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Land Eco-Security Assessment Based on the Multi-Dimensional Connection Cloud Model

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Abstract: The evaluation of land eco-security is challenging because it is involved with various uncertainty factors. Although the normal cloud model provides an idea for dealing with the randomness and fuzziness of indicators for the evaluation of land eco-security, it cannot simulate the distribution state of the evaluation indicators in a finite interval and their calculation process is complicated for multi-factor problems. Herein, a novel multi-dimensional connection cloud model is discussed to remedy these defects. In this model, combined with the range of evaluation factors in each grade, the identity-discrepancy-contrary principle of set pair theory is adopted to determine the digital characteristics of the multi-dimensional cloud model, which can uniformly describe the certainty and uncertainty relationships between the measured indices and the evaluation criteria and also improve the fuzzy-randomness of evaluation indicators closer to the actual distribution characteristics. The case study and the comparison of the proposed model with the normal cloud model and the matter element model were performed to confirm the validity and reliability of the proposed model. Results show that this model can overcome the subjectivity in determining the digital characteristics of the normal cloud model, providing a novel method for the comprehensive evaluation of land eco-security.

Keywords: land eco-security; multi-dimension; cloud model; set pair theory; evaluation

1. Introduction

Eco-security is defined as the "ecologically sustainable development that meets the environmental and ecological needs of the present generation without compromising the ability of future generations to meet their own environmental and ecological needs" [1,2], which was first introduced by the Insurance Accounting and Systems Association (IASA) in the global eco-security monitoring system of 1989 [3]. Land is a scarce resource at a global scale, and the space carrier of human activities, so it is fundamental in all human existence and development [4–6]. Ecological land offers important functions, such as soil and water conservation, wind prevention and sand-fixing, cleaning air, climate regulation, and biodiversity maintenance, and it has drawn more and more attention from many scholars [7–9]. Thus, land eco-security is an essential component of overall natural eco-security, a state in which it maintains a healthy and balanced structure and function within certain spatial and temporal ranges, and provides natural conditions in which human beings live [10,11]. However, with the large extension of urbanization and the great development of human societies in the past 50 years, some irrational activities of land use have posed a dangerous threat to the health and safety of the ecosystem, resulting in a series of environmental problems, such as biodiversity reduction, soil erosion, and land contamination [6,12–15]. Based on official statistics, there are 400,000 polluted sites in the European countries [16,17]. In America, approximately 600,000 hm^2 brown field sites have been polluted with heavy metals [17–19]. Soil erosion is frequently found in Northwestern

European catchments [20]. Natural disasters, such as the 2011 Tohuku earthquake and tsunami in Japan, and subsequent nuclear meltdowns at Fukushima, can also endanger land eco-security [21]. Extreme meteorological events and disasters, such as droughts, floods, and high temperatures, have frequently occurred worldwide [13,14,22–24]. According to the 2017 World Meteorological Organization Statement on the State of the Global Climate, 2017 has recorded the most serious economic loss in the world due to severe weather and climate events. The loss is estimated to be about US$320 billion. In China, the number of sandstorms in northern cities has continued to increase, and the cities in the south have suffered serious waterlogging. In 2017, high quality arable land only accounted for 27% of the national total arable land area. The total area of eroded soil was about 2.949 million km^2, accounting for 31.1% of the total area of the land census. As of 2014, the area of desertified land nationwide was 4,337,200 km^2. Such issues have drawn increasing attention of local governments, the public, and academic communities in China [2,25]. In 2018, the report of the 19th National Congress of the Communist Party of China explicitly set the goal of building a "rich, strong, democratic, civilized, harmonious, and beautiful modern socialist country", which also incorporated ecological civilization into the Constitution and established the Ministry of Ecology and Environment. It clearly shows that China has put emphasis on environmental protection. Thus, planners and policymakers of national development are in growing need of significant and scientific knowledge about the state of land eco-security [10].

