Light pollution risk level assessment based on AHP-fuzzy comprehensive evaluation algorithm

Zhixuan Wang[1, *, &] and Zhongyuan Yuan[2, &]

[1]School of Environment and Ecology, Hunan Agricultural University, Changsha, China

[2]School of Information and Intelligent Science and Technology, Hunan Agricultural University, Changsha, China

*Corresponding author: wangzx@stu.hunau.edu.cn

[&] These authors contributed equally to this work

Abstract. Light, which helps us to see better in the dark, exists in many forms. However, on the one hand it does have benefits for us in our daily life and on the other hand the use of unrestricted artificial light can cause some damage to our body and wildlife life. In this paper, we try to develop a model that can move from qualitative to quantitative assessment. 13 typical and common causes of light pollution are selected for further study by AHP-Fuzzy Integrated Evaluation. We divided the 13 causes into 3 types, including human activities, natural environment and ecological factors, and used hierarchical analysis to give the weight of each indicator and construct a judgment matrix M-C to finally obtain the final weight of each factor. After this, we built an evaluation set containing five levels. Using the weight scores for fuzzy evaluation, according to the maximum subordination principle, we obtained an overall evaluation result: M=C* η ×100.

Keywords: AHP; Fuzzy integrated evaluation; Light pollution; Risk level assessment model.

1. Introduction

Light pollution is a new source of environmental pollution after the white light pollution and artificial white light pollution including exhaust gas, waste water, waste residue and noise pollution. Light pollution is threatening people's health.

Although light brings a lot of convenience to human life, light pollution has a certain negative impact on the environment. Almost all organisms are accustomed to the natural rhythm of alternating day and night, and about 30% of the world's vertebrates and more than 60% of invertebrates are nocturnal [1]. Light pollution also has enormous costs and wasted energy, estimated to cost the United States nearly $7 billion annually [2]. Therefore, it is necessary to develop plans to mitigate these impacts.

The purpose of this paper is to develop an evaluation model to identify which factors may influence the level of light pollution risk and to assess the level of light pollution in different areas based on the developed model.

2. AHP-Fuzzy Comprehensive Evaluation Model

The Analytical Hierarchy Process (AHP) is a hierarchical weighted decision analysis method proposed by Professor T.L. Satty , an operations researcher at the University of Pittsburgh in the early 1970s. This method decomposes the relevant influencing factors of a decision problem into objective, criterion and solution levels, and then analyzes and evaluates the essence of complex decision problems, influencing factors and their internal linkages by qualitative and quantitative methods.

The Fuzzy Comprehensive Evaluation Method generally refers to an evaluation method based on fuzzy mathematics theory, which transforms qualitative evaluation into quantitative evaluation using the theory of membership degree and evaluates the relevant influencing factors using fuzzy mathematics. The Fuzzy Comprehensive Evaluation Method has the advantages of accurate results and strong systematic and can effectively solve some complex problems that are difficult to quantify, making it particularly suitable for dealing with non-deterministic problems [3].

The AHP-Fuzzy Comprehensive Evaluation Method is a combination of the above two methods. This method uses the Analytical Hierarchy Process to hierarchically process the influencing factors of the index system, determine the weight coefficients of each index factor, and then use the Fuzzy Comprehensive Evaluation Method to determine the membership degree of each factor, and finally use fuzzy mathematics to calculate and analyze the evaluation results.

2.1 Determine the evaluation index system

Many factors are involved in assessing the level of risk caused by light pollution [4]. It is necessary to consider not only general influences on geographic factors, natural weather conditions, and ecological cycles, but also specific factors influenced by human development, such as population density, unnatural light sources, and solar radiation reflection coefficients of buildings.

In this paper, we analyze and compare three main aspects of the impact of human activities, natural environmental characteristics, and ecological factors, as shown in Figure 1.

