 4), and the cumulative LCCC histogram (Figure 4). Dalian had the highest LCCC, while and Fuxin had the lowest, with a difference of up to 0.5 between them. These cities had established economies and relatively strong infrastructure. Despite Fuxin's carrying capacity for resources and the environment being 1.22 times more than Dalian's, Fuxin's carrying capacity for economic scale was less than half of Dalian's. The two largest cities in Liaoning Province in terms of total land-carrying capacity were Dalian and Shenyang. Although Dalian had the lowest carrying capacity for resources and the environment, its carrying capacity for economic scale was much higher than that of other cities. Thus, it maintained the highest LCCC in Liaoning Province, which was consistent with the current state of land development in the region.

Table 4. Evaluation index of LCCC in Liaoning Province.

City	Geological Condition	Resources and Environment	Economic Scale	Urban Construction	LCCC
Shenyang City	0.23	0.92	1.42	0.65	3.22
Dalian	0.26	0.89	1.48	0.62	3.24
Anshan	0.21	0.96	1.22	0.61	3.00
Fushun	0.24	1.12	1.08	0.61	3.06
Benxi	0.25	1.13	1.14	0.64	3.16
Dandong	0.26	1.54	0.68	0.58	3.07
Jinzhou	0.26	1.33	0.72	0.61	2.92
Yingkou	0.27	1.28	0.79	0.65	2.98
Fuxin	0.22	1.22	0.67	0.64	2.74
Liaoyang	0.20	1.26	0.74	0.69	2.88
Panjin	0.23	1.31	0.85	0.66	3.06
Tieling	0.29	1.36	0.68	0.61	2.94
Chaoyang City	0.22	1.26	0.67	0.67	2.83
Huludao	0.27	1.13	0.67	0.69	2.77

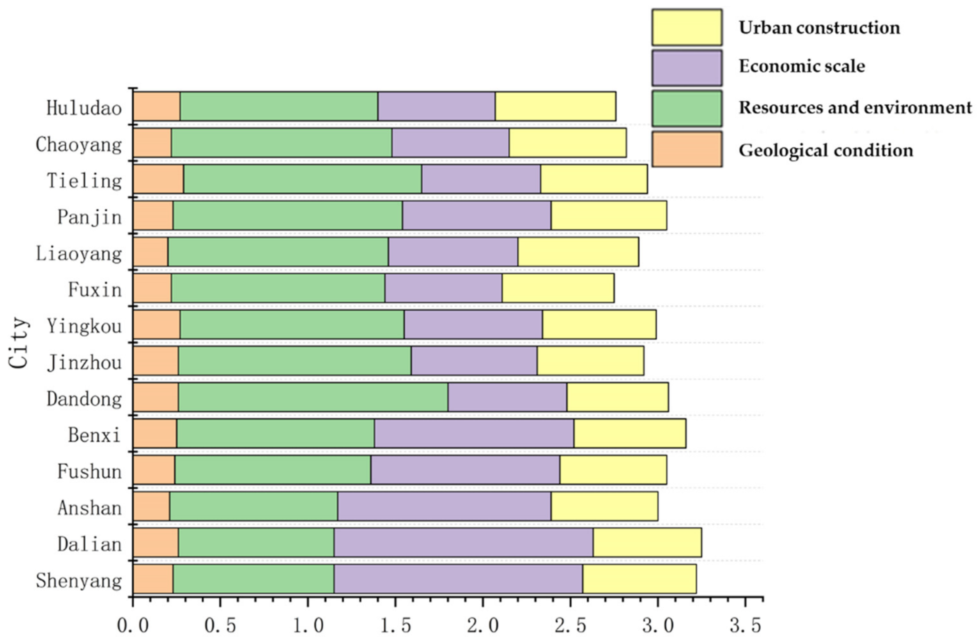

Figure 4. Stacking histogram of LCCC subsystem.

Using the natural discontinuity classification method in the ArcGIS software, LCCC values were divided into five categories: low, relatively low, medium, relatively high, and high (the natural breakpoint method is a statistical method for grading and classifying classes according to the distribution of numerical statistics, which maximizes the difference between classes) [46,47]. A spatial distribution map of these categories was then created to further analyze the LCCC (Figure 5). In the Liaoning Province, the "low in the west and high in the east" geographical distribution characteristic was distinctly visible in Figure 4, which illustrated the spatial differentiation of LCCC. From a large-scale perspective, Liaoning Province's total land carrying capacity was relatively high, with only four prefecture-level cities being classified as low or relatively low. These cities' comparatively low economic carrying capacities, per capita GDP, per capita investment in fixed assets, and other variables with high weights had an impact on the total land carrying capacity. While Huludao, Chaoyang, and Fuxin in the west belonged to the low and relatively low levels of LCCC, Dalian, Dandong, Benxi, and Fushun are in the east of Liaoning Province and showed an upward trend. Economic development in the western region was gradual and its overall level was low because of unfavorable transportation conditions, limited resources and environment, and weak industrial foundations.

