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Ecological Environment Evaluation of Forest Ecosystem Nature Reserves Using an Unweighted Cloud Model

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Abstract: The ecological environment is the foundation of human survival and development, and forest ecosystem nature reserves play an important role in the protection of the ecological environment. The evaluation of forest ecosystem nature reserves facilitates the formulation of relevant management policies. At present, the evaluation of the ecological environment of forest ecosystem nature reserves is mainly based on detailed evaluation of some elements of the ecological environment, rather than on a comprehensive quantitative evaluation that reflects the ecological environment in many aspects. To address this shortcoming, the quantitative evaluation indicator system of comprehensive ecological environment for forest ecosystem nature reserves was established based on the water, air, soil, and biological environments, according to the consensus on ecological environment in the past research and characteristics of the research area. The weight is still a necessary and important link in the evaluation of forest ecosystem nature reserves, but the accuracy of the weight results is difficult to get a scientific judgment. To prevent the evaluation results being influenced by weighting uncertainty, an unweighted cloud model was constructed to provide an evaluation mechanism without weight. The ecological environment evaluation was then carried out using the unweighted cloud model, taking Songshan Nature Reserve as a research area. The results show that the grades of the ecological environment of Songshan Nature Reserve are 21% excellent, 67% good, and 12% qualified, and that the state of the ecological environment is stable and performing well. The evaluation results for the grades of the environmental dimension layers are water environment > soil environment > biological environment > air environment. The study's research results can provide theoretical support for the evaluation of forest ecosystem nature reserves, and for evaluation work in general when weights are difficult to determine or uncertain.

Keywords: ecological environment; forest ecosystem nature reserve; comprehensive quantitative evaluation; no weight; cloud model

1. Introduction

The ecological environment is the foundation on which human society depends for survival and development. Nature reserves play an important role in supporting biodiversity and in improving the ecological environment [1]. Forest ecosystem nature reserves are an important type of nature reserve, and are the most prevalent type of nature reserve in China, which account for more than half of China's nature reserves [2,3].

The accurate evaluation of the ecological environment of the forest nature reserves facilitates the formulation of management policies and measures in them, and is of great significance for the protection of the ecological environment.

Because of the significance of forest ecosystem nature reserve for the protection of the ecological environment, many researchers have carried out in-depth evaluations of these reserves. Song et al. [4] selected seven first-level indicators (including biodiversity, typicality, and rarity) and 15 secondary indicators to evaluate the ecological quality of the Maolan National Nature Reserve. Hu [5] used landscape ecology to analyze landscape spatial patterns, the distribution pattern of landscape patch characteristics, and the influence of external disturbances on the landscape pattern of a protected area. Hu applied the analytic hierarchy process, RBF (Radial Basis Function) networks, a projection pursuit model, and a support vector machine to evaluate the eco-quality of a forest landscape. Dong et al. [6] studied the spatial patterns of plant species diversity, functional diversity, and aboveground plant biomass, and their relationships with environmental factors in the Aerjin Mountain Nature Reserve (AMNR) on the Qinghai-Tibet Plateau. Their results showed that (1) the integrated effects of geographic factors, soil factors, and meteorological conditions contributed to the spatial heterogeneity of species biodiversity and the vegetation biomass of the plant communities in the AMNR, and (2) soil and climatic factors had a much stronger effect than geographical factors. In the past, the evaluation of the ecological environment of forest ecosystem nature reserves mainly focused on a certain aspect of the ecological environment (such as species diversity, landscape ecology). Although a few comprehensive quantitative evaluations have been carried out, the evaluation indicator system has often not been comprehensive or the quantitative degree has been incomplete. For example, insufficient data on non-biological factors were used in the evaluation indicators, and quantitative assessments were based on qualitative descriptions, which weakened the quantitative nature of the evaluation work [7–9]. Ecosystems are complex and highly interconnected structures that contain numerous and interconnected factors. Thus, the ecological evaluation of forest ecosystem nature reserve in a certain aspect of ecological environment, as has been done in previous research, does not fully reflect the state of the ecological environment. Comprehensive quantitative evaluations at a macro level can more accurately reflect the condition of the ecological environment of nature reserves, and the fully quantitative evaluation indicator system also has higher reference value and portability, which are rare in the ecological evaluation of forest ecosystem nature reserves.

Whether an incomplete or a comprehensive evaluation, past evaluations of the ecological environment of forest ecosystem nature reserve have mainly used composite indices, the corresponding ecological indices, and fuzzy comprehensive evaluation [10,11]. For example, Zhang et al. [12] used the integrative ecological sensitivity index (IES) to evaluate tourism impacts on vegetation landscapes in the Baihua Mountain Reserve of Beijing, China. Yang and Xiao [13] determined seven evaluation indicators from the basic characteristics of the Taibai Mountain National Nature Reserve, and used the composite index method to evaluate the ecological environment of the protected area. Their results showed that the ecological quality of the reserve was good. Liu et al. [14] established a comprehensive hierarchical structure evaluation model for nature reserves, and used it with the fuzzy comprehensive evaluation method to investigate the Jiuwanshan National Nature Reserve in Guangxi, China. These three methods all require weights to integrate factors at different levels, and the eco-environmental assessment system is usually more complex so that the weight is used more frequently. Thus, the weights have a large impact on the evaluation results. The current main weight determination methods (objective weighting and subjective weighting) have specific advantages and disadvantages. It is difficult to assess scientifically the accuracy of the weights. Weight remains an uncertain factor that affects the accuracy of evaluation results in current evaluations of nature reserves. To avoid the influence of the uncertainty of the weighting results on the evaluation results, this paper adopted the cloud model evaluation method to realize the evaluation mechanism without weights. The cloud model is the uncertainty conversion model between qualitative description and quantitative expression proposed by academician Li Deyi in 1995 [15].

The cloud model expresses the fuzziness of things and the randomness of membership uniformly. Compared with the fuzzy mathematics that also studies uncertainty, the cloud model has more considerations and is more in line with the actual situation.

The overall aim of this paper is to address the problems that exist in the evaluation of the ecological environment of forest ecosystem nature reserve. The specific aims are to: (1) Construct a comprehensive quantitative evaluation indicator system including water, soil, air, and biological environments that is suitable for forest ecosystem nature reserve; (2) introduce a cloud model to provide an unweighted evaluation mechanism, and to compare it with weight-based cloud model evaluation to verify the reliability of the unweighted cloud model evaluation results; and (3) conduct quantitative evaluation of the ecological environment using Songshan National Nature Reserve as a research area, and thus provide guidance on methodologies to be used in the analysis of the status of the nature reserves. We believe that this guidance will facilitate future policy development.