Land eco-security evaluation is both the core and the foundation of the sustainable utilization of land resources [10]. Many scholars take full advantage of mathematics, computer science, and ecology in the study of land eco-security so that research results have been continuously enriched. In 1996, Canadian ecological economist William E. Rees proposed an ecological footprint calculation model to measure sustainable development. Based on the ecological footprint method, Li et al. [26] proposed an ecological pressure index method for the evaluation of land eco-security of Shandong Province. However, this method only measured the degree of ecological sustainability, emphasizing the impact of human development on the environmental system without considering economic, social, and technological sustainability [27–29]. Park et al. [30] suggested a linkage between the grey method and the artificial neural-network model in regional eco-environmental quality assessment. Additionally, the neural-network method needs historical data, which presents a problem in using existing domain knowledge in the learning process. To overcome these shortcomings, the fuzzy comprehensive evaluation method [31–33] and the matter element method [34–36] were used to analyse land eco-security, and the objective and reasonable results have been obtained. Although the fuzzy comprehensive evaluation method can quantify the fuzzy uncertainty, its result is dependent on the rational definition of membership function. The matter element method might miss some constraint conditions during the evaluation procedure so that it may lead to the deviation of the evaluation results from reality. Due to the effect of the subjective factor and multiple evaluation factors, the evaluation of land eco-security consists of uncertainties of both fuzziness and randomness. To depict fuzziness and randomness of evaluation indicators, Gao et al. [37] presented a one-dimensional normal cloud model for the land eco-security assessment. However, the traditional normal cloud model may have the disadvantages of being both cumbersome and slow in the calculation of the evaluation process with the increase in evaluation indices and samples.

This study is aimed at introducing a novel multi-dimensional connection cloud model for the assessment of land eco-security. The authors intend to develop a novel cloud model that can dialectically describe the fuzziness and randomness in evaluation indicators over a finite interval, and the certainty and uncertainty relationships between the measured evaluation indicators and each classification standard in a unified way on the basis of set pair theory. The proposed method can also express the conversion tendency of the result on the classification boundary. Moreover, the feasibility and validity of the proposed method are further discussed by case study taking the Wanjiang region as an example, followed by a comparison with the one-dimensional normal cloud model and the matter element model.

2. Methodology

The cloud model proposed by Li [38] is a useful tool for transforming a qualitative concept into quantitative data, and widely adopted to analyse problems with characteristics of fuzziness and randomness [39]. The traditional one-dimensional cloud model has the obvious deviation of the evaluation result from reality when there is a considerable difference in the interval spans of the evaluation levels. Therefore, the multi-dimensional normal cloud model is proposed to overcome the above problems by comprehensively considering all the evaluation factors. In addition, in the past, there was no substantial basis for the selection of the digital characteristics of the multi-dimensional normal cloud model, so that the simulation results may have considerable contingency and limitations. The set pair theory developed recently provides an idea for overcoming the deficiencies of the above normal cloud model since it has an advantage in terms of a unified description of the certainty and uncertainty relationships [40,41]. For this reason, this paper couples the normal cloud model with the set pair theory to present a multi-dimensional connection cloud model, which makes the selection of the digital characteristics of cloud model more objective, and makes the evaluation result more accurate and reliable. The definition of the calculation model is shown below.

Let $U = \{x_1, x_2, \ldots, x_m\}$ be an m dimension universe of discourse with precise values, and C be a qualitative concept in U. If $x \in U$ is a random instantiation of concept C, which satisfies $X\,(x_1, x_2, \ldots, x_m)\sim N\,(Ex\,(Ex_1, Ex_2, \ldots, Ex_m), \left(En'\left(En'_1, En'_2, \ldots, En'_m\right)\right)^2)$, and, $En'\left(En'_1, En'_2, \ldots, En'_m\right)\sim N\,(En\,(En_1, En_2, \ldots, En_m), (He\,(He_1, He_2, \ldots, He_m))^2)$, and the certainty degree of x belonging to concept C satisfies:

$$\mu[x(x_1, x_2, \ldots, x_m)] = e^{-\sum\limits_{j=1}^{m} \frac{(x_j - Ex_j)^2}{2(En'_j)^2}}, (j = 1, 2, 3, \ldots, m), \tag{1}$$

then the distribution of x in the universe U is called the multi-dimensional normal cloud [42]. Here, set pair theory is introduced into the process of establishing the multi-dimensional cloud model, and this multi-dimensional cloud is called the multi-dimensional connection cloud. Namely, the entropy value En is determined according to the identity-discrepancy-contrary relationship between the simulation cloud drop and the evaluation interval, and the possibility that the simulated cloud drop is on the boundary of the discussed level and adjacent level is 0.5. Assuming that there are n (i = 1, 2, ..., n) grades of the evaluation of land eco-security, m (j = 1, 2, ..., m) evaluation indicators, the ith grade of the classification standard for m evaluation indicators can be represented through the m dimensional connection cloud of the digital characteristics $\left(Ex^i_1, En^i_1, He^i_1; Ex^i_2, En^i_2, He^i_2; \ldots; Ex^i_m, En^i_m, He^i_m\right)$ and the number of cloud drops N, and connection degree $\mu^i\left(x^i\left(x^i_1, x^i_2, \ldots, x^i_m\right)\right)$ of the cloud drop $x^i\left\{x^i_1, x^i_2, \ldots, x^i_m\right\}$ satisfies:

$$\mu^i\left[x^i\left(x^i_1, x^i_2, \ldots, x^i_m\right)\right] = e^{-\sum\limits_{j=1}^{m} \frac{(x^i_j - Ex^i_j)^2}{2(En^{i\prime}_j)^2}}, \tag{2}$$

$$Ex^i_j = \frac{\mathrm{Cmin}^i_j + \mathrm{Cmax}^i_j}{2}, \tag{3}$$

$$He^i_j = \beta. \tag{4}$$

where Ex^i_j, En^i_j, He^i_j are the expected value, entropy, and hyper-entropy of grade i of evaluation indicator j, respectively. Cmax^i_j and Cmin^i_j are the upper limitation and lower limitation of the interval in the ith evaluation grade of evaluation indicator j, respectively. β is a parameter and amended by the fuzzy degree, β = 0.01.

3. Multi-Dimensional Connection Cloud Model-Based Evaluation Model

3.1. Basic Procedure

The basic evaluation principle of the proposed model was presented as follows: Classification standards and evaluation factors are firstly determined, respectively, and the range of evaluation factors for each grade [Cmax_j^i, Cmin_j^i] is determined. Then, digital characteristics $(Ex_1^i, En_1^i, He_1^i; Ex_2^i, En_2^i, He_2^i; \ldots; Ex_m^i, En_m^i, He_m^i)$ are calculated. Based on *Ex*, *En*, and *He*, the *m* dimensional connection cloud in a finite interval is simulated. Next, the connection degrees of evaluation indicators are achieved. Finally, the sample evaluation level is expected. The corresponding evaluation process is shown in Figure 1.

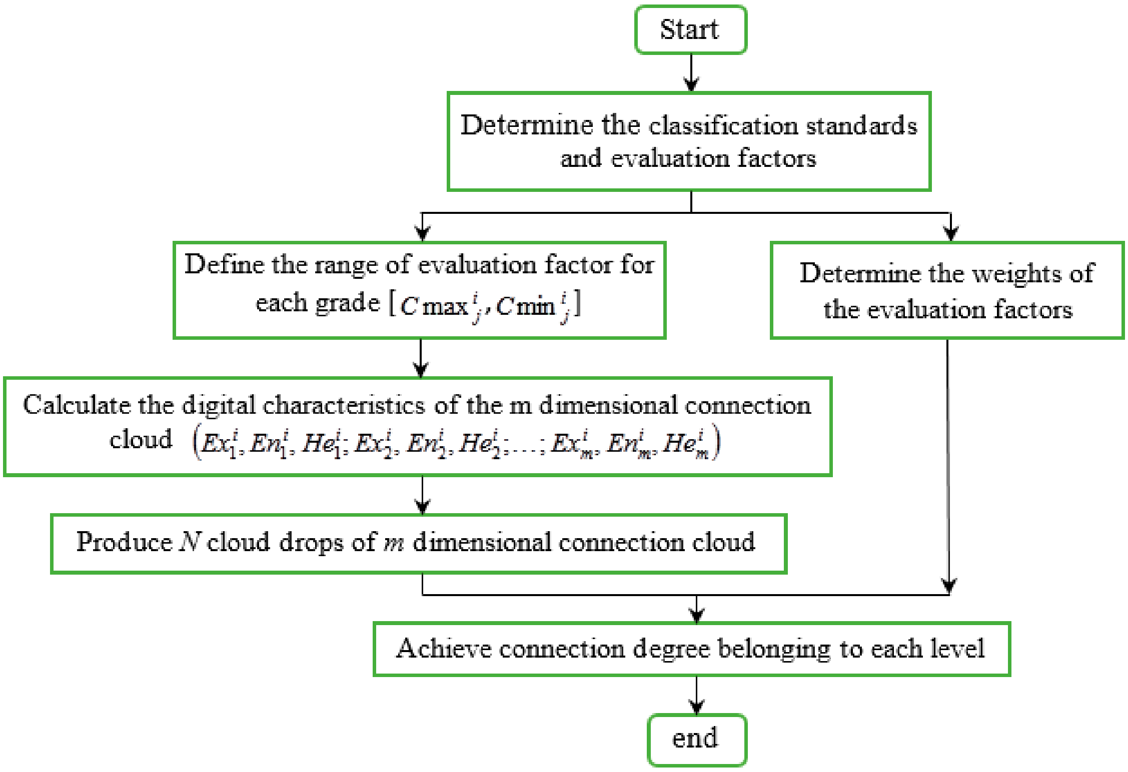

Figure 1. Flowchart of the proposed model.