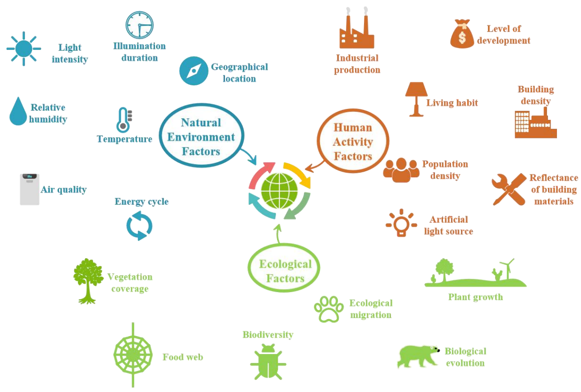

Fig. 1 Influencing Factors Chart

2.1.1 Human activities

The influence of human activities mainly includes: residents' work and rest patterns, regional development level, population density, building density, artificial light sources, and reflectivity of building materials. When comparing programs, the representatives with high scores are relatively influential, and vice versa are less influential.

First, the working and resting habits of residents are an important factor affecting light pollution. Irregular working hours can lead to an increase in light hours at night, increasing the level of light pollution in the city. Second, the level of regional development is also a key factor influencing the degree of light pollution. Developed regions are highly urbanized, with high building density, abundant artificial light sources and more serious light pollution. In addition, population density, high building density, and light pollution are also more serious in the region. The high reflectivity of building materials will enhance the reflection of artificial light sources and increase the degree of light pollution. Finally, artificial light source is also one of the main factors causing light pollution.

2.1.2 Natural Environment

The characteristics of natural environment mainly include light intensity, light duration, relative humidity, temperature and air quality. When comparing schemes, those with high scores represent low relative cost, while those with high scores represent high relative cost.

First, the intensity and duration of light are the main factors contributing to light pollution. At night, the presence of artificial light sources leads to an increase in the intensity of light at night, which interferes with the biological rhythms of animals. During the day, the reflection and absorption of natural light generated by human activities lead to changes in the duration of light, thus altering the growth cycles of some plants and animals. Relative humidity and temperature can also contribute to light pollution. High temperatures and low humidity can increase the concentration of aerosols, one of the main sources of light pollution, which can affect the visibility of the sky at night. In addition, deterioration in air quality can lead to increased light pollution, such as urban air pollution, which can have an impact on the nighttime light environment.

2.1.3 Ecological factors

Ecological factors mainly include vegetation coverage rate and ecological diversity. When comparing schemes, those with high scores represent low relative cost, while those with high relative cost. Ecological diversity and vegetation coverage rate are important factors for maintaining ecosystem stability, and they are very important for preventing or mitigating the impact of light pollution. Ecological diversity includes the number and degree of diversity of different species. When the number of species decreases or the ecosystem is disturbed, the ecological diversity will be affected. Vegetation coverage is the percentage of land surface covered by plants. The presence of vegetation can reduce the effects of light pollution on organisms, and it can also absorb and filter some sources of light pollution, such as street lamps.

The light pollution risk level assessment factors are integrated above, and the light pollution risk level assessment indexes are designed in a hierarchical way using hierarchical analysis to establish the light pollution risk level assessment system and hierarchical analysis structure model, as shown in Figure 2.

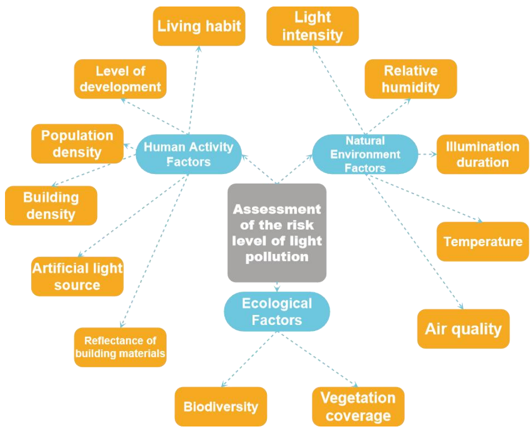

Fig. 2 Hierarchical Analysis Chart

2.2 Hierarchical analysis to determine the weights

2.2.1 Determining importance weights

According to the assessment system of light pollution risk level and the hierarchy analysis structure, starting from the first criterion layer and moving down, the importance weights of different elements in each layer relative to those in the upper layer are gradually determined. The weight setting method of the Analytic Hierarchy process (AHP) is preferred for the light pollution risk level, and the calculation process refers to the reference [5,6].

