Comprehensive Assessment and Intervention: Analyzing and Mitigating Light Pollution Level in Different Regions Using the Entropy Weight Method, TOPSIS, and Fuzzy Comprehensive Evaluation Method

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Abstract. **Light pollution** is wreaking havoc on a global scale, which affects the environment, the rhythms of living things, and even our health and safety. In order to calculate the light pollution level in different regions, **the entropy weight method** was used to calculate the weight of light pollution evaluation indicators of eight cities of four types. Then, the light pollution risk level of eight cities was calculated using **TOPSIS(the Technique for Order Preference by Similarity to an Ideal Solution)**, which was defined as LPRI. Finally, the degree and order of light pollution in four types of regions are obtained. According to each evaluation indicator of light pollution, we put forward corresponding measures to reduce light pollution, and obtained the most effective measures for each region by **fuzzy comprehensive evaluation method**. The entropy weight method and TOPSIS can make full use of the original information of each indicator data in eight cities to obtain an objective and ac-curate light pollution risk level. When it is impossible to obtain the specific data of the impact of different measures on the LPRI index values of each region, the fuzzy comprehensive evaluation method using fuzzy mathematical concepts is used to objectively obtain the most effective intervention measures for different regions.

1 Introduction

Due to the excessive use of artificial light and other reasons, light pollution has become a new environmental pollution source after waste gas, waste water, waste residue and noise pollution. In order to reduce the impact of light pollution on humans and nature and create a more comfortable living environment, it is necessary to evaluate the level of light pollution in various regions of the world and give corresponding intervention measures. To achieve these goals, it is necessary to establish a universal evaluation model of light pollution level and propose effective intervention measures based on this model. Faichi et al.[1] produced a detailed map of global light pollution based on satellite data and precise measurements of sky brightness, revealing that many parts of the world are affected by light pollution. Kyba et al. (2017)[2] studied the growth of light pollution on a global scale and found that it is on the rise in many regions. Neither study delved into how to quantify and assess the risk of light pollution in specific areas. Gaston et al. (2013)[3] explored the impact of light pollution on biodiversity, highlighting the negative effects of light at night on many biological populations. Holker et al. (2010)[4] described in detail in their study how light pollution affects human communities and their quality of life. While their study discussed in detail the ecological and human impacts of light pollution, there is less discussion of how to quantify this impact and suggest specific measures to reduce it. Taking into account the shortcomings of previous studies, the main contents of this study are as follows: In order to calculate the light pollution level in different regions, we use entropy weight method to obtain the weight of the light pollution evaluation index combined with the data of eight cities of four types. Then we use TOPSIS(the Technique for Order Preference by Similarity to an Ideal Solution)to calculate the light pollution risk level of eight cities, which was called LPRI. Considering each light pollution evaluation indicator, we propose corresponding interventions to reduce the degree of light pollution, and use fuzzy comprehensive evaluation method to obtain the most effective measures for each region.

The following structure is: the third chapter introduces the main algorithm, the fourth chapter introduces the experimental results of the algorithm, and the fifth chapter is the summary.

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2 Method

2.1. Selection of cities to be evaluated

To make the assessment universal, we divided four different types of regions[5]: Protected land, rural community, suburban community and urban community. After abstracting the characteristics of these four types of regions, we use eight cities with corresponding characteristics around the world to represent different regions to obtain the data of the light pollution evaluation index. The corresponding cities and regions are as follows: The urban community corresponds to Shenzhen in China and New York in the United States; the suburban community corresponds to Shijiazhuang in China and Rio de Janeiro in Brazil; the rural community corresponds to Lhasa in China and Kigali in Rwanda; the protected land corresponds to Sansha in China and Dili in East Timor.

2.2 Selection of indicators

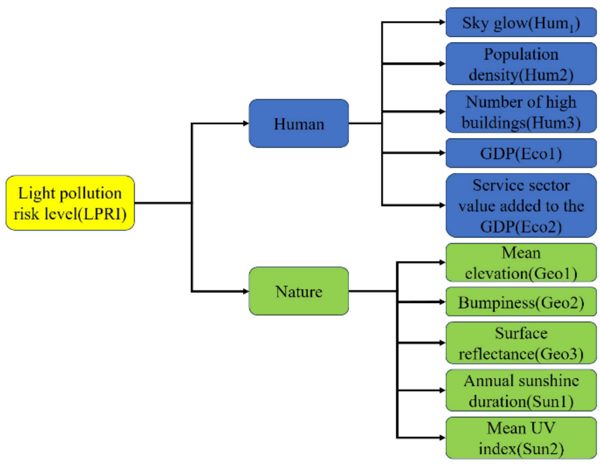

Figure 1 Evaluation indicators of light pollution level

Start with the possible causes of light pollution, the influencing factors of light pollution are divided into human factors[6] and natural factors[7], and then list the specific indicators. The selected indicators are shown in Figure 1.

