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Risk assessment system and prevention measures for light pollution

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Abstract: Based on existing research on light pollution, this article comprehensively considers factors such as social development level, and designs an indicator system suitable for evaluating the risk level of light pollution. By selecting relevant data from four representative areas: urban, suburban, nature reserves, and rural areas, and selecting indicators from three levels: socio-economic, ecological environment, and species diversity, the entropy weight method and TOPSIS method are used to evaluate the level of light pollution risk in the region. The results indicate that the risk level of light pollution in cities is the highest, followed by suburban areas, rural areas, and nature reserves. It is necessary to adopt intervention strategies to reduce the risk level of light pollution from the perspectives of light environment management and pollution source management.

1. Introduction

The international astronomical community believes that light pollution is caused by outdoor lighting in cities that brightens the sky and has a negative impact on astronomical observations. Later, countries such as the United States and the United States referred to it as interference light, while Japan became a light hazard[1]. Nowadays, light pollution is flooding the starry sky in many parts of the world, and the situation is deteriorating every year[2]. These light pollution impacts not only cause energy waste, but also ecological damage and damage to biodiversity[3-4]. There are also studies indicating that light pollution can have certain impacts on human physiology and psychology[5-6]. Therefore, establishing evaluation indicators for light pollution is crucial for implementing intervention strategies to reduce the negative impact of light pollution.

In the study of evaluating light pollution, Feng Kai et al. analyzed the evolution characteristics of light pollution maps in four cities in China using R language quantification method based on satellite images, and verified the feasibility of analyzing the evolution characteristics of urban lighting light pollution through satellite image methods[7]; Liu Xianghe et al. established a light pollution evaluation model through the integration of a large amount of data and principal component analysis, and proposed intervention strategies for building light pollution problems[8]; Liu Ming conducted theoretical research and investigation analysis on various forms of light pollution, proposed a light pollution evaluation procedure, and summarized the overall evaluation indicators[9]. The above studies lack measurement of the global light pollution level in indicator selection. Based on existing research, this article designs an evaluation index system for the light pollution risk level. The entropy weight method and principal component analysis method are used to evaluate and compare the light pollution risk level in the selected areas, and intervention strategies are provided based on the results.

2. Construction of a Light Pollution Evaluation Model

2.1 Study Areas

The article selects four regions as research samples, as shown in Table 1.

Table 1: Regions to which the study samples belong

Region	Regional representative
City Center	Paris urban community
Suburb	Tokyo Suburban Community
Village	Sydney Rural Community
Nature Reserve	Yellowstone National Park

2.2 Data sources

The data is mainly obtained from the VIIRS National Statistical Database, Wind Database, and National Bureau of Statistics. Table 2 summarizes the data sources. This article extracts the following data completed over the past decade, which is consistent with reflecting global fairness and adjusting the value of basic units.

Table 2: Source of Study Sample Data

Database	Websites
Wind Database	Wind Database App
World Bank Database	https://data.worldbank.org/indicator
VIIRS country database	https://www.lightpollutionmap.info/
National Bureau of statistics	https://data.stats.gov.cn/gjwz.htm

2.3 Evaluation indicators and indicator selection

The evaluation of the risk level of light pollution should not only consider the economic development level of the region, but also reflect the ecological environment level and species diversity level of the region. The specific evaluation criteria are as follows.

Table 3: Index system for evaluating the risk level of light pollution

Primary indicators	Secondary indicators
Development level	GDP
	Annual year-on-year rise and fall in consumer prices
	Life expectancy at birth for males
	Life expectancy at birth for women
	Adolescent fertility rate
Biological diversity	The proportion of nature reserves to the area under its jurisdiction
	Vegetation coverage area
	Total number of biological species
Population	Total Fertility Rate
	Population year-on-year growth rate
	Crude death rate
Nature	Forest area as a percentage of land
	The percentage of agricultural land to land area
	Carbon dioxide emissions

Based on the causes of light pollution, this article analyzes and processes data on light pollution in various regions, and selects four primary indicators: development level, biodiversity, population, and nature. Under these primary indicators, there are a total of 12 secondary indicators, as shown in Table 3.

2.4 Model building

Due to the large number of indicators, KMO and Bartlett sphericity tests were performed to reduce the dimensionality of the indicators. Principal component analysis was used to reduce the dimensionality of the indicators that passed the test. For the dataset that did not pass the test, entropy weight method was used for dimensionality reduction. Finally, establish a multiple linear regression model and introduce the constant "S" to divide the light pollution levels into low, medium, and high. The specific steps are as follows.

2.4.1 KMO test and Bartlett sphericity test

Through testing, it can be concluded that the development level is suitable for dimensionality reduction using principal component analysis, while the other three primary indicators are reduced using entropy weight method.