2. Study Area and Data

2.1. Study Area

Songshan Nature Reserve is located at the southern foot of Haituo Mountain in the northwest of Yanqing County, Beijing, and has an area of 4671 ha, as shown in Figure 1. Songshan was the first national nature reserve in Beijing [16]. The topography is relatively complex. The highest elevation is 2199.6 m, most of the mountainous areas lie within an elevation of 1200–1600 m, and the slope is mostly 15°–35°. The area has a medium latitude monsoon climate. Topographical conditions help creating a typical mountain climate [17]. Because of the diversity and complexity of microclimates caused by topographic differences, the area is rich in biodiversity. The area comprises a well-preserved warm temperate mountain forest ecosystem, and is a wild animal and plant nature reserve for northern China [18].

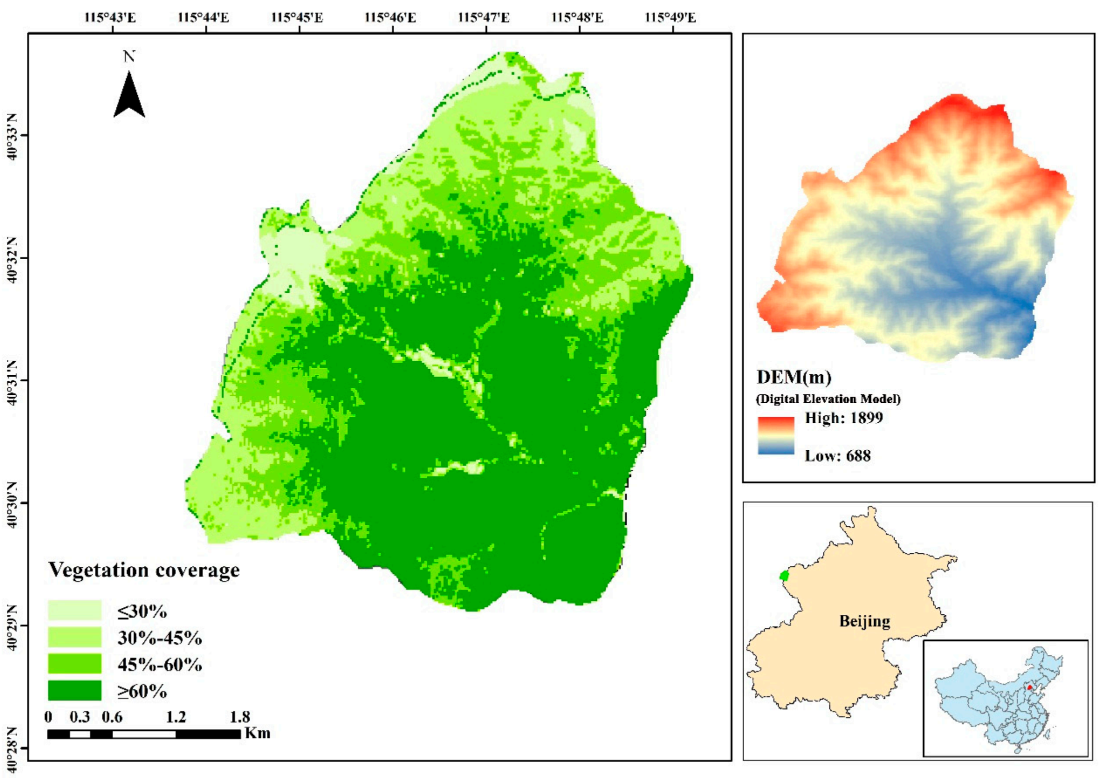

Figure 1. Geographical location, DEM (Digital Elevation Model) and vegetation coverage of the Songshan Nature Reserve.

2.2. Data

Multiple monitoring points were established in the reserve for the measurement of surface water, groundwater, soil environment, and air environment parameters. Monitoring of all parameters was carried out in 2017. There were 29 surface water monitoring parameters, and six items met the detection standard; 41 groundwater monitoring parameters, and seven items met the detection standard; 13 soil monitoring parameters, and eight items met the detection standard; nine air monitoring parameters, and seven items met the detection standard. The monitoring parameters that meet the detection standard are shown in the membership factor column of Table 1.

Table 1. Ecological environment evaluation indicator system for a forest ecosystem nature reserve.

Target	Dimension	Indicator	Membership Factor
Ecological environment	Water environment	Surface water quality	Permanganate index, total phosphorus, dissolved oxygen, fluoride, sulphate, nitrate nitrogen
		Groundwater quality	Total hardness, total dissolved solids, permanganate index, chloride, fluoride, sulphate, nitrate nitrogen
	Air environment	Air environment factor	SO_2, NO_2, PM_{10} (particulate matter less than 10 microns in diameter), $PM_{2.5}$ (particulate matter less than 2.5 microns in diameter), CO, SO_2, O_3
	Soil environment	Soil quality factor	Cd, Hg, Pb, Zn, Ni, Cu, As, Cr
		Degree of soil erosion	Different grades of soil erosion
	Biological environment	The ratio of vegetation cover	
		Biodiversity index	
		Shannon–Wiener index of plants	Shannon–Wiener index of available trees Shannon–Wiener index of protected plants Shannon–Wiener index of protected trees
		Shannon–Wiener index of animals	Shannon–Wiener index of mammal Shannon–Wiener index of amphibious reptile Shannon–Wiener index of birds

Plants were surveyed by means of transects and quadrats. Wild animals were surveyed and analyzed using transects or plots. The survey was conducted from 2016 to 2017, and past research data were also used in our study.

Landsat 8 OLI remote sensing data, DEM elevation data were obtained from the relevant websites (http://www.gscloud.cn/, http://www.dsac.cn/), and the 2015 land use type data purchased from relevant agencies.

3. Method

3.1. Evaluation Indicator System

The ecological environment is a large and complex phenomenon. At present, the academic community has not reached a consensus on the specific meaning of ecological environment [19–21]. However, when overviewing the evaluation of the ecological environment, researchers generally include four aspects: climatic factors, biological factors, water resources, and land environment [22–25]. Consequently, the present study considered the water, soil, air, and biological environments, when investigating the characteristics of forest ecosystem nature reserve and the availability, representativeness, and quantification of data to determine evaluation indicators belonging to each dimension. The indicator system constructed is shown in Table 1.

Surface water quality, groundwater quality, air quality, and soil quality are the evaluation results that integrate all the chemical factors that belong to the indicator.