2.3 Calculation of indicator weights

In general TOPSIS, the weight of all indicators is equal, which is obviously not in line with objective facts. Entropy weight method is an objective weighting method, which believes that the smaller the change degree of data value, the less information reflected, and the corresponding weight value is lower. The specific calculation steps are as follows[8]:

(1) Positivize and standardize. Since the indicators considered in this paper are all of the larger and better indicators, there is no need to positivize(that is, the larger the index value, the higher the degree of light pollution). There are 8 evaluation objects and 10 evaluation indicators, and the original data matrix X obtained is:

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{110} \\ x_{21} & x_{22} & \cdots & x_{210} \\ \vdots & \vdots & \ddots & \vdots \\ x_{81} & x_{82} & \cdots & x_{810} \end{pmatrix} \tag{1}$$

Since the index data are all positive, each element in matrix X is standardized using the following method:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{2}$$

(2) Calculate the proportion of the i sample in the j index and regard it as the probability used in the calculation of relative entropy. Each term in the probability matrix is calculated as follows:

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \tag{3}$$

(3) Calculate the information entropy of each indicator. The calculation formula is as follows:

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{4}$$

(4) Calculate the information utility value and normalize it to get entropy weight. The greater the information entropy of an indicator, the less information it reflects, so the information utility value is defined as:

$$d_j = 1 - e_j \tag{5}$$

The entropy weight of each index is obtained by normalization:

$$w_j = \frac{d_j}{\sum_{i=1}^{m} d_j} \tag{6}$$

2.4 Use TOPSIS to calculate LPRI of eight cities

When there is no data of the evaluation object, the analytic hierarchy process (AHP) is often used. However, when various index data of evaluation objects have been obtained, TOPSIS which can make full use of the original data is often used, and the result can accurately reflect the gap between evaluation objects[9]. The main steps for calculating LPRI using TOPSIS are as follows:

(1) Positivize and standardize. This step is done in the entropy weight calculation. **(2) Calculate the score and normalize.** The data matrix obtained after step 1 is as follows:

$$Z = \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{110} \\ z_{21} & z_{22} & \cdots & z_{210} \\ \vdots & \vdots & \ddots & \vdots \\ z_{81} & z_{82} & \cdots & z_{810} \end{pmatrix} \tag{7}$$

Define the maximum and minimum values Z^+ and Z^- as:

$$Z^+ = (Z_1^+, Z_2^+, \cdots, Z_{10}^+) \tag{8}$$

where Z_j^+ equals $\max\{z_{1j}, z_{2j}, \cdots z_{8j}\}$.

$$Z^- = (Z_1^-, Z_2^-, \cdots, Z_{10}^-) \tag{9}$$

where Z_j^- equals $\min\{z_{1j}, z_{2j}, \cdots z_{8j}\}$.

Calculate the distance between the evaluation object and the maximum and minimum values:

$$D_i^+ = \sqrt{\sum_{j=1}^{10} \omega_j (Z_j^+ - Z_{ij})^2} \tag{10}$$

$$D_i^- = \sqrt{\sum_{j=1}^{10} \omega_j (Z_j^- - Z_{ij})^2} \tag{11}$$

ω_j is the weight of each index determined by entropy weight method. The unnormalized index of each city is calculated as follows:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{12}$$

The LPRI value of each city is obtained by normalizing the score:

$$LPRI = \frac{S_i}{\sum_{i=1}^{n} S_i} \tag{13}$$

2.5 Use fuzzy comprehensive evaluation to get the optimal measure

Considering the indicators of light pollution mentioned above, we put forward ten possible measures to reduce light pollution: (1) Sky glow(Hum_1): Promote the use of low illumination and directional lighting. (2) Population density(Hum_2): Implement strict lighting regulations and standards in densely populated places. (3) Number of high buildings(Hum_3): Specify the materials and design of new buildings to reduce reflection and direct lighting. (4) GDP(Eco_1): Raise public awareness of light pollution through education and publicity to encourage more environmentally friendly ways of living and working. (5) Service sector value added to the GDP(Eco_2): Set up special lighting regulations for commercial areas. (6) Mean elevation(Geo_1): The altitude of a place is immutable, but we can give special management can to higher elevations. (7) Bumpiness(Geo_2): Designing and planning terrain can help reduce light pollution. (8) Surface reflectance(Geo_3): Choosing materials with low reflectivity for roads, buildings and other artificial surfaces can reduce the reflection of light and thus reduce light pollution. (9) Annual sunshine duration(Sun_1): Develop effective lighting strategies based on the number of hours of sunlight in the region. (10) Annual average UV index(Sun_2): Raise public awareness of UV pollution and encourage the use of sunshade devices.