2.2.2 Model solution

(1) Construct the judgment matrix M-C: compare the three elements C_1, C_2 and C_3 in the base layer C to obtain the pairwise comparison matrix as shown in Table 1.

Table 1. M-C judgment matrix **Table 2**. C1-P judgment matrix

M	C_1	C_2	C_3
C_1	1	2	4
C_2	0.5	1	2
C_3	0.25	0.5	1

C_1	P_1	P_2	P_3	P_4	P_5	P_6
P_1	1.0000	0.5000	0.5000	0.7500	0.5000	0.3000
P_2	1.9000	0.9000	0.9000	1.4000	1.4000	0.7000
P_3	2.0000	1.0000	1.0000	1.5000	1.5000	0.6000
P_4	1.4000	0.7000	0.7000	1.0000	0.8000	0.6000
P_5	2.3000	1.9000	1.5000	1.7000	1.0000	0.7000
P_6	2.7000	2.3000	2.0000	2.2000	1.4000	1.0000

Solving the eigenvalues of $M-C$, it is easy to solve $\lambda_{\max}=2.7247$, and the weight vector $\omega_{\mathrm{i}}=(0.4914,0.3390,0.1695)^T$, calculated by the formula, $CI=\frac{\lambda_{\max}-n}{n-1}$, we get $CR=-0.2647<0.1$, which passed the consistency test.

(2) Construct the judgment matrix C_1-P、C_2-P、C_3-P ,as shown in Table 2.

(3) The weight vectors calculated from the above three judgment matrices, the maximum eigenvalue is λ_I and the consistency index is CR_{j}.

As can be seen from the values of CR_{j}, the matrix C_1-P、C_2-P、C_3-P all passed the consistency test.The final weights of each factor to the target layer are shown in Figure 3.

Fig. 3 Weight distribution diagram of each factor

2.3 Fuzzy integrated evaluation model

2.3.1 Principle of multi-level fuzzy evaluation

Fuzzy mathematics is a mathematical method that uses fuzzy set and membership function to accurately describe the fuzzy evaluation problem. According to the viewpoint of system theory, evaluation is a multi-factor, multi-index and multi-level comprehensive evaluation process in essence, so it is a multi-level fuzzy comprehensive evaluation problem. Its mathematical model is as follows:

$$U'\begin{bmatrix} U_1 & - & (\mathrm{u}_{11} & \mathrm{u}_{12}\cdots\cdots\mathrm{u}_{1\mathrm{j}}) \\ U_2 & - & (\mathrm{u}_{21} & \mathrm{u}_{22}\cdots\cdots\mathrm{u}_{2\mathrm{j}}) \\ U_3 & - & (\mathrm{u}_{31} & \mathrm{u}_{32}\cdots\cdots\mathrm{u}_{3\mathrm{j}}) \\ U_4 & - & (\mathrm{u}_{41} & \mathrm{u}_{42}\cdots\cdots\mathrm{u}_{4\mathrm{j}}) \end{bmatrix} \tag{1}$$

It is assumed that light pollution evaluation can be composed of several single factors to form the total set of evaluation factors theoretical domain: $U'=\{U_1U_2\cdots U_{\mathrm{n}}\}$. Each single factor U_n is in turn composed of j first-level evaluation factors. This constitutes a hierarchical factor model, $U_{\mathrm{n}}=\{U_{n1}U_{n2}\cdots U_{\mathrm{nj}}\}$; the set of rubrics is $V=\{v_1v_2\cdots v_m\}$.

For each single factor U_{n} , the fuzzy relationship between the factor domain and the rubric domain can be represented by the fuzzy matrix R_n :

$$R_n = (r_{ij})_{n\times m}\begin{bmatrix} u_{11} & u_{12} & \cdots\cdots & u_{1m} \\ u_{21} & u_{22} & \cdots\cdots & u_{2m} \\ u_{31} & u_{32} & \cdots\cdots & u_{3m} \\ u_{41} & u_{42} & \cdots\cdots & u_{4m} \end{bmatrix} \quad (2)$$

Where U_{jm} indicates that the j th factor was rated as the m th rubric affiliation.

