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BEYOND THE GLOW: A HOLISTIC EVALUATION INDEX SYSTEM FOR LIGHT POLLUTION

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Abstract
Light pollution encompasses the adverse effects of light intrusion, characterized by excessive and misdirected artificial illumination. This phenomenon is not confined to specific geographical regions and is typified by various forms, including artificial daylight, visual pollution, and colored light pollution. The repercussions of light pollution reverberate through our daily routines, influencing activities ranging from animal migration to plant growth, as well as affecting biological rhythms.

1. Introduction

By light pollution we generally mean the phenomenon of light intrusion, excessive lighting and light clutter due to excessive or poor use of artificial light. The occurrence of light pollution is not geographically restricted, and its manifestation types are usually divided into artificial daylight, visual pollution and colored light pollution. In addition, light pollution has an impact on our daily life, animal migration, plant growth, biological rhythms and many other aspects.

2. Comprehensive evaluation index system of light pollution

Evaluation index system building principles: scientific normative and overall representativeness. The indicators are independent of each other and interconnected, and can form an organic whole. Through the study of the currently used standards, combined with the actual situation, taking into account regional development, ecology, environment, health and other aspects, we finally selected six categories, a total of 20 indicators, to establish a comprehensive evaluation index system of light pollution, the specific evaluation index system is shown in Table1.

Table 1: Indicator system

Target layer	Guideline layer	Indicator layer
Light pollution level	Glass Curtain Wall	Illumination extremes ratio
		Curtain wall light pollution impact range S
		Curtain wall target brightness B
		Reflectivity of glass curtain wall ρ

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	Residential area	Average road illumination
		Vertical illumination of interior windows
		Illumination uniformity
	Road Zone	Road illumination uniformity
		Average brightness of road surface
		Half column surface illumination
	Business District	Brightness of advertising light box
		LED screen brightness
		LED screen color contrast
		Average illumination
	Level of urban development	Number of people in the region
		Regional population density
		Regional natural population growth rate
		Gross regional economic product
		Regional GDP per capita
	Nighttime Lighting Index	Nighttime Lighting Index

3. Hierarchical analysis (AHP) to determine the weights of the comprehensive evaluation indexes of light pollution

The following describes how to determine the weight of each indicator of the comprehensive evaluation of light pollution, because the evaluation index system consists of numerous interrelated and mutually constraining factors, complex and lack of quantitative data, we adopt the hierarchical analysis (AHP) to determine the weight value of each indicator.

AHP is a simple, flexible and practical multi-criteria decision-making method for quantitative analysis of qualitative problems. It is characterized by dividing various factors in a complex problem into interconnected and ordered levels, making them organized, directly and effectively combining expert opinion and the analyst's objective judgment results according to the structure of subjective judgment of certain objective experience (mainly two-by-two comparison), and quantitatively describing the importance of two-by-two comparison of elements in a level. And then, the weights reflecting the relative order of importance of the elements of each level are calculated using mathematical methods, and the relative weights of all elements are calculated and ranked by the total ranking between all levels[2].

The problem was analyzed using AHP through the following four steps:

1) Build a recursive hierarchy model
2) Construct all judgment matrices in each level
3) Hierarchical ordering and consistency testing
4) Weighting calculation
5) Extraction of data features from the indicator layer to the criterion layer

3.1 Building a recursive hierarchy model

The indicators contained in the system are decomposed according to different levels using hierarchical analysis to form a tree hierarchy. The highest level has only one element as the intended goal of the analyzed problem and is called the goal level; the middle level contains the intermediate aspects involved in order to achieve the goal and consists of several levels including the criteria and sub-criteria to be considered and is called the criterion level; the bottom level: this level includes the various measures and decision options available to achieve the goal and we call it the indicator level.

The target layer is the light pollution level, and the guideline layer is divided into 6 types: glass curtain wall indicator, residential area indicator, road area indicator, commercial area indicator, regional development level indicator and night light index indicator.

Among them, the evaluation index of glass curtain wall is further divided into four: illuminance polarity ratio□curtain wall light pollution influence range S, curtain wall target brightness B and glass curtain wall reflectivity ρ.