(1) Determine the factor set. Here the factor set consists of each light pollution evaluation index:

$$\mathbf{U} = \{\mathrm{Hum}_1, \mathrm{Hum}_2, \cdots, \mathrm{Sun}_2\} \tag{14}$$

(2) Determine the evaluation set. We set the evaluation set as possible effect of measures on indicator value:

$$\begin{aligned} \mathbf{V} = \{ & \text{'substantial increase'}, \\ & \text{'slight increase'}, \\ & \text{'little effect'}, \\ & \text{'slight reduction'}, \\ & \text{'substantial reduction'}\} \end{aligned} \tag{15}$$

(3) Determine the weight of each factor. In the previous article, We have used the entropy weight method to get the weights of each index:

$$\mathbf{A} = \{0.0110, 0.1937, \cdots, 0.0300\} \tag{16}$$

(4) Determine the fuzzy comprehensive evaluation matrix. The degree of membership of factors for each evaluation is defined as follows: “bound to occur” as 1, “very likely to occur” as 0.7, “likely to occur” as 0.3, and “almost unlikely” as 0. Taking the impact of measure (1) “Promote the use of low illumination and directional lighting” on urban community as an example, according to the above definition of evaluation set and membership degree, we can obtain the fuzzy comprehensive evaluation matrix. (5) Make comprehensive evaluation. From the weight **A** and fuzzy comprehensive evaluation matrix **R**, the fuzzy vector **B** about the evaluation set **V** can be obtained:

$$\mathbf{B} = \mathbf{A} \cdot \mathbf{R} = [0, 0, 0.8231, 0.1659, 0.0110] \tag{17}$$

Bi represents the degree of membership of the urban community to evaluation i when implementing measure (1). We assign each element in the evaluation set a score of {10, 4, -1, -4, -10}, with the positive number representing the increase and the negative number representing the reduction. The greater the negative value, the better the effect of the measure. Therefore, we can calculate the comprehensive effect value of measure (1) on the urban community:

$$I = [10, 4, -1, -4, -10] \cdot \mathbf{B} = -1.5968 \tag{18}$$

Repeat step(4) and step(5) to calculate the comprehensive effect value *I* when different measures are applied to the four regions(Urban community, suburban community, rural community and protected land), and we can obtain the comprehensive effect value of each measure in the four regions(The horizontal axis shows ten measures and the vertical axis shows four categories of areas).

3 Results and analysis

3.1 Indicator weight size analysis

The weights of indicators calculated by the steps of 2.2 are as follows in Table 1:

Table 1 Weights of indicators

Indicator	Weight
Hum_1	0.0110
Hum_2	0.01937
Hum_3	0.3581
Eco_1	0.3152
Eco_2	0.0442
Geo_1	0.0258
Geo_2	0.0171
Geo_3	0.0006
Sun_1	0.0043
Sun_2	0.0300

We can find that the weights of the number of high buildings(Hum_3) and GDP(Eco_1) are 0.3581 and 0.3152 respectively, which is large, while the weights of surface reflectance and annual shine duration are 0.0006 and 0.0043, which is very small. The direct reason is that the data of the first two fluctuates greatly while the data of the latter two fluctuates little. We try to analyze the underlying reasons as follows: For the "number of high buildings (Hum_3)", its greater weight may be due to the widespread use of artificial light sources in tall buildings, especially in commercial areas. For the "GDP (Eco_1)" , its greater weight may be because GDP tends to correlate with the degree of industrialization and population density of an area, both of which can increase light pollution. For "surface reflectance (Geo_3)", it may have less weight because this indicator mainly reflects the light reflection of natural sur-faces (such as soil, vegetation, etc.). While this factor has some effect on light pollution, it may appear relatively small compared to the effect of artificial light. The lower weight of "annual sunshine duration (Sun_1)" may be because although natural light has some effect on light pollution, the effect of artificial light may be greater. On sunny and rainy days, the effects of natural light can vary greatly, but the effects of artificial light are relatively stable.