Suppose the weight of each factor $(u_{n1} \quad u_{n2} \quad \cdots\cdots \quad u_{n4})$ in each factor U_n on the factor theory domain $A_n = \{a_{n1} \quad a_{n2} \quad \cdots\cdots \quad a_{n3}\}$, then the single-factor fuzzy integrated evaluation model is $B_n = A_n * R_n$.

The results of the single-factor evaluation were used to form the overall fuzzy evaluation relationship matrix:

$$R' = \begin{bmatrix} B_1 \\ B_2 \\ \cdots\cdots \\ B_n \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots\cdots & b_{1m} \\ b_{21} & b_{22} & \cdots\cdots & b_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix} \quad (3)$$

The weight value of each evaluation factor $(U_1 \quad U_2 \quad \cdots\cdots \quad U_n)$ in U' is found out: $A' = \{A_1 \quad A_2 \quad \cdots\cdots \quad A_n\}\left(\sum_{j=1}^{n} A_j = 1\right)$, and after fuzzy composite operation: $B' = A' * R'$, the comprehensive evaluation result is determined by the principle of maximum subordination.

2.3.2 Determination of evaluation indicators

There are many factors affecting light pollution, including human activity factors, natural environment factors and ecological factors, such as human and non-human factors. Although the influencing factors are many and complex, the degree of influence of each factor is different. After comprehensive consideration, 13 evaluation indexes were determined, which were living habits (P_1), development level (P_2), population density (P_3), building density (P_4), artificial light (P_5), reflectance of building materials (P_6), light intensity (P_7), light duration (P_8), relative humidity (P_9), temperature (P_{10}), air quality (P_{11}), biodiversity (P_{12}) and vegetation coverage rate (P_{13}), and the evaluation factor set was constructed. The 13 evaluation indexes of 34 provincial-level administrative regions (23 provinces, 5 autonomous regions, 4 municipalities directly under the Central Government and 2 special administrative regions) in China were evaluated. (Data source: China Statistical Yearbook) The light pollution degree was divided into 5 levels, namely: good, good, average, poor and poor, which were represented by 1, 2, 3, 4 and 5 respectively.

2.3.3 Constructing affiliation functions

Using the triangular fuzzy distribution graph as shown in Figure 4, the affiliation function is determined based on the 5-level semantic scale of the score as shown in Equation 4.

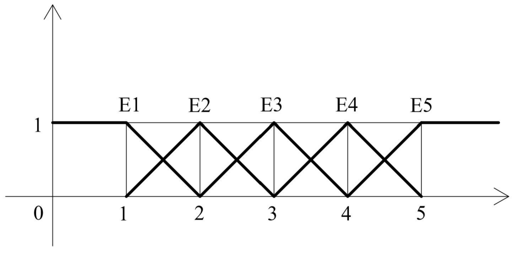

Fig. 4 Triangular fuzzy distribution figure

$$\mathrm{M_j}(x_i)=\begin{cases}1 & (x_i=a_j)(j=2,3,4)\\ x_i-a_{j-1} & (a_{j-1}+0.5<x_i<a_j)\\ a_j-x_i & (a_{j-1}<x_i<a_{j-1}+0.5, a_j+0.5<x_i<a_{j+1})\\ a_{j+1}-x_i & (a_j<x_i<a_j+0.5)\\ 0 & (x_i\le a_{j-1}, x_i\ge a_j+1)\end{cases} \quad (4)$$

Where, $\mathrm{M_j}(\mathrm{x_i})$ indicates the impact of the i th factor score being rated at level j ; a_j is the score of the j th rating level.

2.3.4 Multi-level fuzzy integrated evaluation

Multiplying the affiliation matrix with the weight coefficient matrix of the same level, the fuzzy comprehensive evaluation results of the upper level evaluation factors can be obtained, and then the evaluation results of the factors at that level can be used as the affiliation matrix of the higher level, and in applying the same method, the final evaluation results can be calculated.

$$\mathrm{C_i} = \mathrm{W_i} * \mathrm{R_i} \quad (5)$$

Where: $\mathrm{C_i}$ is the result of fuzzy operation, namely the vector of evaluation results; $\mathrm{W_i}$ is the fuzzy weight vector to determine the evaluation factors; $\mathrm{R_i}$ is the corresponding affiliation matrix.