The evaluation index of residential area is divided into 3: average illuminance of road, vertical illuminance of indoor windows and uniformity of illuminance; the evaluation index of road area is divided into 3: average brightness of road surface, uniformity of illuminance of road surface and uniformity of illuminance; the evaluation index of commercial area is divided into 4: brightness of advertising light box, brightness of LED screen, color contrast of LED screen and uniformity of illuminance.

The indicators of regional development level are divided into five: regional population size, regional population density, regional natural population growth rate, regional gross economic product and regional gross economic product per capita[3]. and the nighttime lighting index.

The resulting hierarchy is shown in Figure 1.

Figure 1: Structure of light pollution evaluation index system

By constructing all judgment matrices in each level and conducting consistency tests on the judgment matrices of the indicator layer before weight comparison, we obtained that the consistency ratio CR of all indicators satisfied $CR < 0.10$, and thus we considered the consistency of the judgment matrices to be acceptable. Here we calculate the weight values of the indicator layer.

3.2 Data processing based on PCA and K-means++

PCA is a linear transformation that transforms the data into a new coordinate system such that the first large variance is on the first principal component, the second large variance is on the second principal component, and so on. Principal component analysis is used to reduce the dimensionality of the dataset, keeping the features of the dataset that contribute the most to the variance. This is achieved by retaining low-order principal components and ignoring high-order principal components. Low-order components are able to retain the most important aspects of the data.

After the indicator layer data features are extracted to the criterion layer, there may be correlations between variables, increasing the complexity of the problem analysis. Separate analysis of each indicator is isolated, not integrated. Blindly reducing the indicators will lose information and easily produce wrong conclusions. PCA can be done to reduce the indicators to be analyzed while minimizing the loss of information contained in the original indicators to achieve a comprehensive analysis [4]. In data processing, the use of k-means++ clustering algorithm can be well coordinated with other statistical methods to pre-process the data.

After performing KMO and Bartlett's sphericity test on the criterion level data through SPSS, we obtained the KMO sampling fitness number and substituted to calculate the Bartlett's sphericity test significance $p<0.05$, indicating that the data are more suitable for principal component analysis.

The final principal component data were clustered into two categories using SPSS to derive the principal component data, as shown in Table 2.

Table 2: Principal component data

Serial number	Component 1	Component 2	Component 3	Component 4
1	0.2203	-0.0601	-0.1312	0.1495
2	-0.3544	0.0490	0.0234	0.1181
...				
29	0.1308	0.0001	-0.0006	0.0449
30	0.2620	0.0192	0.1509	-0.0623

Subsequently, we used SPSS to cluster the principal component data into two categories and obtained two types of clustered data as shown in the following table 3 and table 4.

Table 3: The first type of principal component clustering data

Serial number	Component 1	Component 2	Component 3	Component 4
1	0.0513	0.01780	-0.0302	0.1809
2	0.1308	0.0012	-0.0006	0.0449
...				
14	0.2263	0.0538	0.1121	0.0430
15	0.1350	-0.0175	0.0528	-0.0767

Table 4: The second type of principal component clustering data

Serial number	Component 1	Component 2	Component 3	Component 4
1	-0.3544	0.0490	0.0234	0.1181
2	-0.2161	-0.0030	0.0566	-0.1222
...				
5	-0.1611	-0.0758	0.1864	-0.0251
6	-0.4771	0.0654	-0.0998	-0.0021

3.3 Solution model of TOPSIS method based on entropy weight method (EVM)

Entropy weight method is an objective assignment method, which uses information entropy to calculate the entropy weight of each indicator, and then corrects the entropy weight according to each indicator to get more objective indicator weights. This is largely able to maintain and effectively extract data features after applying AHP on the indicator layer indicators to ensure the objectivity of the subsequent processing. Topsis method (Technique for Order Preference by Similarity to an Ideal Solution, TOPSIS) is a multi-objective decision analysis in A commonly used and effective method, also known as the superior-inferior solution distance method. topsis comprehensive evaluation method is a method of ranking the relative superiority of existing objects based on the proximity of a finite number of evaluation objects to an idealized target, and is a ranking method that approximates the ideal solution[5]. We perform topsis comprehensive evaluation on a set of data, get the combined score of each data, and the average score of a set of data can well reflect the magnitude of light pollution.