2.4.2 Principal component analysis

(1) For the 10 collected evaluation objects, $S_1, S_2, \ldots, S_{10}$, each evaluation object has 5 indicators, with an observation value of $a_{ij}, i=1,2,\ldots,10; j=1,2,\ldots,5$, Using the standard sample transformation method, each indicator value a_{ij} is converted into a standardized indicator $\tilde{a}_{ij}$, make

$$\tilde{a}_{ij} = \frac{\alpha_{ij} - \mu_j}{s_j}, \quad i=1,2,\cdots,10, \quad j=1,2,\cdots 5 \tag{1}$$

$$\mu = \frac{1}{n}\sum_{i=1}^{n}\alpha_{ij};$$
$$s_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\alpha_{ij} - \mu_j\right)^2}, \; j=1,2,\ldots,5$$
$$n = 10 \tag{2}$$

Namely, μ_j, s_j are the sample mean and standard deviation of the jth indicator. Correspondingly it is referred to as the Standardized indicator variable.

$$\tilde{x}_j = \frac{\tilde{x}_j - \mu_j}{s_j}, \quad j=1,2,\ldots 5 \tag{3}$$

In the formula: $r_{ii} = 1; \quad r_{ij} = r_{ji}, \quad r_{ij}$ is the correlation coefficient between the ith index and the jth index.

(2)Calculate eigenvalues and eigenvectors. The eigenvalues $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_5 \geq 0$ of the coefficient matrix R correspond to standardized eigenvectors $\mu_1, \mu_2, \cdots, \mu_5$. Among them

$$\mu_j = [\mu_{1j}, \mu_{2j}, ..., \mu_{5j}]^T \quad (4)$$

$$\begin{aligned} y_1 &= \mu_{11}\tilde{x}_1 + \mu_{21}\tilde{x}_2 + \cdots + \mu_{51}\tilde{x}_5 \\ y_2 &= \mu_{12}\tilde{x}_1 + \mu_{22}\tilde{x}_2 + \cdots + \mu_{52}\tilde{x}_5 \\ &\vdots \\ y_5 &= \mu_{15}\tilde{x}_1 + \mu_{25}\tilde{x}_2 + \cdots + \mu_{55}\tilde{x}_5 \end{aligned} \quad (5)$$

In the formula, y_1, y_2, y_3, y_4, y_5 ,correspond to the first, second, third, fourth, and fifth principal components, respectively.

(3)Calculate the contribution rate b_j and cumulative contribution rate α_p of eigenvalue $\lambda_j (j = 1,2,\cdots,5)$:

$$b_j = \frac{\lambda_j}{\sum_{k=1}^{n} \lambda_k}, \quad j = 1,2,\cdots,10 \quad (6)$$

r is the contribution rate of the main component y_j.And the cumulative contribution rate of the main components $y_1, y_2, \cdots, y_5$,namely $\alpha_p = \frac{\sum_{k=1}^{p} \lambda_k}{\sum_{k=1}^{5} \lambda_k}$ is also stated.

(4)They can be objectively weighted based on their contribution rate to calculate the comprehensive score. For the five principal components obtained, their weight coefficients can be considered as 0.78132, 0.2083, 0.00647, 0.00316, and 0.0075, respectively. Use this weight to calculate the comprehensive score.

$$Z = \sum_{j=1}^{p} b_j y_j \quad (7)$$

2.4.3 Entropy weighting method

(1) Construct the original matrix. N evaluation indicators from m samples form the original matrix $X = (x_{ij})_{m\times n}$, among them, x_{ij} the jth indicator in the ith sample, $1 \le i \le m, 1 \le j \le n$。.

(2) Non dimensional processing.

In positive indicators:

$$X_{ij} = \frac{X_{ij} - \min\{X_{1j}, ..., X_{nj}\}}{\max\{X_{1j}, ..., X_{nj}\} - \min\{X_{ij}, ..., X_{nj}\}}, \quad i = 1,2,..., m; \ j = 1,2,..., n \quad (8)$$

In negative indicators:

$$X_{ij} = \frac{\max\{X_{1j}, ..., X_{nj}\} - X_{ij}}{\max\{X_{1j}, ..., X_{nj}\} - \min\{X_{ij}, ..., X_{nj}\}}, \quad i = 1,2,..., m; \ j = 1,2,..., n \quad (9)$$

In the formula $\min\{X_{1j}, ..., X_{nj}\}$ is the minimum value in the original matrix X; $\max\{X_{1j}, ..., X_{nj}\}$

is the maximum value in the original matrix X.

(3) Calculate the specific gravity matrix.

$$\left(p_{ij}\right)=\frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}}, i=1,2,\cdots,\mathrm{m}; j=1,2,\cdots,n \tag{10}$$

In the formula, $\left(p_{ij}\right)_{m\times n}$ is the proportion matrix, where p_{ij} is the proportion of the ith indicator in the i-th sample, $0\le p_{ij}\le 1$.

(4) Calculate entropy value.

$$e_j=-k\sum_{i=1}^{m}\left(p_{ij}\ln p_{ij}\right), i=1,2,\cdots,m; j=1,2,\cdots\mathrm{n}; \mathrm{k}=\frac{1}{\ln \mathrm{m}} \tag{11}$$

In the formula, e_j is the entropy value of the jth indicator, $0\le e_j\le 1$。

(5) Calculate coefficient of difference term

$$g_j=1-e_j, j=1,2,\cdots,n \tag{12}$$

In the formula, g_j is the coefficient of the difference term for the jth indicator.