3.2. Coupling and Coordination Degrees Analysis

Considering findings from previous studies [14–25] and using the ArcGIS software and natural discontinuity classification method, the cities were divided into four categories based on their degree of coupling: barely coupled, primary coupling, intermediate coupling, and good coupling. They were also classified into five categories based on degree of coordination: barely coordinated, primary coordination, intermediate coordination, good coordination, and high-quality coordination. The degree of coordination refers to the degree of benign coupling during interaction. The degree of coupling refers to the degree of interaction between the two sides, regardless of the advantages and disadvantages. According to Figure 6, there was general consistency in the degrees of coupling and coordination of the LCCC system among Liaoning Province's prefecture-level cities.

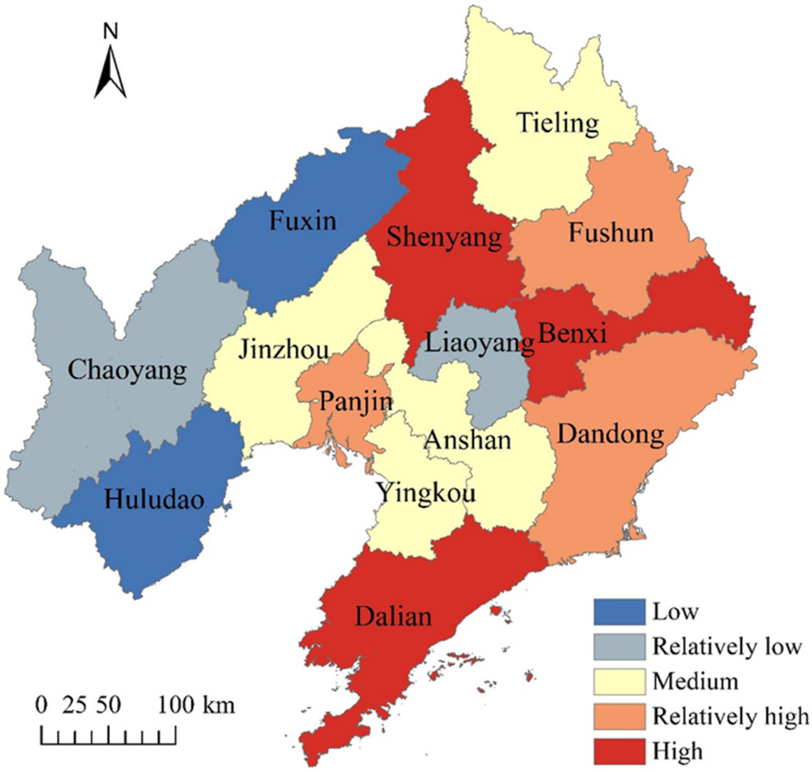

Figure 5. Spatial distribution pattern of LCCC in Liaoning Province.