Since the unit of measurement of each index is not uniform, it should be normalized before calculating the integrated weights, i.e., the absolute values of the indexes are converted into relative values. Finally, the clustered principal component data are substituted into the calculation process to obtain the weight values clustered into two categories respectively, as shown in the following table 5 and table 6.

Table 5: The relative weight value of the first type of principal component

Serial number		Component 1	Component 2	Component 3	Component 4
1		0.3455	0.2733	0.1902	0.1910

Table 6: The relative weight value of the second type of principal component

Serial number		Component 1	Component 2	Component 3	Component 4
1		0.1813	0.3090	0.1922	0.3174

3.4 Use TOPSIS method to obtain evaluation scores and grades

1) TOPSIS calculation method

Firstly, we set the set of multi-attribute decision solutions as D d d□{ 1;·2, ,d_m} , and the variables to measure the superiority or inferiority of the solutions are. x1,..., xn, and the vector of n attribute values of each solution in solution D is[a_{i1}, ,a_{in}] , as a point in the n-dimensional space to uniquely represent a solution of the table. Then by constructing the positive and negative ideal solution,

$CC^{*\ 0}$ whose attribute values are the optimal/inferior values of that attribute in the decision matrix. In the n-dimensional space, the solution in the solution set D is compared with the distance of$CC^{*\ 0}$ and the solution that is both close to the positive ideal solution and far from the negative ideal solution is the optimal solution.

3.5 Calculate the evaluation score

The comprehensive evaluation score between 0~100 is divided into five levels, which are I: 0~20, II: 20~40. III: 40~60, IV: 60~80, V: 80~100, of which, the greater the comprehensive evaluation score Q means the more serious light pollution, I means not reached light pollution, II means mild light pollution, III means moderate light pollution, IV means Level I means no light pollution, Level II means light light pollution, Level III means moderate light pollution, Level IV means heavy light pollution, and Level V means serious light pollution.

The data from both categories of the clusters were substituted into the calculation process to obtain the scores, as shown in the table 7 below.

Table 7: Comprehensive evaluation score

Clustering categories	Maximum value	Minimum value	Average value
1	83.24	79.10	81.03
2	85.46	78.01	80.64

The scores were compared with the area found on the global light pollution map (Figure 2), and then according to the Porters Dark Sky Classification, the area is 8-9, which is a severely polluted area, which is similar to the model results and proves the reasonableness of the model.

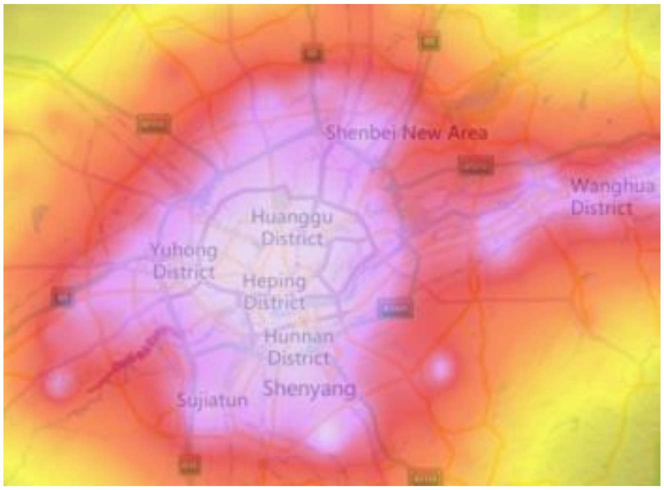

Figure 2: Map of light pollution in Shenyang

4. Analysis of experimental results

4.1 Evaluation results and cause analysis of light pollution in urban communities

The original data were calculated according to the model building process, and the principal component data and weights were obtained as follows table 8,table 9 and table 10.