Degree of soil erosion: Degree of soil erosion is graded according to the erosion state of the original soil profile [26]. The indicator was determined according to the official document “Standard for classification and gradation of soil erosion” (SL190-2007) of the Ministry of Water Resources of the People’s Republic of China [27]. This document states that in the absence of actual measurements and investigations of erosion modulus data, the degree of soil erosion can be classified according to the erosion method (surface erosion, gully erosion, gravity erosion). The study area is a forest ecosystem in the northern mountainous area, and vegetation coverage and slope are the main controlling factors of surface erosion. The slope was obtained from the DEM data of the study area using Arc GIS software (Environmental Systems Research Institute (ESRI), Redlands, CA, USA). Vegetation coverage was calculated using ENVI software (Exelis Visual Information Solutions, Inc., Broomfield, CO, USA), Landsat 8 OLI remote sensing data, and land use data. The two types of data were integrated and analyzed in Arc GIS to enable the degree of regional soil erosion to be determined.

The ratio of vegetation cover: The ratio of vegetation cover refers to the ratio of vegetation coverage area to total land area. Landsat 8 OLI remote sensing data were displayed in false color in ENVI software and the vegetation coverage area was visually interpreted to obtain vegetation coverage. The vegetation area was visually interpreted in Landsat 8 OLI remote sensing data to obtain the ratio of vegetation cover. Since there are almost no human activities in the nature reserves, their land use usually does not change in a short period of time. Therefore, the accuracy of vegetation coverage could be improved by comparing with the land use type data in 2015 produced by relevant agencies.

Biodiversity index: The BI is the indicator for evaluating biodiversity which is provided by the "Standards for the assessment of regional biodiversity" (HJ623-2011) issued by the Ministry of Ecology and Environment of the People's Republic of China [28]. The document uses the county-level administrative unit as the evaluation unit. Equations in the document assign 635 and 3662 as the reference maximum values for wild animal species and wild vascular plant species in the county, respectively. However, the evaluation unit of this article is the forest nature reserve in north China. According to a large volume of literature on similar nature reserves in China, it is found that the maximum value of wild animal species is about 300, and the maximum number of wild vascular plant species is about 2000 [7,8,29]. Therefore, the maximum reference values for wild animal species and for wild vascular plant species were set to 300 and 2000 respectively. Except for the modification, calculation method and parameter setting of BI index are carried out in accordance with the "Standards for the assessment of regional biodiversity" (HJ623-2011) [28].

Shannon–Wiener index: The Shannon–Wiener index is a function that combines species richness with the number of species, and is one of the most commonly used species diversity indices [30]. The Shannon–Wiener index can comprehensively evaluate the richness and uniformity of community species composition, and the data are easily obtained, flexible, and convenient to use [31].

$$\text{Shannon} - \text{Wiener index} = -\sum_{i}^{n} p_i \times \ln p_i, \tag{1}$$

where $p_i = n_i/N$ is the relative abundance of the ith specie; n is the number of species in the community; n_i is the number of individuals of the ith specie; and N is the total number of individuals of all species in the community.

Shannon–Wiener index of plant diversity: The Shannon–Wiener indices were determined for three types of plants: available trees, protected trees, and protected plants. The Shannon–Wiener indices for these three types of plants were integrated using the unweighted cloud model to obtain the Shannon–Wiener index of plant diversity.

Shannon–Wiener index for animals: The Shannon–Wiener indices for mammals in different months of the year were integrated using the cloud model into the Shannon–Wiener index for mammals. The Shannon–Wiener index for birds in different habitats and the Shannon–Wiener index for amphibious reptiles and other reptiles in different habitats were integrated into the Shannon–Wiener index for birds and the Shannon–Wiener index for amphibious reptiles, respectively, using the same cloud model approach as calculating the Shannon–Wiener index of mammals. The Shannon–Wiener indices for the three types of animals were then integrated into the Shannon–Wiener index of animals using the unweighted cloud model.

3.2. Evaluation Indicator Threshold

Based on the actual situation of the Songshan Nature Reserve, the corresponding national grade standards for the indicators, and the threshold range of the indicator grades in related literature, all the evaluation objects are divided into four grades. The threshold range for each evaluation object is shown in Supplementary Materials S1 [32–35].

The national standards referenced were the: "Environmental quality standards for surface water" (GB3838-2002), "Standard for groundwater quality" (GB/T14848-2017), "Ambient air quality standards" (GB3095-2012), "Environmental quality standard for soils" (GB15618-1995), "Standard for the assessment of regional biodiversity" (HJ623—2011), and "Standards for classification and gradation of soil erosion" (SL190-2007) [27,28,36–39].

3.3. Cloud Model

3.3.1. The Cloud Model Concept

A cloud model is an uncertainty transformation model that deals with qualitative concepts and quantitative descriptions. There is a quantitative domain U with an accurate numerical representation, in which C is one of the qualitative concepts. Assume that x is a random implementation of qualitative concept C ($x \in U$), which is usually implemented by a certain probability distribution function, reflecting the qualitative randomness of the concept. The degree of certainty of x to the concept C ($\mu(x) \in [0, 1]$) is a set of random numbers that tend to be stable and within a certain range, and can be explained by the membership function based on fuzzy set theory, which reflects the fuzziness of the qualitative concept [40]. The joint distribution of (x, μ) is used to characterize the qualitative concept and to determine the position of x in U, that forms a cloud drop at U. The final result formed by all cloud drops on the universe U is called the cloud.

In the cloud model, there are three digital features to represent the overall characteristics of the concept: expectation (E_x), entropy (E_n), and hyper entropy (H_e). Expectation is the measure of the basic certainty of the qualitative concepts, and is given by the values that best represent the qualitative concepts. Entropy represents the range of uncertainty in the qualitative concepts, and the range of cloud drop values that can be accepted by the qualitative concepts. Hyper entropy is the uncertainty measure of entropy, and is reflected in the degree of dispersion of the cloud drops [41]. The specific effects of the three digital features on the cloud are shown in Figure 2.