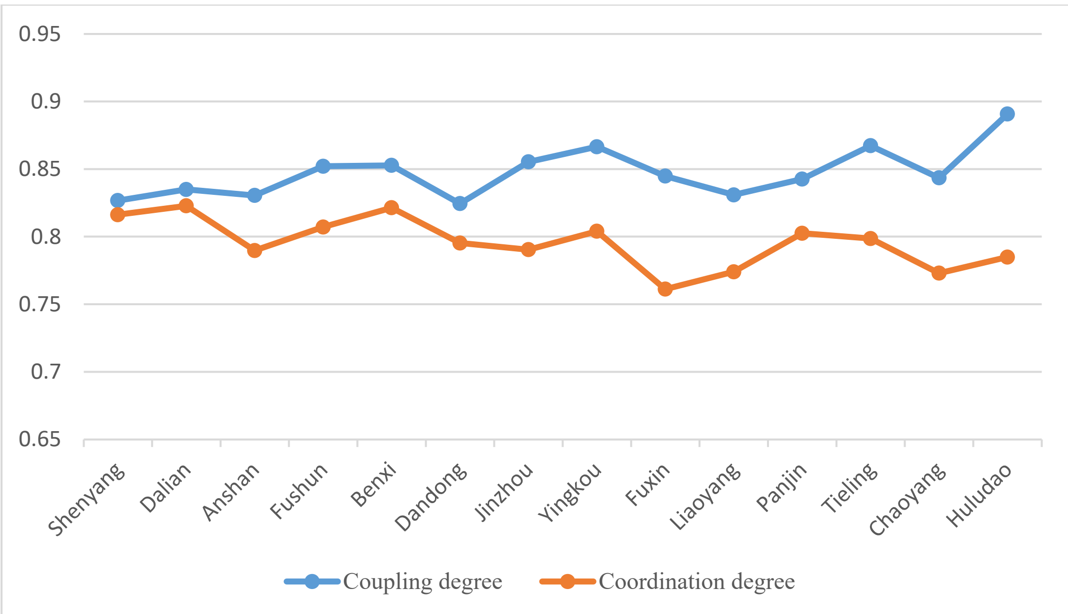

Figure 6. Line chart of coupling and coordination degrees of LCCC system in Liaoning Province.

Huludao had the highest coupling degree. Yingkou and Tieling also had high-level coupling, with significant interdependence between subsystems. Across the entire province geological condition, and resource and environmental carrying capacities were higher in terms of coupling, while economic and social carrying capacities were lower. This was primarily because the geological environment restricted urban, economic, and social development to a certain extent, which in turn placed strain on resources and the environment. Second, the running-in stage was represented by the coupling degrees of Jinzhou City, Benxi City, and Fushun City. Shenyang, Dalian, Anshan, Dandong, and Liaoyang were cities with low-level coupling, indicating weak interactions between their subsystems. Liaoning Province's 14 prefecture-level cities generally had good coordination, with eight of them being above the intermediate coordination level (Table 5). The numerical coordination values of Shenyang, Dalian, and Benxi, which were all undergoing high-quality coordinated development, ranged from 0.8071 to 0.8228. Despite several issues such as growing population density, expanding construction land scales, and increasing population concentration in the cities, Shenyang and Dalian had good geological condition, rapid economic development, and substantial investments in public resources, infrastructure, and environmental protection. As a result, these regions can achieve high-quality coordinated development. Fuxin, Liaoyang, and Chaoyang had cooperative coordination levels between 0.7612 and 0.7740, indicating reluctant coordination. Although the ecological environments in these three prefecture-level cities were good, the overall coordination of the LCCC was subpar due to relatively unfavorable geological conditions, slow rates of economic development, and low degrees of infrastructure improvement.

Table 5. Coupling coordination degree of LCCC system in Liaoning Province.

City	Coupling Degree	Coupling Stage	Degree of Coordination	Coordination Phase
Shenyang	0.8267	Barely coupled	0.8162	Quality coordination
Dalian	0.8349	Barely coupled	0.8228	Quality coordination
Anshan	0.8305	Barely coupled	0.7897	Primary coordination
Fushun	0.8521	Inter-mediate coupling	0.8071	Good coordination
Benxi	0.8527	Inter-mediate coupling	0.8214	Quality coordination
Dandong	0.8245	Barely coupled	0.7953	Intermediate coordination
Jinzhou	0.8553	Inter-mediate coupling	0.7904	Primary coordination
Yingkou	0.8665	Good coupling	0.8040	Good coordination
Fuxin	0.8448	Primary coupling	0.7612	Reluctantly coordinate
Liaoyang	0.8309	Barely coupled	0.7740	Reluctantly coordinate
Panjin	0.8426	Primary coupling	0.8025	Good coordination
Tieling	0.8673	Good coupling	0.7986	Intermediate coordination
Chaoyang	0.8435	Primary coupling	0.7730	Reluctantly coordinate
Huludao	0.8907	Good coupling	0.7849	Primary coordination

Each prefecture-level city in the Liaoning Province had similarly coupled and coordinated LCCC systems, and the benign interaction of subsystems demonstrated "low in the west and high in the east" spatial distribution (Figure 7). Figure 7 shows the gradient in coordination, from Chaoyang City and Fuxin City (in the west), which were at a reluctant coordination level, to the eastern part of the Liaoning Province, which contained regions of high-quality and good coordination in a semi-circular shape. To ensure the development of high-quality land space in Liaoning, the province had established two regional development coordination groups for the regions of Shenyang, Fushun, and Benxi, and Dalian, Yingkou, and Panjin.