3.2. Evaluation Process

The evaluation process consists of four steps, as follows:

Step 1: Select evaluation factors and classification standards. The selection of land eco-security assessment indicators is an important and complicated task. There is a lack of clear and unified standards so far, and the selection of indicators also has a great influence on the evaluation results.

The selection of indicators should not only take into account the state of the ecological environment, the safety of the land ecosystem itself, and sustainability for humanity, but also follow the principles of completeness and availability of data, etc. At least, the natural geography and socio-economic development of the Wanjiang region, especially the specific conditions of land resources and land usage should be considered. Concretely speaking, the following indicators should be emphasized: Firstly, these indicators which can reflect the natural environment conditions and confirm the land eco-security level with more objective and reasonableness, such as per capita cultivated area, per capita water resources, and forest coverage rate, etc.; Secondly, the indicators that reflect the negative impact on economic and social industry development, such as industrial wastewater discharge rate, industrial waste gas (SO_2) treatment rate, and the comprehensive utilization rate of industrial solid wastes, etc.; Finally, the indicators reflecting the sustainability for humanity and the ecosystem, such as unit area farmland fertilizer load and unit area farmland pesticide load. Here, 17 evaluation indicators, as shown in Table 1, were selected on the basis of national and local technical codes, and from the literature on land eco-security evaluation, environmental sustainable development evaluation, and ecological city evaluation [10,43–46].

Table 1. Evaluation index system and weight of land eco-security [36].

Evaluation Indicators	Weight
Per capita cultivated farmland (X_1, hm^2)	0.0371
Proportion of cultivated land on steep slopes with a slope of more than 25 (X_2, %)	0.2796
Forest coverage rate (X_3, %)	0.1450
Harmonious degree between water and soil (X_4, %)	0.0005
Forest pest control rate (X_5, %)	0.0272
Land natural disaster prevention rate (X_6, %)	0.0010
Proportion of natural disaster area (X_7, %)	0.0481
Population density (X_8, people per m^2)	0.0692
Land diversity index (X_9)	0.0176
Regional development index (X_{10})	0.0014
Per capita water resources (X_{11}, m^2)	0.1363
Sulphur dioxide emissions per unit of GDP (in ten thousand Yuan) (X_{12}, kg)	0.0884
Unit area farmland fertilizer load (X_{13})	0.0047
Unit area farmland pesticide load (X_{14})	0.0753
Industrial wastewater discharge rate (X_{15} %)	0.0004
Industrial waste gas (SO_2) treatment rate (X_{16}, %)	0.0582
Comprehensive utilization rate of industrial solid wastes (X_{17} %)	0.0100

Given the large number of evaluation indicators, it is difficult to directly determine the impact of each indicator on the ecological safety of the region (the weight of each indicator). In this study, the entropy weight method was utilized to calculate the weight of each index objectively [36]. At the same time, it is also convenient to compare with other methods.

As shown in Table 2, classification standards for evaluation indicators are divided into five levels, from very safe (I) through safe (II), marginally safe (III), marginally unsafe (IV), to unsafe (V). Based on the land eco-security classification standards, the evaluation factor range of each grade [Cmax_j^i, Cmin_j^i] is determined. For a factor that has only one side grade limit [Cmin, +∞], and its value monotonously increasing with the grade level, its upper limit value is specified as $\mathrm{Cmax} = Ex^{n-1} + (Ex^{n-1} - \mathrm{Cmin}^{n-2})$, while for a factor whose interval value monotonously decreases with the grade level, the upper limit value is $\mathrm{Cmax} = Ex^{n+1} + (Ex^{n+1} - \mathrm{Cmax}^{n+2})$.

Step 2: Calculate the digital characteristics. According to Equation (2), the connection degree at the boundary between grades i and $i-1$ or $i+1$ is 0.5. Namely, the sample at the classification boundary belonging to grade i or $i-1$, and the possibility belonging to grade i or $i-1$ is equal to each other. This particular feature is consistent with the identity-discrepancy-contrary principle of set pair theory. According to set pair theory, the identical-discrepancy-contrary relationship between the measured index and the ith level of the corresponding indicator j can be defined as follows: When the measured index is located in the level [Cmin^i, Cmax^i], it is defined as an identity relation. In addition, based on the criteria $3En$, the discrepancy and contrary relations are defined when the measured point lies on $\left[Ex^i - 3En^i, \mathrm{Cmin}^i\right] \cup \left[\mathrm{Cmax}^i, Ex^i + 3En^i\right]$ and the negative field, respectively. In order to quantitatively and uniformly describe the identity-discrepancy-contrary transformational potential corresponding to the connection degree of the connection cloud, En of evaluation indicator j for grade i can be calculated as follows:

$$En_j^i = \frac{\mathrm{Cmax}_j^i - Ex_j^i}{\sqrt{\ln 4}}. \tag{5}$$

Taking as an example of X_1, the digital characteristics are as shown in Table 3.