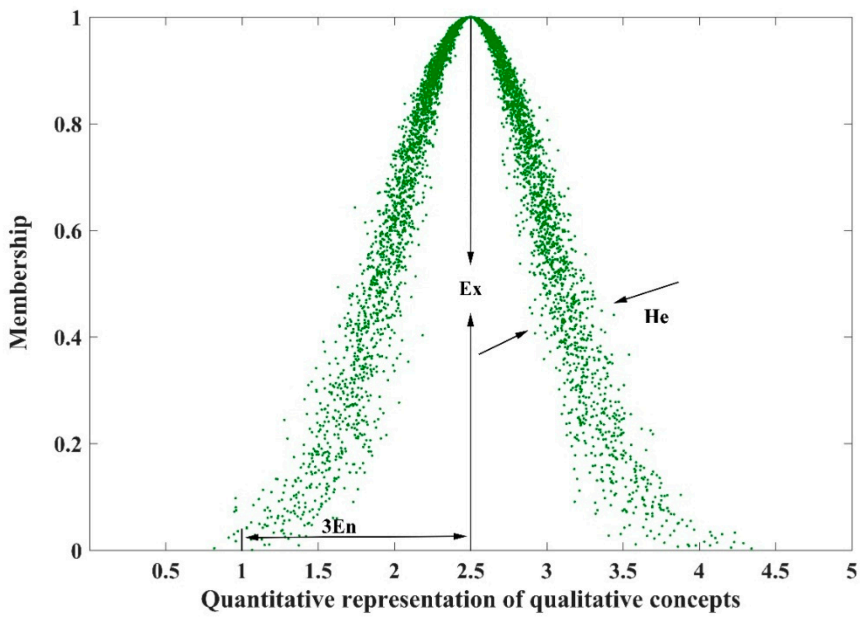

Figure 2. Three digital features of the cloud model.

The cloud generator is a mechanism for generating a cloud model, and includes a forward and a backward cloud generator. In the forward cloud generator, a series of cloud drops are obtained by inputting three digital features, and the cloud drop is the quantitative representation of the qualitative concepts. The backward cloud generator involves the reverse process: three digital features are obtained by entering a large number of data (quantitative representations of qualitative concepts) [42]. For example, when the three digital features of the indicator are known, the forward cloud generator can be used to obtain the cloud model of the indicator; if the many data of the indicator are known, these data can be entered into the backward cloud generator to get the three digital features.

3.3.2. Cloud Model Evaluation Process

(1) Standard Cloud

The expectation (E_x), entropy (E_n), and hyper entropy (H_e) of different grades are obtained according to the threshold range of the grade of the evaluation object, and a forward cloud generator is used to generate the standard cloud.

$$E_x = \frac{T_{gmax} + T_{gmin}}{2} \tag{2}$$

$$E_n = \frac{T_{gmax} - T_{gmin}}{6} \tag{3}$$

$$H_e = k \times E_n, \tag{4}$$

where T_{gmax} and T_{gmin} are the maximum and minimum values of the grade threshold range, respectively. When $H_e < E_n/3$, the cloud droplets showed a pan-normal distribution; when $H_e > E_n/3$, the cloud droplets showed an atomized state [43]. Based on multiple past researches, a value of $k = 0.1$ was used to maintain the stability of the assessment [44]. Set the extreme cases of $H_e = E_n/3$ and other values of k, and compare the evaluation results in these cases with the evaluation results of in $H_e = 0.1E_n$, finding that the gap between the results is extremely small (the maximum sum of the changes in each grade is 0.044, the minimum is 0). Therefore, this article chooses $k = 0.1$.

(2) Evaluation cloud

The current value of each evaluation object is input to the backward cloud generator to generate three digital features. These are entered in the forward cloud generator to generate the evaluation cloud map representing the evaluation object. The process of calculating the three digital features using the backward cloud generator is shown in the following Equation:

$$E_x = \frac{1}{n}\sum_{i-1}^{n} x_i \tag{5}$$

$$E_n = \sqrt{\frac{\pi}{2}} \times \frac{1}{n}\sum_{i=1}^{n} |x_i - E_x| \tag{6}$$

$$H_e = \sqrt{\left|\frac{1}{n-1}\sum_{i=1}^{n} (x_i - E_x)^2 - {E_n}^2\right|}, \tag{7}$$

where x_i are the data inputted to the backward cloud generator, and n is the number of inputted data.

(3) Evaluation results

The evaluation cloud is compared with the standard cloud to calculate the membership of the evaluation cloud for each grade.

Because of the uncertainty in the cloud drop random number generated by the forward cloud itself, the average value of the membership results of 5000 cloud models was used as the evaluation result to obtain stable and reliable membership results [45]. Finally, the membership results are normalized to obtain the grade percentage that is used as the final evaluation result.

$$p_g = u_g / \sum_{g=1}^{4} u_g \tag{8}$$

where u_g is the membership of the evaluation object for grade g; p_g is the normalization result of the membership of the evaluation object for grade g, and 1–4 represents failed, qualified, good, and excellent.

3.3.3. Cloud Model Evaluation Based on Weight

(1) Evaluation results for the membership factor layer

Except for the ratio of vegetation cover, BI, and degree of soil erosion, all other indicators include membership factors those need the evaluation of the membership factor layer.

In the cloud model evaluation process (Section 3.3.2), each membership factor belonging to the indicator is used as the evaluation object, and the evaluation results of all membership factors are obtained.

(2) Evaluation results for the indicator layer

The ratios of vegetation cover and BI were used as evaluation objects, and evaluation results were obtained using the cloud model. The degree of soil erosion is given by the ratios of the areas of different erosion grades in the study area, and the indicator data were directly used as the result of the membership evaluation in cloud model.

The evaluation results for the remaining indicators were weighted according to the cloud model evaluation results of the membership factors and the corresponding weights.

$$I_g = \sum_{i=z}^{y} P_{ig} \times W_i, \tag{9}$$

where I_g is the membership of the indicator for grade g; z and y represent the starting number and ending number, respectively, of the membership factors included in the indicator; and W_i is the weight of the membership factor i regarding the indicator.

(3) Evaluation results for the dimension land target layers

The evaluation results of the dimension layer and the target layer were weighted according to the corresponding weights of the indicator layer and the dimension layer, respectively, the weighting method is shown in Equation (9).

(4) Weighting results

The weights were mainly determined by the entropy weight method and the analytic hierarchy process (AHP) method.

Analytic hierarchy process (AHP) method is a multi-objective decision analysis method that combines qualitative and quantitative analysis methods [46]. The importance between indicators is judged based on the subjective will and constructs a judgment matrix. The maximum eigenvalue and corresponding eigenvector of the judgment matrix are calculated, which is the weight result. If the judgment matrix passes the consistency test, it is regarded as a reasonable weight result.

The entropy weight method is an objective weight method that calculates weight based on information entropy [47].

In information theory, the entropy value reflects the degree of disorder of information, which can be used to measure the amount of information. The larger the amount of information is, the smaller the entropy value and the greater the weight.

The specific weight determination method information and weight results are shown in Supplementary Materials S2.