(6) Calculate the weights of each indicator.

$$w_j=\frac{g_j}{\sum_{j=1}^{n} g_j}, j=1,2,\cdots,n \tag{13}$$

In the formula, w_j is the weight of the jth indicator.

2.5 Multiple linear regression

Based on the results of indicator selection, independent variables and dependent variables are set up for the regression model as shown below.

Setting the value of VIIRS as the dependent variable y, this article sets the development level after principal component dimensionality reduction to x_1. Set the three primary indicators of biodiversity, population, and nature after dimensionality reduction using entropy weight method to x_2, x_3, x_4 respectively. Perform Pearson correlation analysis on independent and dependent variables to establish a multiple linear regression model.

$$\begin{cases} y=\beta_0+\beta_0\mathrm{x}_1+\beta_2 x_2+\beta_3 x_3+\beta_4 x_4 \\ \xi\sim N(0,\ \ \sigma^2) \end{cases} \tag{14}$$

In the formula, ξ follows a normal distribution, $\beta_1,\ \beta_2,\cdots,\ \beta_4$ are the coefficients of their respective variables, β_0 is the coefficient of the constant term.

Import the collected data into MATLAB and use the regression function to perform multiple linear regression. The results are shown in the table 4 below.

Table 4: Regression Equation Coefficients

Parameter	Parameter Estimate	Parameter confidence interval
β_0	9663834.926	[-3085974.653,22413644.51]
β_1	2183032.273	[-849524.9964,5215589.542]
β_2	5658256.485	[-2900353.596,14216866.57]
β_3	1619327.378	[-5965017.308,23646589.24]
β_4	8840785.99	[-6168410.8,9407065.556]

The regression equation is:

$$y = 9663834.926 + 2183032.273x_1 + 5658256.485x_2 + 1619327.378x_3 + 8840785.99x_4$$

Introducing constant S=9634057. Using $R = \frac{y}{S}$ as the evaluation metric. The specific evaluation system is as follows:

$$\begin{cases} R < 1.603 \text{——Low light pollution} \\ 1.603 \le R \le 2.031 \text{——Medium light pollution} \\ 2.031 < R \text{——High light pollution} \end{cases}$$

Divide the risk level of light pollution into three levels: low, medium, and high.

3. Analysis of the results of the light pollution risk level

Substitute the indicator data of the four selected locations into the regression equation, and after processing, obtain the following Table 5.

Table 5: R values for each region

Region	R
Paris urban community	2.403
Tokyo Suburban Community	1.752
Sydney Rural Community	1.536
Yellowstone National Park	0.897

It can be seen that the risk level of light pollution in urban communities in Paris, France is high, the risk level of light pollution in suburban communities in Tokyo is medium, and the risk level of light pollution in rural communities in Sydney and Yellowstone National Park is low, with basically no pollution.

The analysis is as follows. For the urban communities in Paris: with a high level of social development and an abundance of high brightness lighting tools. At the same time, urban population density is high, and the vast majority of areas are residential and industrial areas, with a high demand for lighting. For communities in the suburbs of Tokyo: Urban suburbs have a relatively high level of social development, with most nighttime lighting being provided by factories and residents. For rural communities in Sydney: the development level of rural communities is relatively low, the population is small, the biodiversity is high, the natural environment is relatively not urbanized, and the number of lighting fixtures and nighttime travel demand are concentrated on certain roads. For land in protected areas: undeveloped areas with extremely low levels of development, lack of artificial light sources, and a relatively small population. Therefore, these areas have extremely low demand for nighttime lighting.

4. Intervention strategies

Light pollution prevention and control should go faster [10].The government can accelerate special legislation on light pollution, establish environmental standards, and strengthen the planning, control, and management of urban glass curtain walls. Strengthen the ecological design of night lighting and reduce artificial daytime pollution. As citizens, we can raise environmental awareness and reduce unnecessary lighting. The specific intervention strategies for preventing and controlling light pollution are as follows.

(1) Incorporate light pollution into the scope of environmental prevention and control, and strengthen the planning, control, and management of urban glass curtain walls. Starting from climate, environment, functionality, and planning requirements, conduct a thorough investigation on whether buildings use glass curtain walls to control the total amount.

(2) Strengthen the ecological design of night lighting and reduce artificial daytime pollution. The main function of night lights is illumination. Lighting with a certain level of light intensity is sufficient. Excessive brightness can interfere with vehicles and pedestrians, and even damage the ecological environment.

(3) Enhance citizens' environmental awareness and reduce unnecessary lighting. China is a country with a large population base, and through various means, we educate the public about the hazards of light pollution, so as to deepen environmental awareness and reduce the harm of light pollution.

5. Conclusion

With the continuous improvement of urbanization, while light provides convenience to people, light pollution is also intensifying, posing a threat to people's health, and the problem of light pollution urgently needs to be solved. This article provides a light pollution evaluation model and proposes intervention strategies for different degrees of light pollution, which is of great significance for improving light pollution.

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