Table 8: Principal component data

Serial number	Component 1	Component 2	Component 3	Component 4
1	0.2804	0.1706	0.1062	0.0135
2	0.2766	-0.0806	-0.0714	-0.0460
...				
30	0.2440	0.0174	-0.0460	0.0066

Table 9: Weight values

	Component 1	Component 2	Component 3	Component 4
Weighting	0.2539	02355	0.3013	0.2093

Table 10: Score

Overall Score	Maximum value	Minimum value	Average value
	88.69	81.32	84.25

Note: The original data are the indicators of Changchun City, Jilin Province, China

The average model score is 84.25, which is a V level of light pollution, severe light pollution, and the area is shown on the global light pollution map as Figure 3.

Porters Dark Sky is rated class 8-9, proving the results correct.

The results are generated by the cause.

Urban communities are characterized by high population density, extensive infrastructure and high levels of artificial lighting; and Changchun is dominated by heavy industry, which is prone to higher levels of light pollution, and in recent years the development of Changchun has been slower, and many older lighting facilities are more likely to produce greater light pollution, among other reasons for the higher levels of light pollution in Changchun[6].

4.2 Evaluation results and cause analysis of light pollution in suburban communities

The original data were calculated according to the model building process, and the principal component data and weights were obtained as follows table 11, table 12 and table 13.

Table 11: Principal component data

Serial number	Component 1	Component 2	Component 3	Component 4
1	0.0302	0.0072	-0.1073	0.1932
2	-0.0451	-0.0028	-0.0237	-0.1110
...				
30	0.0316	-0.0197	-0.0423	0.0381

Table 12: Weights values

	Component 1	Component 2	Component 3	Component 4
Weighting	0.2764	0.2870	0.3260	0.1106

Table 13: Scores

Overall Score	Maximum value	Minimum value	Average value
	69.34	50.03	57.89

Note: The original data are the indicators of Nong'an County, Changchun City, Jilin Province, China

The average model score is 57.89, which is a Class III light pollution level, moderate light pollution. The area is shown on the global light pollution map (Figure 4) as.

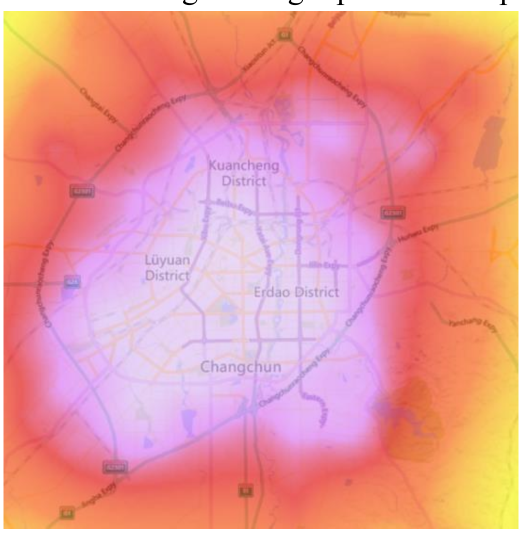

Figure 3: Map of light pollution in Changchun

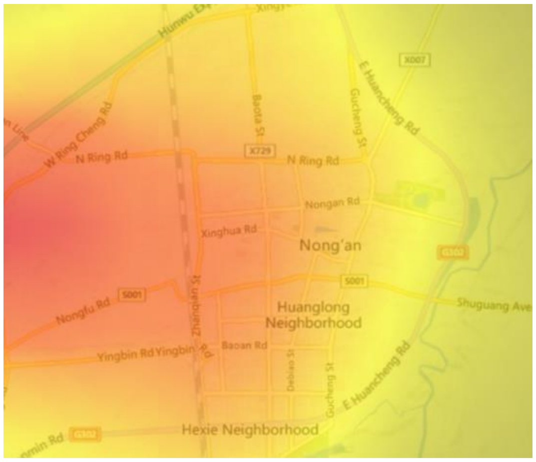

Figure 4: Map of light pollution in Nongan County The Porters classification of class 4-5 justifies the results.

Reasons for results: Suburban communities are usually located at the edge of urban areas, with moderate population density and a mix of residential, commercial and industrial land uses. With slow population movement, low international integration, and a certain development base, there is moderate light pollution[7].

4.3 Evaluation results and cause analysis of light pollution in rural communities

The original data were calculated according to the model building process, and the principal component data and weights were obtained as follows table 14,table 15 and table 16.