2.3.5 Analysis of evaluation results

The calculation result of fuzzy evaluation is a fuzzy vector, which represents the comprehensive affiliation of the evaluation object to the evaluation level. For more intuitive and convenient preference, a scale can be given to each evaluation level, such as $\eta = \{\eta_1, \eta_2, \eta_3, \ldots, \eta_n\}$, then the specific score of the overall evaluation result can be calculated as $\mathrm{M} = \mathrm{C} * \eta \times 100$.

3. Explanation of the risk assessment model in four aspects

3.1 Data Collection

In order to verify the model that we built in last section , we selected some data from the China Statistical Yearbook 2021.Chinese topography from west to east ,showing the distribution of ladder ,due to this unique landform ,we selected Jiuzhaigou valley ,Aba Tibetan Autonomous Prefecture, Sichuan province as the sample of the first step. Shennongjia Forestry Distirct , northern west part of Hubei province as the sample of the second step ,and Changbai mountain groups ,southern east part of Jilin province as the sample of the third step as shown in Figure 5. Each sample includes protected land ,urban community ,rural community and suburban area. We compared these three samples to get a conclusion that relates the four types area to the factors that cause light pollution.

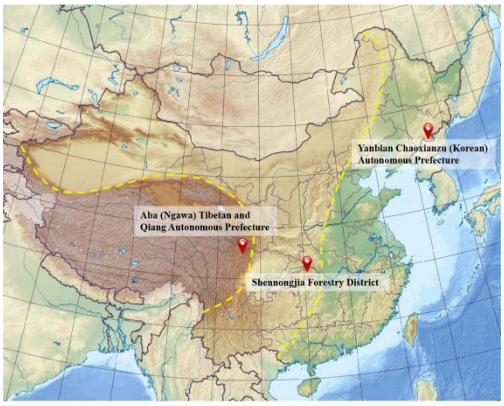

Fig. 5 Three-stage ladder site selection map

3.2 Solutions for risk assessment models

3.2.1 First-order fuzzy integrated judgment

According to the order from step one to step three， we analyzed those three samples mentioned above by using the Fuzzy comprehensive evaluation method short for FCE and AHP .We built an evaluation set including perfect、 preferable、 average、 inferior and poor. We've got 13 single factors related to three different layers including human activities、natural environment、 ecological factors in question 1 , tried to figure out the membership degree of the 13 single factors to the three different layers first to help us find out the final result. Here we chose the data of Jiuzhaigou for example.

Using the weight score to have fuzzy variation ,$C = w * r$,then making weighted average type synthesis operation to get the synthesizing evaluation vector quantity $C = C_1, C_2, \ldots, C_n$,. According to the maximum membership degree principle ,the evaluation degree of light pollution is the degree that C_i refers to. Evaluation result is showing Table 3.

Table 3. First level fuzzy result table

C	Very good	Good	General	Poor	Very poor
C_1	0.734	0.143	0.058	0.051	0.014
C_2	0.643	0.231	0.083	0.022	0.021
C_3	0.789	0.164	0.021	0.016	0.010

3.2.2 Second-order fuzzy integrated judgment

In this section we tried to figure out the relationship between three layers: social activitie、natural environment、ecological environment and four different areas: S short for protected land(index Ⅰ), T short fot urban community(index Ⅱ), A short for rural community(index Ⅲ) and R short for suburban area(index Ⅳ).