Table 2. Classification standard for evaluation indicators [36,37].

Evaluation Indicators	I	II	III	IV	V
X_1	[0.10, +∞]	[0.07, 0.10]	[0.05, 0.07]	[0.02, 0.05]	[0.00, 0.02]
X_2	[0, 2]	[2, 7]	[7, 10]	[10, 24]	[24, +∞]
X_3	[47, +∞]	[34, 47]	[25, 34]	[10, 25]	[0, 10]
X_4	[95, +∞]	[90, 95]	[85.5, 90]	[80, 85.5]	[50, 80]
X_5	[97, +∞]	[85, 97]	[80, 85]	[70, 80]	[0, 70]
X_6	[97, +∞]	[85, 97]	[80, 85]	[70, 80]	[0, 70]
X_7	[0, 1]	[1, 8]	[8, 10]	[10, 50]	[50, +∞]
X_8	[100, 550]	[550, 1400]	[1400, 1600]	[1600, 2900]	[2900, +∞]
X_9	[0.90, +∞]	[0.55, 0.90]	[0.35, 0.55]	[0.10, 0.35]	[0.00, 0.10]
X_{10}	[0.95, +∞]	[0.89, 0.95]	[0.85, 0.89]	[0.74, 0.85]	[0.00, 0.74]
X_{11}	[1800, +∞]	[1450, 1800]	[1350, 1450]	[900, 1300]	[300, 900]
X_{12}	[0, 3]	[3, 8]	[8, 11]	[11, 15]	[15, +∞]
X_{13}	[150, 270]	[270, 380]	[380, 450]	[450, 650]	[650, +∞]
X_{14}	[0, 10]	[10, 20]	[20, 25]	[25, 40]	[40, +∞]
X_{15}	[97, +∞]	[85, 97]	[80, 85]	[70, 80]	[0, 70]
X_{16}	[97, +∞]	[85, 97]	[80, 85]	[70, 80]	[0, 70]
X_{17}	[97, +∞]	[85, 97]	[80, 85]	[70, 80]	[0, 70]

Table 3. Digital characteristics of the cloud model for X_1.

Cloud	*Ex*	*En*	*He*
I	0.110	0.008493	0.01
II	0.085	0.01274	0.01
III	0.060	0.008493	0.01
IV	0.035	0.01274	0.01
V	0.100	0.08493	0.01

Step 3: Produce N cloud drops of the m dimensional connection cloud. The multi-dimensional connection cloud in a finite interval is simulated on the basis of the corresponding digital characteristics (Ex, En, He). For the jth evaluation factor, there is a distinct difference in connection clouds between the internal grade (i = 2, 3, . . . , $n - 1$) and both ends (i = 1, n). In the clouds at both ends, half of the clouds far from the intermediate grade actually have a uniform distribution of 1. When calculating, let $x_j^i = Ex_j^i$, then the contribution of the measured value to the overall connection degree is 1. The corresponding cloud drop generation algorithm is as follows:

(1) Generate a normally-distributed random number $En'\left(En'_1, En'_2, \ldots, En'_m\right)$, with expectation $En(En_1, En_2, \ldots, En_{\mathrm{m}})$ and variance $He(He_1, He_2, \ldots, He_m)$.

(2) Generate a normally-distributed random number $x(x_1, x_2, \ldots, x_m)$, with expectation $Ex(Ex_1, Ex_2, \ldots, Ex_m)$ and variance $En'\left(En'_1, En'_2, \ldots, En'_m\right)$.

(3) Calculate connection degree of the evaluation indicator according to Equation (1).

(4) Repeat steps (1)–(3) until N cloud drops are generated.

Step 4: Achieve connection degree belonging to each grade level. Based on the measured indicators of a sample, combined with the weight of the evaluation factors, the connection degree of a certain grade of land eco-security is calculated and the sample eco-security grade is determined. Since the normal cloud model satisfies the criteria $3En$ and the evaluation scope of the ith cloud model is $[Ex^i - 3En^i, Ex^i + 3En^i]$, when x_j^i is within the range of the contrary relationship, the contribution of the index x_j^i to the overall connection degree is equivalent to $x_j^i = Ex^i \pm 3En^i$, and $x_j^i = Ex^i \pm 3En^i$ and can be substituted into the calculation.