3.3.4. Unweighted Cloud Model Evaluation

In the cloud model theory, a large amount of data (many cloud drops) representing the evaluation object are used to build a cloud model, and obtains the evaluation results directly. In this approach, all data need not be combined into evaluation results in the form of weights. Based on the evaluation mechanism of the cloud model, the present study conducted unweighted evaluation at each level, from low to high, according to a multi-level evaluation index system that was constructed. For example, surface water quality indicator was composed of six chemical substances, where multiple sample data were monitored in multiple spatiotemporal states. Because these chemical substances belonged to the membership factor layer of surface water quality, the sample data of all chemical factors could be directly used to construct a cloud model for evaluating surface water quality without weights which distinguish the importance of each membership factor. The evaluation steps for the unweighted cloud model are as follows:

(1) Evaluation results at the indicator layer

(a) Ensure uniform data standards

The unweighted cloud model requires all the data of each evaluation object at the same layer to build a cloud model. Consequently, the data for different evaluation objects need to be unified into a system. The internal threshold system of membership factors for some indicators is inconsistent (surface water quality, groundwater quality, air quality, and soil quality, Shannon–Wiener index of plants). To address this, the data of membership factors first need to be unified to the score system based on the composite index method theory, that is, the scored standard cloud shown in Figure 3. The remaining indicators are used to establish a standard cloud based on the indicator threshold system.

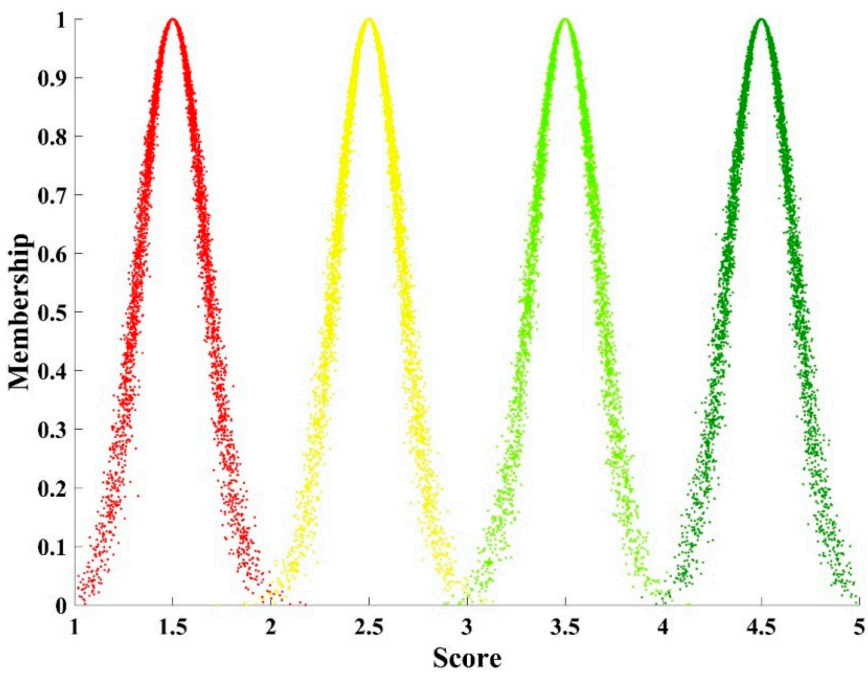

Figure 3. Scored standard cloud.

The score system is as follows: an excellent grade was equal to a (4, 5] score interval, a good grade was equal to a (3, 4] score interval, a qualified grade was equal to a (2, 3] score interval, and a failed grade was equal to (1, 2] score interval. The indicator data, or membership factor data, can be divided into two types. The first type is positive data: the larger the value, the more positive the indicator. For example, the larger the value of the BI is, the more positive the evaluation result, and the higher the score. The calculation method is shown in Equation (10). The second type is negative data: the larger the value, the more negative the evaluation result. For example, in the case of the permanganate index, which was the membership factor of surface water quality, the larger the value, the more negative the evaluation result, and the lower the score. The calculation method is shown in Equation (11).

$$S_i = S_{gm} + \left(N_i - T_{gmin}\right)/\left(T_{gmax} - T_{gmin}\right) \tag{10}$$

$$S_i = S_{gn} - \left(N_i - T_{gmin}\right)/\left(T_{gmax} - T_{gmin}\right), \tag{11}$$

where S_i is the score of the evaluation object i; N_i is the data of the evaluation object i; S_{gm} is the minimum score of the grade g corresponding to the data of the evaluation object i; S_{gn} is the maximum score of the grade g corresponding to the data of the evaluation object i; g refers to four grades of excellent, good, qualified, and failed, respectively; T_{gmin} is the minimum value of the threshold range of the grade g corresponding to the data of the evaluation object i; and T_{gmax} is the maximum value of the threshold range of the grade g corresponding to the data of the evaluation object i.

(b) Evaluation results

Based on the cloud model evaluation process, the scored membership factor data (all membership factors of the same indicator) were used as the evaluation object to obtain the evaluation results of each indicator based on the cloud model, and the remaining indicator were directly evaluated as evaluation object. The indicators containing the membership factors took the scored data of all membership factors as the input data of the backward cloud generator (evaluation cloud step in Section 3.3.2); the remaining indices used the indicator data to input the backward cloud generator (evaluation cloud step in Section 3.3.2). The Shannon–Wiener index of animals is different from the other indicators that contain membership factors. The data of each membership factor are different. It is inappropriate to gather all the membership factors to directly evaluate the indicator, for the membership factors with more data will have a greater impact on the evaluation results of the indicators, which is unfair. Therefore, in this step, each membership factor is used as the evaluation object to evaluate based on the cloud model, and the evaluation result of the membership factor is obtained.

(2) Dimension layer evaluation results

(a) Transformation of cloud model evaluation results

The evaluation result at the dimension layer was an unweighted integration of the evaluation results at the indicator layer. Thus, the membership evaluation results of the cloud model needed to be converted into a data form that the cloud model could recognize. Because the unweighted cloud model was based on scores, the membership results were transformed into a single score result as the input data for the backward cloud generator. The conversion Equation is as follows:

$$S_c = P_f \times 1.5 + P_q \times 2.5 + P_g \times 3.5 + P_e \times 4.5 \tag{12}$$

where S_c represents the scoring result of the cloud model; P_f, P_q, P_g, and P_e represent the normalized membership of the failed grade, qualified grade, good grade, and excellent grade, respectively; and 1.5, 2.5, 3.5, and 4.5 are the best score for each grade.