Table 14: Principal component data

Serial number	Component 1	Component 2	Component 3	Component 4
1	0.1397	0.1460	-0.0198	0.1153
2	0.2011	0.0237	-0.0540	-0.3330
...				
30	0.2307	-0.1756	0.1401	0.2131

Table 15: Weights values

	Component 1	Component 2	Component 3	Component 4
Weighting	0.3348	0.1563	0.3550	0.1539

Table 16: Score

Overall Score	Maximum value	Minimum value	Average value
	48.56	29.37	35.68

Note: The original data are for various indicators in Bajiji Town, Nong'an County, Changchun City, Jilin Province, China.

The average model score is 35.68, which is a level II light pollution, light light pollution, and the area is shown on the global light pollution map (Figure 5).

Figure 5: Map of light pollution in Bajirao town The Porters classification of class 3 justifies the results.

Reasons for results: Rural communities are often characterized by low population density and limited infrastructure. Industrial and recreational sites are scarce, and light pollution levels are low.

4.4 Light pollution evaluation results and cause analysis for a protected location

The original data were calculated according to the model building process, and the principal component data and weights were obtained as follows table 17,table 18 and table 19.

Table 17: Principal component data

Serial number	Component 1	Component 2	Component 3	Component 4
1	0.0911	-0.0015	-0.0511	0.0140
2	0.0867	0.0060	-0.0939	-0.0031
...				
30	-0.0812	0.0230	0.044	0.0315

Table 18: Weights values

	Component 1	Component 2	Component 3	Component 4
Weighting	0.2606	0.3381	0.1656	0.2357

Table 19: Score

Overall Score	Maximum value	Minimum value	Average value
	3.54	0.00	0.89

Note: The original data is the index data of Changbai Mountain, China

The average model score is 0.89, which is a level I light pollution, and there is no light pollution, and the area is shown on the global light pollution map as (Figure 6).

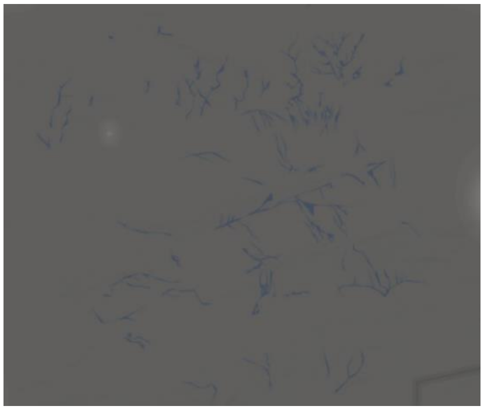

Figure 6: Map of light pollution in Changbai Mountain The Porters classification of class1 justifies the results.

Reasons for results: Changbai Mountain contains unique and sensitive ecosystems, wildlife, and cultural and historical features. Therefore, in order to protect the ecology and species diversity, the government has made great efforts to protect them, so there is no light pollution.

5. Conclusion

In this paper, we first selected the public data of Shenyang City, Liaoning Province, China, used hierarchical analysis, data processing based on PCA and K-means++, and validated the established comprehensive light pollution evaluation index system by solving the model based on the TOPSIS method of entropy weight method (EVM), etc. We finally determined the feasibility of this evaluation index system, and divided the light pollution level into no light pollution (I level), light pollution (II level), light pollution (III level), light pollution (IV level), light pollution (V level) according to the comprehensive evaluation score. The light pollution level is divided into five levels: no light pollution (level I), light light pollution (level II), moderate light pollution (level III), heavy light pollution (level IV), and severe light pollution (level V) (the larger the comprehensive evaluation score Q means the more serious light pollution). The established evaluation model was also substituted into the data of Changbai Mountain, China; Bajiji Town, Nongan County, Changchun City, Jilin Province, China; Nongan County, Changchun City, Jilin Province, China; and Changchun City, Jilin Province, China for light pollution risk level calculation, and the accuracy of the results was verified by Light Pollution Map. In the next step, we will propose an intervention strategy based on the proposed indexes, taking into account the weighting factors, and provide a model approach for regional reduction of light pollution levels

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