4. Case Study

4.1. Study Area

Located in Eastern China (29°41′–34°38′ N, 114°54′–119°37′ E), Anhui Province has a total area of approximately 139,600 km^2. At the end of 2017, the total permanent population of Anhui Province reached 70.592 million, and the total GDP of the province was about $42.98 billion, which was about 43% higher than that of 2013. The Wanjiang region consists of nine cities, including Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chizhou, Chaohu, Chuzhou, and Xuancheng. It is an important hinterland and natural extension zone of the Yangtze River Delta economic circle, and also the most developed manufacturing base in Anhui Province. In the past 50 years, with the implementation of the extensive economic growth pattern, the introduction of chemical plants, cast iron and forging plants, and building materials plants has unbalanced the land eco-security in the Wanjiang region, caused a significant increase in population density and a clear decline in cultivated area and forest coverage, and there also exist significant differences within the nine cities. In 2010, the national government set up some industrial transfer demonstration districts in the Wanjiang region, focusing on new chemical industries, equipment manufacturing, and metallurgical industries. This provides a golden opportunity to the economic development of the Wanjiang region, but brings about a severe test to the ecological environment, which will determine if the sustainable economic development of the Wanjiang region can be realized.

4.2. Data

In order to verify the validity and feasibility of this proposed model, the data from the literature [36,37] were used to conduct the analysis. Measured values of evaluation indices are listed in Table 4, respectively.

Table 4. Measured values of indicators [36].

	Maanshan	Wuhu	Tongling	Chizhou	Anqing	Xuancheng	Chaohu	Chuzhou	Hefei
X_1	0.04	0.04	0.03	0.05	0.04	0.06	0.06	0.09	0.05
X_2	1.84	2.05	3.46	15.24	8.78	11.60	3.45	1.25	1.15
X_3	8.1	20.9	32.1	56.9	35.6	54.0	12.6	11.9	15.5
X_4	100	100	100	100	96.86	95.42	96.78	88.36	97.28
X_5	73.1	100	37.84	67.76	92.87	51.72	90.84	82.28	90.27
X_6	96.74	92.01	90.49	91.39	86.30	96.73	93.96	83.35	97.76
X_7	23.85	21.89	18.17	14.83	25.74	7.92	24.69	16.80	19.18
X_8	751	690	657	190	395	222	480	331	668
X_9	0.72	0.64	0.88	0.39	0.75	0.94	0.64	0.68	0.71
X_{10}	0.88	0.94	0.80	0.86	0.85	0.80	0.85	0.94	0.94
X_{11}	567.5	602.2	566.2	2851.1	856.1	2307.7	852.7	1238.3	928.84
X_{12}	12.19	5.08	14.14	13.36	15.29	12.89	16.70	5.32	2.54
X_{13}	537.72	783.90	765.58	711.27	804.50	690.20	774.11	779.36	800.47
X_{14}	52.98	26.44	40.61	61.86	57.08	30.78	21.42	15.69	21.22
X_{15}	97.48	97.84	99.58	99.74	94.16	94.11	99.27	88.98	96.14
X_{16}	10.14	10.08	11.02	5.73	15.12	8.81	17.10	6.18	4.89
X_{17}	91.53	100	71.54	98.77	96.88	57.46	95.39	100	99.61

4.3. Model Implementation

Based on the proposed model, 17 evaluation factors of the example are taken as 17 dimensions of the multidimensional connection cloud. Now, a comprehensive cloud model with a security grade of V is employed as an example to illustrate the process of establishing a 17-dimensional connection cloud. Through Equations (3)–(5), the digital characteristics of each evaluation factor of the V grade multi-dimensional connection cloud are calculated, as showed in Table 5. In order to facilitate the comparative analysis, the index weight value is the same as Yu et al. [36], ω = {0.0371, 0.2796, 0.1450, 0.0005, 0.0272, 0.0010, 0.0481, 0.0692, 0.0176, 0.0014, 0.1363, 0.0884, 0.0047, 0.0753, 0.0004, 0.0582, and 0.0100}. Taking the sample of Maanshan City as an example, the data in Table 5 and measured values were substituted into the Equation (2), and μ^{V} = 0.1209 was obtained, indicating that the connection degree of V was 0.1209. The calculation process of other grades is the same, and the results of the evaluation are shown in Table 6.

Table 5. Digital characteristics and weight of each evaluation factor of the multi-dimensional connection cloud model of grade V.