According to the determination method of the three digital features of the standard cloud in the cloud model, E_x (expectation) is represented by the middle value of the threshold interval which is the value best representing the qualitative concept. Similar to the cloud model, the middle value of each grade's score interval is the score that best represents each grade.

(b) Evaluation results

The transformed score results were used as input data for the backward cloud generator, and the evaluation results were obtained based on the scored cloud model.

In the scoring of the cloud model results, the membership of each grade regarded as the grade weight, the intermediate value that can be regarded as the representative of the grade interval of one point, and the scoring result, were obtained by weighted calculation. The score interval of a grade is a range value, and the process of scoring generalizes it into point values, in which the result of the score will lose the information on the left and right sides of the grade interval. To compensate for the impact of the lack of score information on the evaluation results, it is necessary to consider the fuzziness of the boundaries of each grade, appropriately enlarge the threshold range of each grade, and modify the standard cloud entropy (E_n) algorithm.

The boundary value is a transition value from one grade to another, and is ambiguous. The boundary value should belong to two adjacent grades at the same time, and have the same membership for the two grades, as shown in Equation (13). The revised standard cloud image is shown in Figure 4.

$$e^{\{-\frac{(T_{gmax}-T_{gmin})^2}{8E_n{}^2}\}} = 0.5 \tag{13}$$

$$E_n = \frac{T_{gmax} - T_{gmin}}{2.355} \tag{14}$$

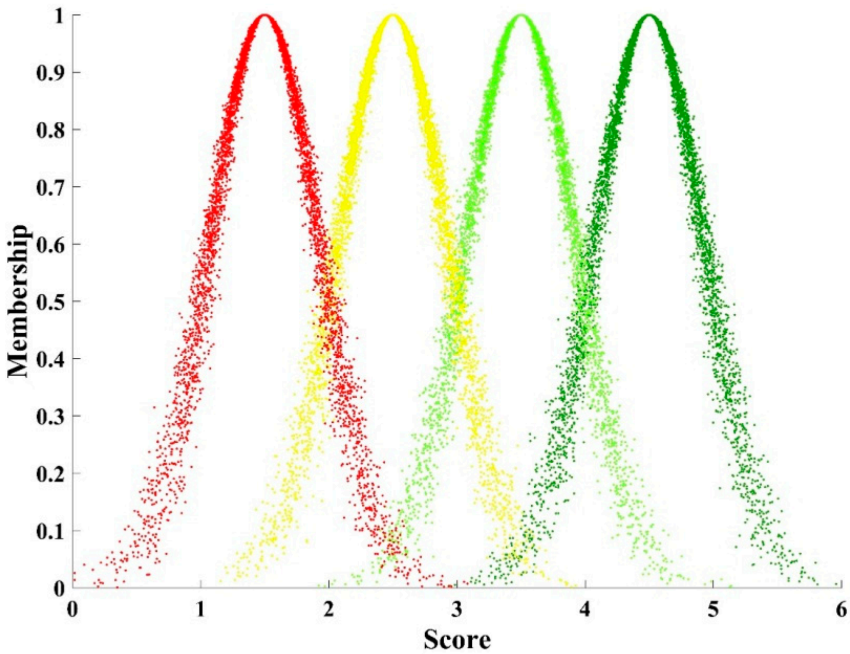

Figure 4. Modified scored standard cloud.

The evaluation result for the Shannon–Wiener index of animal diversity was obtained from the evaluation results of the membership factors according to the above steps so that the dimensional layer evaluation results can be calculated.

(3) Evaluation results of the target layer

The "evaluation results of the dimension layer" step is repeated, and the scored results from the cloud model results for the dimension layer are input into the backward cloud generator to obtain the evaluation results of the target layer.

The evaluation mechanism process for the two cloud models is shown in Figure 5.

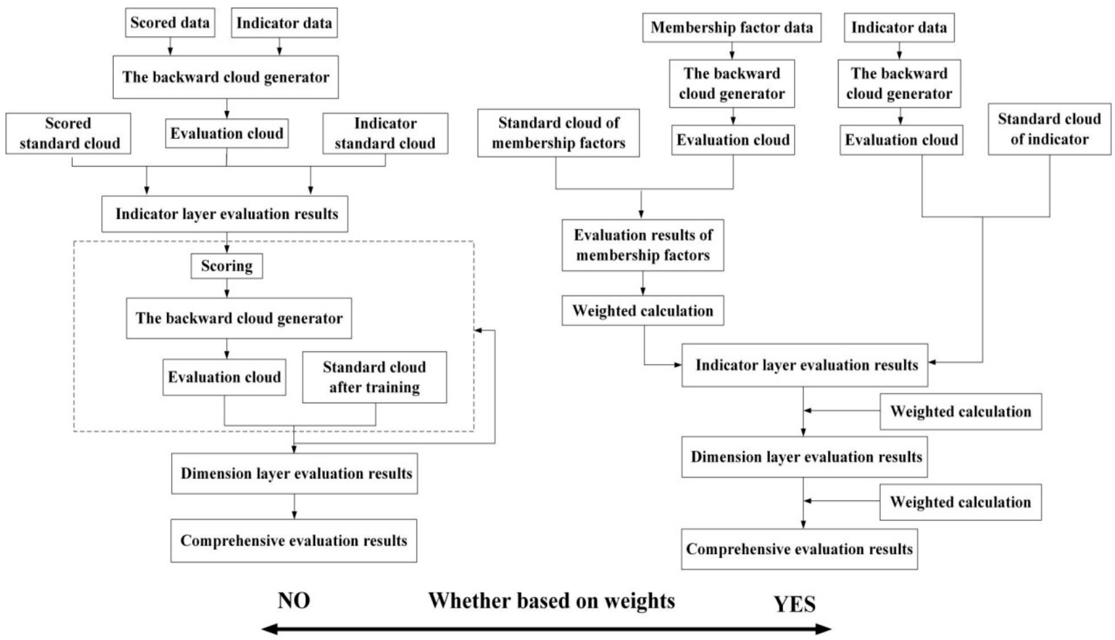

Figure 5. Evaluation mechanisms for the unweighted and weighted cloud models.

4. Results

The unweighted cloud model evaluation results at various layers for the ecological environment of Songshan Nature Reserve are shown in Figure 6. The results show that the overall ecological environment of the Songshan Nature Reserve is divided into three grades: excellent (21%), good (67%), and qualified (12%). Thus, 88% of the ecological environment status of Songshan Nature Reserve is above the qualified grade, and the excellent and good grades predominate. Overall, the ecological environment of Songshan Nature Reserve is stable and performing well.