We've calculated the weight scores of each single factor in criterion layer C that influences light pollution level. After multiplying matrices we got:

$$C = W * R = (0.5881, 0.3002, 0.1117) * \begin{bmatrix} 0.734 & 0.143 & 0.058 & 0.051 & 0.014 \\ 0.643 & 0.231 & 0.083 & 0.022 & 0.021 \\ 0.789 & 0.164 & 0.021 & 0.016 & 0.010 \end{bmatrix} \tag{6}$$

We chose $\eta = \{1(\text{perfect}), 0.8(\text{perferable}), 0.6(\text{average}), 0.4(\text{inferior}), 0.2(\text{poor}),\}$ as the membership degree of the evaluation grade of the index factor. We came to an conclusion that the score I gained is 78.36,repeating the steps mentioned above we got the scores of the three other index ,they are: 63.43, 58.25, 44.32. Doing the same to the two other samples we got the result showing in the Figure 6.

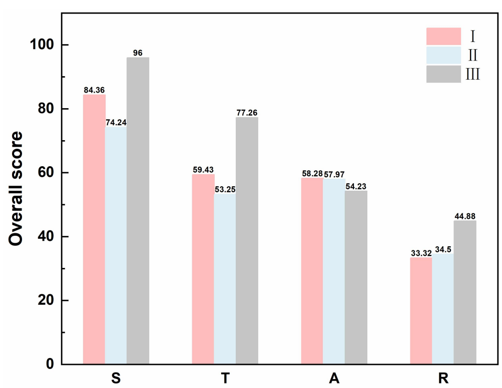

Fig. 6 Comprehensive evaluation chart

3.3 Interpretation of results on the risk level of light pollution

During the process of building a model to analyze the risk level of light pollution， we consider social factors、natural environment、 ecology which may influence the risk level of light pollution as a whole system. We used specific data to support our model to get reliable results:

1. The light pollution level of protected area is largely lower than which in other areas:

Vegetation coverage in protected Area is highest ,the building density and population density is lowest ,due to the two main reasons ,the degree of light pollution is lower here.

2. The degree of light pollution in urban community is higher than which in other areas:

There are lots of buildings ,roadways and vehicles which stand for human life routine in urban area .From our study result ,population density ,building material reflectivity and even artificial lights are the main cause in light pollution .They are also components of the city ,that’s why light pollution in urban community is higher than any other areas.

One research, Lyytimäki, J. (2013). Urbanization, green areas, and environmental health: how strong is the relationship? Journal of environmental and public health, suggests that vegetation in forest can reduce the level of light pollution ,which is suitable to our result.

Another research in Nature suggests that there are nearly 99 percents of the world population are living in the light polluted areas, light pollution in urban areas are much higher in suburban community and rural area， which is suitable to our result.

Above all, results of risk evaluation model can well explain the main cause of the light pollution in different areas, it also has some basis in reality.

4. Summary

In this paper, when constructing the AHP-fuzzy integrated evaluation model, we considered human activities, natural environment and ecological factors, covering a wide range of disciplines, which are fully representative. Moreover, we selected data from several authoritative data collection countries, and the data set covers a wide range, so our model is supported by sufficient data. Our model analyzes from shallow to deep layer by layer, from explanation to prediction, with theoretical foundation and rigor, and sensitivity analysis.

However, to simplify the analysis process, our model does not consider the impact of unexpected events. Due to the limited time and capacity, there is still room for improvement of our indicator factors and the data collected could be more extensive. We can further improve the AHP-fuzzy integrated evaluation model by spending more time and effort on data collection, and also by adding global influencing factors and interactive indicator relationships to the model analysis. In the analysis of the data results, we can reflect the society according to the social reality.

References

[1] Su X M. Comprehensive evaluation of residential light pollution [D]. Tianjin University,2012.

[2] Zho Z T. Environmental light pollution and its countermeasures [J]. Legal Review, 2021, No.841(17): 174-175.

[3] Cao M. Study on evaluation system of residential area light pollution at night in Tianjin [D]. Tianjin University,2008.

[4] Zhang C H. The plight of the urban light pollution prevention legislation and the [D]. Hunan university of science and technology, 2020.

[5] Liao Y. Based on the interference model of China's grain production forecast analysis [J]. Journal of social science front, 2017, 6 (7) : 955-963.

[6] Franz Hölker, Christian Wolter, Elizabeth K. Perkin,Klement Tockner. Light pollution as a biodiversity threat[J]. Trends in Ecology & Evolution, 2010, 25(12).