Indicators	*Ex*	*En*	*He*	ω
X_1	825	148.63	0.01	0.0371
X_2	60	16.99	0.01	0.2796
X_3	20	4.25	0.01	0.1450
X_4	0.1	0.08	0.01	0.0005
X_5	600	254.80	0.01	0.0272
X_6	3450	467.13	0.01	0.0010
X_7	5	4.25	0.01	0.0481
X_8	65	12.74	0.01	0.0692
X_9	65	12.74	0.01	0.0176
X_{10}	0.05	0.04	0.01	0.0014
X_{11}	29.5	4.67	0.01	0.1363
X_{12}	35	29.73	0.01	0.0884
X_{13}	35	29.73	0.01	0.0047
X_{14}	35	29.73	0.01	0.0753
X_{15}	35	29.73	0.01	0.0004
X_{16}	35	29.73	0.01	0.0582
X_{17}	0.37	0.31	0.01	0.0100

Table 6. Evaluation results of the multi-dimensional connection cloud model and comparison with those of other methods.

Samples	μ					Proposed Model	One-Dimensional Cloud Model [37]	Matter Element Model [36]
	I	II	III	IV	V			
Maanshan	0.0777	0.0484	0.0146	0.0679	0.1209	V	V	V
Wuhu	0.0921	0.0838	0.0201	0.0641	0.0426	I	II	II
Tongling	0.0301	0.0880	0.0206	0.0748	0.0698	II	II	II
Chizhou	0.0605	0.0145	0.0139	0.0943	0.0692	IV	IV	IV
Anqing	0.0314	0.0642	0.0666	0.1037	0.0707	IV	III	IV
Xuancheng	0.0634	0.0230	0.0262	0.0972	0.0630	IV	I	I
Chaohu	0.0335	0.0877	0.0190	0.1157	0.0916	IV	II	II
Chuzhou	0.1303	0.1208	0.0128	0.0679	0.0625	I	I	I
Hefei	0.1457	0.0852	0.0177	0.0864	0.0509	I	I	I

5. Results and Discussion

It was discovered from Table 6 that the results from the proposed model were almost consistent with those from the one-dimensional cloud model and the matter element model. For Wuhu City, there are six indicators at I and five indicators at II. For μ^{I} = 0.0921 and μ^{II} = 0.0838, the data are relatively close to the proposed model, which also shows that the ecological environment of Wuhu City is relatively stable and the degree of safety is relatively high. Additionally, for Xuancheng City and Chaohu City, the results of the proposed method were IV, but I and II by the other methods. However, there are 10 and 8 measured indicators belonging to III, IV, and V grades for the two cities, respectively, so it is conservative that they were specified as IV. In addition, the economic growth of Chaohu and Xuancheng mainly shows extensive growth, and the traditional high-pollution, high-energy-consumption industries, such as cement, papermaking, chemicals, and steel are still dominant in the city's economy. While industrial gas and solid wastes have not been properly treated, causing pollutants, such as SO_2, to be excessive. At the same time, both cities are mountainous regions with less per capita cultivated farmland and excessive use of chemical fertilizers and pesticides. All of these threaten the land eco-security in the two cities [47–49]. The results indicated that the proposed method was feasible and more effective than other methods.

5.1. Comparison between the Multi-Dimensional Connection Cloud Model and One-Dimensional Cloud Model

The multi-dimensional connection cloud model is an improved model over the one-dimensional cloud model with respect to aspects of both the modelling process and selecting parameters.

(1) The multi-dimensional connection cloud model considers all evaluation indicators, but sets up only one comprehensive multidimensional connection cloud model, that is to say, five 17-dimensional connection clouds are set up to evaluate the eco-security grade based on the multi-dimensional connection cloud model. However, the one-dimensional cloud model needs to set up a one-dimensional normal cloud model at each evaluation grade of each evaluation factor. Namely, it needs to build 85 one-dimensional normal cloud models to assess the same land eco-security.

(2) The time of calculating connection degree of the multi-dimensional connection cloud model decreases. At the same grade, the multi-dimensional connection cloud model only needs to calculate one connection degree so that the last connection degree can be determined, while the one-dimensional cloud model needs to calculate 17 kinds of certainty, and then calculate these 17 kinds of certainty to determine the last certainty.

(3) The multi-dimensional connection cloud model improves the selection of digital features. *En* represents the evaluation scope corresponding to the eco-security level. According to the set pair theory and the criteria 3*En*, the multi-dimensional connection cloud model chooses Equation (5), as *En* covers the scope of all the eco-security levels, which can quantitatively and uniformly describe the identity-discrepancy-contrary transformational potential corresponding to the connection degree of the connection cloud.