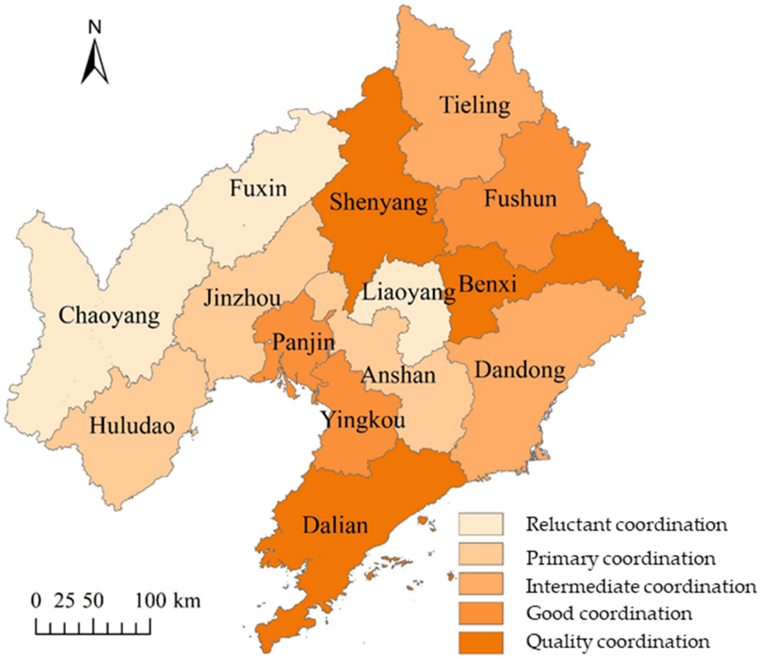

Figure 7. Distribution of coordination stage types of LCCC in Liaoning Province.

4. Discussion

Normal distributions are widely represented in natural phenomena, social phenomena, science and technology, and in activities associated with production. Many random phenomena encountered in practice completely or approximately obey normal distributions. While emphasizing the status of the normal distribution, it is important to note that many random phenomena cannot be depicted by a normal distribution. The use of the cloud model to describe such randomness extends the normal distribution to a generalized normal using a new independent parameter, superentropy, to measure deviations from the normal distribution, with the advantage of being more generalizable than the normal-terrestrial conditional distribution [48]. Use of technical methods in the construction of indicator systems and research methods have a greater impact on evaluation results of LCCC. The normal cloud model allows for the conversion from qualitative to quantitative assessment, especially when the amount of data is small [49]. For example, in this study there were only 14 study units and a lot of uncertainty in the data. Hence, using the normal cloud model had the advantage of simplifying the study population when applied to small sample data processing.

Evaluating carrying capacity is complex, hence multi-factor, multi-index, and multi-level evaluation theories are widely used [28]. As a result, it is challenging to evaluate carrying capacity comprehensively using a simple index system. The qualitative evaluation descriptions in this study were transformed into quantitative values through a normal cloud model, generating accurate and unified quantitative evaluation results. The normal cloud model method used three numerical features to describe the results, and by combining the meanings of the different numerical features, the accuracy of the evaluation results were judged and the influence of ambiguity on the results was greatly reduced [23–25,45]. Through comparative analysis with the Liaoning Department of Natural Resources Land Carrying Capacity Evaluation Project [50], the expert consultation method was simple and subjective, and this study improved the reliability and generalizability of the research results in the case of a complex LCCC system with high uncertainty, while considering the balance between the index system and assessment methodologies. However, the indicators selected in this study are still subjective even though they are selected on the basis of existing studies. In addition, the study data are cross-sectional, and the comparative analysis of the study results over time is lacking, which has certain limitations.

5. Conclusions

This study developed a multi-dimensional index system of LCCC based on the theory of carrying capacity, evaluated the LCCC of Liaoning Province using the normal cloud model and entropy methods, and examined its interaction using coupling and coordination degrees. To address issues such as incomplete indicators, mixed qualitative and quantitative descriptions, and uncertainty in the process of LCCC evaluation, a multi-dimensional LCCC evaluation method based on the normal cloud model was proposed in this study. It included four primary indicators (geological conditions, resources and environment, economic scale, and urban construction) and 19 secondary indicators to evaluate LCCC. The results showed that the determinacy of the different evaluation levels Ex, En and He can be obtained according to the numerical characteristics obtained from the normal cloud model through the generator algorithm, so as to determine the carrying capacity level of the land. Since this model was able to consider LCCC in terms of both quantitative results and the reliability of the results, it promotes the scientific application of uncertainty theory in the field of comprehensive land evaluation as well as carrying capacity.

In addition, the practical results of applying the normal cloud model to LCCC evaluation showed that prefecture-level cities in Liaoning Province had significantly different LCCCs. Greater capacity was seen in cities with mature economies and comparatively adequate infrastructure. As a result, Liaoning Province's spatial distribution of total land carrying capacity remained unbalanced, exhibiting "low in the west and high in the east" characteristics overall. In Liaoning Province's prefecture-level cities, there was minor variation in the coupling and coordination degrees of the LCCC system, with overall consistency. However, the coordination degree also exhibited the "low in the west and high in the east" spatial distribution characteristics.

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