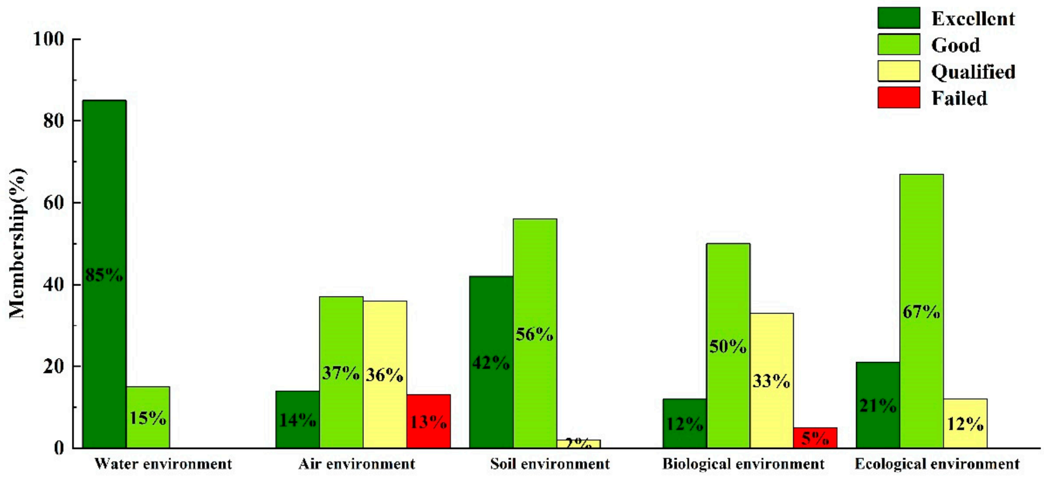

Figure 6. Dimension layer and evaluation results for the ecological environment in the Songshan Nature Reserve.

The water environment contributes the most to the good ecological environment of the Songshan Nature Reserve, and it is the healthiest environment in the dimensional layer. The excellent grade in the water environment accounts for up to 85%, which is critical. The absolute excellence of the water environment is the result of the unpolluted groundwater (100% of which is classified as excellent), while the quality of the surface water is relatively poor (70% assigned to the excellent grade). If the water environment is to be improved, attention needs to be paid to the purification of surface water.

The quality of the soil environment is second only to that of the water environment. Excellent (42%) and good (56%) grades are evenly distributed in the soil environment. Thus, 98% of the soil environment quality is higher than the qualified grade, and it is reasonable to assume that these grades will be maintained in the long term. It should be noted, however, that the high quality of the soil environment is largely the result of low soil pollution: the soil quality factor, which represents the content of soil pollutants, had an excellent grade for 86% of the area. In contrast, soil erosion grades were distinctly lower: excellent grade = 26% and good grade = 53%. Thus, 53% of the Songshan Nature Reserve has moderate degrees of erosion (moderate corresponds good). Most of the nature reserve belongs to moderate soil erosion, which means that water flows easily take some substances from the soil into the water body, which may cause pollution of surface water bodies. Soil erosion is a major problem for the soil environment of the Songshan Nature Reserve.

In the biological environment, good grades account for 50%, while qualified grade ranks second with 33%, and thus 83% belong to intermediate states. Although the performance of the biological environment can be maintained at an intermediate level for a long period of time, this is inconsistent with the area's status as a national nature reserve and fails to recognize the importance of the protection of the ecological environment. The BI, which represents the species richness in the biological environment, was in the good grade for 100% of the environment. Species richness is of great significance for the biological environment.

However, the Shannon–Wiener index for plants and the Shannon–Wiener index for animals account for 100% and 81% of the qualified grades, respectively, and the species distribution of animals and plants are similar. This means that, although the species richness in the area is good, the degree of uniformity of the species distribution is only qualified. Ninety-eight percent of the ratio of vegetation cover indicator in the protected area belongs to the excellent grade, which is the best performing indicator, and shows that the reserve has a sufficiently plant population. Within the biological environment, each indicator has a very similar situation, and the indicators are concentrated in one grade, which implies that the current performance of the biological environment will persist. For example, Shannon–Wiener index of animals is 81% qualified, Shannon–Wiener index of plants is 100% qualified, the ratio of vegetation cover is 98% excellent, BI index is 100% good. In terms of the biological environment of the nature reserve, the coordination of the distribution of species is the most urgent task, and the number of species needs to be increased.

The air environment is the worst performing environmental dimension, with good and qualified grades of 37% and 36%, respectively, and excellent and failed grades of 14% and 13%, respectively. The positive and negative states of the air environment account for 51% and 49%, respectively, and represent the dividing line between positive and negative trends. The positive state of the air environment is not as stable as that of the other environmental dimensions. To consolidate the positive state of the air environment, the most effective measure would be to reduce the content of PM_{10} and $PM_{2.5}$ in the air. These two pollutants are the biggest contributors to the poor air environment. Excessive levels of PM_{10} and $PM_{2.5}$ are closely related to the noticeable air pollution problems that have occurred in Beijing in recent years. Air quality issues persist and Beijing authorities need to continue to address these issues.

5. Discussion

5.1. Rationality of the Unweighted Cloud Model Evaluation

Using the constructed evaluation indicator system, the present study conducted an unweighted cloud model evaluation of the data at each layer. The essence of the unweighted cloud model is to raise the data of the evaluation object by one layer. The sample data of the evaluation object not only represent the situation of the evaluation object, but also directly represent the situation of the upper-layer target to which the evaluation object belongs.

Therefore, there is no need to define the importance of the evaluation object on the upper-layer target by weight, and the data of all evaluation objects directly define the situation of the upper-level target across the evaluation objects. For example, surface water quality and groundwater quality are both indicators of the water environment dimension, and the data for these two indicators represent the situation of the indicator itself, and also represent the situation of the water environment dimension. The data for surface and groundwater quality together build the evaluation cloud of the water environment, and also directly represent the water environment to the same extent. Theoretically speaking, the situation of the evaluation target is composed of the evaluation object attached to it, and the sample data of the evaluation object is also part of the upper-layer target in addition to representing yourself. The unweighted cloud model evaluation is based on these components.