5.2. Comparison between the Multi-Dimensional Connection Cloud Model and Matter-Element Model

Compared with the matter-element model, the multi-dimensional connection cloud model comprehensively considers multiple evaluation factors, each evaluation factor is independent of the others, and then combines the weight, avoiding inaccurate evaluation results caused by the influence of a certain factor that is too large.

In addition, the challenge for the selection of land eco-security evaluation indicators was to achieve a balance between anthropogenic activities and land ecological carrying capacity in order to advance land ecological sustainability. In light of this, the "Driving forces–Pressures–State–Impacts–Responses" (DPSIR) framework, proposed by the Organisation for Economic Co-operation and Development and the United Nations Environment Programme, was chosen as the basis for defining indices to assess land eco-security. The driving forces are the load of human activities on the land ecological environment. Pressures are defined as the direct or indirect form of stresses arising from driving forces, which are anthropogenic in nature. The state is defined as the quality of the ecological environment, natural resources, and ecosystem. Impacts are defined as forms of vulnerability that humans and the natural environment faced due to the changes in the pressures existing in the states. Responses are actions and measures to tackle ecological and environmental issues. Land eco-security has a rich connotation, and the depth and breadth of researchers' understanding influence the construction of the land eco-security evaluation index system. From the analysis of the DPSIR framework and indicator selection principle in this paper the following can be found: Firstly, the selected indicators can reflect the health and sustainability of the land ecosystem from the perspective of the land ecosystem; secondly, the determined indicators have an ability to provide stable ecological services or guarantee functions for human beings by considering human development needs. According to the development status of different countries or regions, the selection of indicators may be different. The research of this paper has evident and significant reference for other regions.

Summing up, the case study has shown the superior accuracy and practical application of the model. We are confident that the results acquired in this study will contribute to the promotion of further future work for predicting the land eco-security.

6. Conclusions

Evaluation of land eco-security is a complex and uncertain problem since it is dependent on many factors. Based on the measured values of evaluation indicators, a novel multi-dimensional connection model coupled with set pair theory for the evaluation of land eco-security was addressed in this paper.

(1) The proposed model is a comprehensive connection cloud model and corresponds to each eco-security level on the consideration of all the evaluation factors. It is a clear modelling procedure with a concise algorithm and evaluation credibility. At the same time, the method for the selection of the cloud model parameters is improved. A case study of nine representative cities in Anhui, China indicates that the comprehensive cloud model proposed here is capable of assigning an eco-security level based on the consideration of randomness and fuzziness uncertainties of evaluation indicators distributed in a finite interval, and depict the certainty and uncertainty of indicators and the transformation tendency of the gained grade in a unified way. In addition, comparative analyses with the one-dimensional cloud model and the matter element model show that the proposed model is more comprehensive, objective and accurate to evaluate the land eco-security than other methods. Despite the above merits, the choice of β does not have a verdict, and a reasonable determination will be needed to be studied in the future.

(2) Evaluation results show that the land eco-security of the study area behaves in an unfavourable trend, and the marginally unsafe and unsafe levels are dominant. It should be noted that the negative impact of economic and social industry development on land eco-security accounts for a very large proportion. Excessive use of chemical fertilizers and pesticides, excessive industrial gas and solid wastes, and ineffective cleaning are the main reasons for the decrease of land eco-security. Under the supervision of the national government, some measures should be made for improving the land eco-security through environmental protection, reasonable employment of resources, proper adjustment of industrial structure, possible abatement of pollution, and so on.

(3) It is noted that, at present, there is no uniform standard for the selection of eco-security evaluation indicators. This study mainly considers the economic, environmental, and social factors, as well as the specific conditions of land resources and land use in the Wanjiang region. In this process, there may be a few factors that are ignored in establishing an indicator system and cause some deviations to the evaluation results. In fact, land eco-security involves multiple disciplines, so the authors also look forward to being able to combine sociology, economics, ecological environment, and cultural aspects to explore more indicators of land eco-security, and establish a universal and flexible indicator system.

In conclusion, this study provides a method for us to evaluate ecological environmental problems, and is a useful tool for decision-makers to judge the advantages and disadvantages of sustainable development, and to forecast land eco-security.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, M.W. and J.J.; Methodology, M.W.; Software, X.W.; Validation, M.W., Q.L. and F.S.; Formal Analysis, M.W.; Investigation, Q.L.; Resources, J.J.; Data Curation, Q.L.; Writing-Original Draft Preparation, Q.L.; Writing-Review & Editing, M.W. and F.S.; Visualization, M.W.; Supervision, M.W.; Project Administration, M.W.; Funding Acquisition, J.J.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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