3.2 Analysis of LPRI in four regions

The calculated LPRI for each city from highest to lowest are shown in Table 2:

Table 2 LPRI of each city

Name of city	**Type of area**	**LPRI**
New York, USA	Urb	0.3849
Shenzhen, China	Urb	0.2767
Rio de Janeiro, Brazil	Sub	0.0898
Lhasa, China	Rur	0.067
Kigali, Rwanda	Rur	0.0646
Shijiazhuang, China	Sub	0.0563
Dili, East Timor	Pro	0.0508
Sansha, China	Pro	0.01

It can be seen that the light pollution degree is ranked from high to low as follows: Urban community, suburban community, rural community and protected land. We try to analyze the differences in light pollution levels in various regions as follows:

Urban Community: In terms of human factors, urban areas usually have higher population density, higher level of economic development, prosperous service industry, greater demand for artificial light, which will inevitably produce more pollution. **Suburban Community:** Human activities in suburban community have a certain demand for artificial light, and fewer buildings and more open terrain make natural light pollution reach a certain degree **Rural Community:** The low population density and low level of economy in rural communities limit the use of artificial light, but there is some natural light pollution due to the open terrain and few buildings. **Protected land:** The protected land is basically unaffected by human activities, so man-made light pollution can be ignored. However, due to the preservation of the original ecological environment, the roughness of the ground and the average altitude are often higher, so there is some light pollution caused by sunlight.

According to the above analysis, although light pollution can be divided into natural light pollution and artificial light pollution, the proportion of influence of human factors on light pollution is significantly greater than that of natural factors, indicating that human activities are the main cause of light pollution. Therefore, to reduce light pollution, the key point is how to adjust and limit the human behavior that is easy to cause light pollution.

3.3 The most effective measures to reduce light pollution in four regions

As shown in Table 3, the calculated comprehensive effect value of each measure in the four regions are as follows:

Table 3 The comprehensive effect value of each measure in the four regions

	Urb	Sur	Rur	Pro
(1)	-1.5968	-1.5968	-1.0231	-1.0099
(2)	-3.3312	-2.5828	-2.1317	-1.1974
(3)	-2.9724	-2.9724	-1.0231	-1.0099
(4)	.1.4679	-1.3751	-1.0099	-1.0000
(5)	-2.8082	-2.0083	-1.5739	-1.0000
(6)	-1.3322	-1.3322	-1.0000	-1.0000
(7)	-1.1330	-1.2067	-1.1539	-1.1539
(8)	-1.0153	-1.0043	-1.0029	-1.0013
(9)	-1.3535	-1.3235	-1.0000	-1.0000
(10)	-1.0000	-1.0000	-1.0000	-1.0000

According to the results in Table 3, the most effective measure for urban com-munity, rural community and protected land is measure (2) – "implement strict lighting regulations and standards in densely populated places". The most effective measure for suburban community is measure (3) – "specify the materials and design of new buildings to reduce and direct lighting". We analyze the reasons as follows:

Urban Community: Strict lighting time management system is required to reduce unnecessary lighting caused by high light demand. **Suburban Community:** By taking effective measures in architectural design, such as using building materials with lower reflectivity and arranging windows strategically to guide natural light, light pollution can be reduced at the source. **Rural Community:** Implementing strict lighting regulations and standards can help control and manage increasing demand for light. **Protected Land:** By implementing strict lighting regulations and standards, the impact of the activities of tourists and researchers on the natural environment of protected lands can be minimized as much as possible.

4 Conclusion and discussion

4.1 Conclusion

In this paper, the entropy weight method is used to calculate the weight of ten indicators to evaluate light pollution, and then TOPSIS is used to calculate the light pollution risk level of eight cities, and the results are corresponding to four types of regions. The study found that human indicators such as the number of high buildings(Hum_3) and GDP(Eco_1) have a high weight, while natural indicators such as sur-face reflectance(Geo_3) and annual shine duration(Sun_1) have a low weight. The light pollution levels in four regions from high to low are: Urban community, suburban community, rural community, protected land. After proposing ten measures to reduce light pollution corresponding to ten indicators, we use fuzzy comprehensive evaluation method to get the most effective measures corresponding to four regions.

4.2 Discussion

Human activities and natural factors are different in different regions, so after obtaining the quantified impact level of each measure on each region, efficient light pollution prevention and control can be targeted. In future studies, the selection of light pollution evaluation indicators can be optimized through multi-source data, expert consultation and preliminary research, and the membership degree in fuzzy comprehensive evaluation can be improved by adjusting model parameters or introducing new data sources.

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