The sample data volume of the evaluation objects participating in the unweighted cloud model needs to be consistent. In the unweighted cloud model, the sample data of all the evaluation objects belonging to the same evaluation target are used to build a cloud model. Thus, the evaluation objects with a higher data volume will be over-represented in cloud model results. In the present study, the evaluation of the unweighted cloud model conducted in layers was to obtain multi-layer evaluation results, and also to address the limitations caused by the inconsistency in the amount of data available for each evaluation object. For example, it is not possible to directly construct a cloud model to obtain the evaluation results of the target layer by using the evaluation results of the indicator layer converted into scores. These indicators represent different attributes of the ecological environment at the objective level, namely, the dimension layer. The number of indicators in different dimensions is different, and directly using the indicator data to build a cloud model will cause the dimensions with more indicators to have a greater impact on the overall evaluation. This will reduce the rationality of comprehensive evaluation. Even if the amount of indicator data in each dimension is the same, the dimension layer should not be omitted and direct unweighted evaluation on the target layer should not be performed. Because the data of the evaluation object directly represent the upper-layer target of the evaluation object in the theory of the unweighted cloud model, expanding the scope of the representativeness by one layer more than the weight-based evaluation method is a reasonable step to take. Excessive expansion of the degree of representation is, however, inconsistent with the actual meaning, and will lead to anomalous results. Therefore, the unweighted cloud model should be evaluated layer by layer, based on layers of realistic meaning.

From the evaluation results of the unweighted cloud model in the study area, good grades accounted for the largest proportion of grades in the unweighted cloud model evaluation results. Gao et al. [17] used a combination of qualitative and quantitative methods to create a forest health evaluation indicator system for the Songshan Nature Reserve, and divided the indicators into five grades: high quality, healthy, sub-healthy, unhealthy, and sick. The evaluation took the small class as the unit and calculated the forest health score of 120 small classes in the forest. The results showed that most of the forests in the Songshan Nature Reserve were in a healthy state (ranked second), and that the healthy state accounted for 56.15% of the total area of the forest. Gao et al.'s results are consistent with our results, which were obtained using an unweighted cloud model to evaluate the forest health of the Songshan Nature Reserve.

5.2. Evaluation Result of Cloud Model Based on Weight

Because the weighting result of the subjective weighting method is dominated by the subjective experience of the evaluator, this paper obtained a variety of weighting results (four indicator layer weighting results and five dimension layer weighting results) based on the opinions of different experts. The specific results are shown in Supplementary Materials S2. Corresponding to these weighting results, 20 kinds of target layer evaluation results were obtained, as shown in the Table 2.

Table 2. Evaluation result of cloud model based on weight.

Weighting Schemes	Evaluation Results				
	Excellent	**Good**	**Qualified**	**Failed**	**Scored Results**
I1, D1	0.4213	0.3269	0.1850	0.0669	3.60
I1, D2	0.3592	0.3713	0.2134	0.0561	3.53
I1, D3	0.4101	0.3299	0.1944	0.0656	3.58
I1, D4	0.4403	0.3142	0.1806	0.0649	3.63
I1, D5	0.3614	0.3609	0.2170	0.0607	3.52
I2, D1	0.4107	0.3650	0.1594	0.0650	3.62
I2, D2	0.3469	0.4156	0.1837	0.0538	3.56
I2, D3	0.3987	0.3711	0.1668	0.0635	3.60
I2, D4	0.4299	0.3520	0.1552	0.0630	3.65
I2, D5	0.3486	0.4073	0.1858	0.0584	3.55
I3, D1	0.4082	0.3351	0.1882	0.0684	3.58
I3, D2	0.3416	0.3824	0.2178	0.0581	3.51
I3, D3	0.3986	0.3372	0.1973	0.0669	3.57
I3, D4	0.4295	0.3210	0.1833	0.0662	3.61
I3, D5	0.3475	0.3697	0.2205	0.0624	3.50
I4, D1	0.3977	0.3732	0.1626	0.0665	3.60
I4, D2	0.3294	0.4267	0.1881	0.0559	3.53
I4, D3	0.3872	0.3784	0.1696	0.0648	3.59
I4, D4	0.4190	0.3589	0.1579	0.0643	3.63
I4, D5	0.3346	0.4161	0.1893	0.0600	3.53

The 20 weighting schemes all passed the consistency test of the AHP method or were determined by the expert's experience and knowledge. There is no standard answer to the weighting results. Therefore, the 20 evaluation results obtained are all reasonable, but the evaluation results of different weighting schemes are obviously different, which is also one of the disadvantages of the weighting-based method. Among the 20 evaluation results, the maximum membership grade of thirteen results is excellent, and the maximum membership grade of seven results is good. The scored result interval is [3.5, 3.65]. The maximum percentage of excellent grade is 44% and the minimum percentage is 33%; the maximum percentage of good grade is 43%, and the minimum percentage is 31%.

Compared with the evaluation result of the target layer of the unweighted cloud model, maximum membership grade is good in the evaluation result of unweighted cloud model, which is consistent with the evaluation result of the 35% weight-based cloud model. The scored result of the unweighted cloud model is 3.59, included in the weighted cloud model score result interval [3.5, 3.65]. Therefore, the evaluation results of the unweighted cloud model are consistent with the past research results of the study area and the evaluation results of the cloud model based on weight to a certain extent, which are reliable. In addition, this comparison also reflects the advantages of the unweighted cloud model, which can avoid the uncertainty of weighting affecting the evaluation results, and is thus suitable for scenarios where weights are not easily determined or are uncertain.

6. Conclusions

Using four environment dimensions (water, air, biological, and soil), this paper constructed an ecological environment evaluation indicator system that is suitable for forest ecosystem nature reserves. The ecological environment of the Songshan National Nature Reserve was comprehensively and quantitatively evaluated using this system.

An unweighted cloud model evaluation mechanism was constructed, and the ecological environment of the Songshan National Nature Reserve was evaluated based on a multi-layered indicator evaluation system to avoid the impact of weighting uncertainty on the evaluation results. In addition, the evaluation results of the unweighted cloud model were compared with the evaluation results from a weighted cloud model. The comparison verified the rationality of the evaluation by the unweighted cloud model.

The unweighted cloud model evaluation results showed that the ecological environment grades for the Songshan Nature Reserve were 21% excellent, 67% good, and 12% qualified. From the predominance of excellent and good grades, it is reasonable to assume that the ecological environment of the Songshan Nature Reserve should remain positive for the foreseeable future.

The overall grade order of the states for each environment dimension is water environment > soil environment > biological environment > air environment. The biological environment and the air environment require the most attention in the Songshan Nature Reserve.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/7/1905/s1, S1 (Table S1: The threshold range of the indicator grades, Table S2: Grading standard of soil erosion), S2 (Table S3: The weight of the indicator membership factor relative to the indicator, Table S4: The weight of the index layer relative to the dimension layer, Table S5: The weight of the dimension layer relative to the target layer).

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