

Research on Light Pollution Evaluation Modeling Based on Comprehensive Weights

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Abstract. Light pollution refers to the excessive or improper use of artificial light. Global light pollution poses environmental and health problems. In order to measure and put forward reasonable suggestions to alleviate these phenomena, we established a light pollution evaluation model to calculate the risk degree of light pollution in a region, and sensitively put forward improvement suggestions to alleviate the degree of local light pollution according to the severity of local indicators. In order to strengthen the correlation between the indicators and the evaluation objectives in the evaluation model, we constructed the relationship between the degree of economic development and the night light data. Then, we analyzed the light pollution evaluation model from six perspectives: GDP, population density, forest area, terrain, temperature and precipitation. Combined with the data over the years, we made a preliminary prediction of the weights of each index, then carried out a consistency test on the weights of each index to judge their rationality, and finally conducted a sensitivity analysis.

Keywords: Light pollution; Community; Comprehensive Weight; Evaluation model.

1. Introduction

Light pollution, as a new form of pollution, has gradually entered our field of vision. In recent years, the rapid development of the global economy has presented a prosperous scene everywhere, but the result of this prosperity is the disorder of animal and plant biological cycle, the decline of human sleep quality, and the increase of traffic accident rate. Light pollution needs to be analyzed through a series of indicators to know how fast it is expanding [1, 2].

To quantitatively analyze the intensity of light pollution and comprehensively consider the influence of various factors on light pollution, we have established a comprehensive evaluation model for assessing light pollution.

2. Model preparation

2.1. Data

The data we used mainly include historical number of night lights, GDP data, ecological data and some climate data. The main data sources include NOAA (National Oceanic and Atmospheric Administration, website: <http://www.noaa.gov/>), Our World in Data (website: <https://ourworldindata.org/>), and CIRES (Cooperative Institute for Research in Environmental Sciences, website: <https://cires.colorado.edu/>).

2.2. Data Cleaning

For the GDP number, we choose Beijing as the research object in the modeling process. In addition, due to the large annual GDP value, it will inevitably increase the computational complexity in the calculation, so in the numerical process, we will locate the unit of GDP trillion yuan.

In terms of data processing the number of night lights , since the data not only reflects the level of local industrialization and urbanization, but also reflects the concentration of population, and the remote sensing data of night lights is collected at night, to a large extent, eliminating the interference of natural light, which can better reflect human activities[3, 4]. We assume that the data is dimensionless and measured in units of tens of thousands.

Both variables of in our DLP model are controlled within single digits, which can greatly reduce the computational complexity and keep the error in a stable range. This also provides greater convenience for the subsequent linear fitting analysis and parameter calculation. We have calculated the data of the two variables from 2011 to 2020, as shown in the Figure 1.

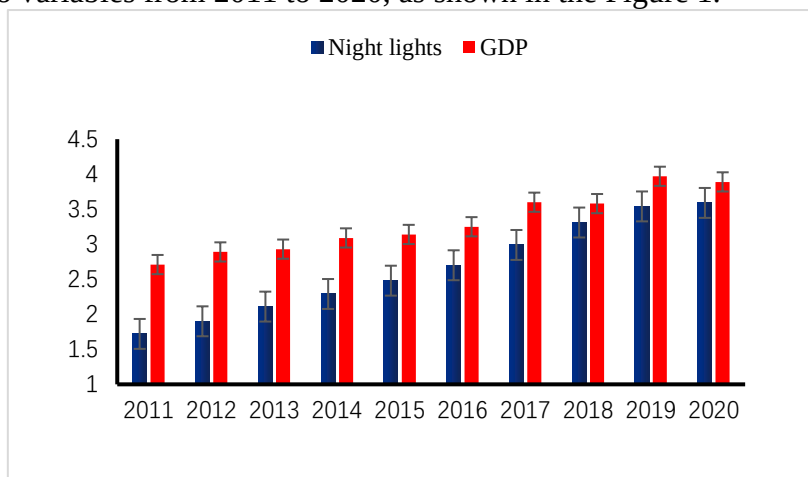


Fig. 1 Data Overview

2.3. DLP Model

There are many forms of light pollution, and the number of lights at night is a common indicators to quantify light pollution because it can avoid many error factors and relatively easy to measure. In order to strengthen the relationship between the research object and the evaluation factor in the evaluation model, we first establish a model with the number of night lights as the independent variable and GDP as the target value(DLP Model)[5].

According to the Assumption 1, GDP is not affected by some small probability events. Therefore, for the target GDP, based on the number of night lights, an expression is created to reflect the relationship between the two variables. As a result, the GDP y_1 of the number of night lights x at year t can be expressed as follows.

$$y_1 = f(x) \quad (1)$$

Where $f(x)$ is the functional relationship between the number of night lights and GDP in the same year.

Since there are many kinds of relationships common to functions, we have to determine the choice of functional relations by the size of correlative coefficient. Therefore, we listed the annual GDP and the number of night lights in one-to-one correspondence, carried out linear fitting analysis, selected the functional relationship with the correlation coefficient closest to 1, and finally determined the parameters in the functional relationship.

The criterion for the relationship between the fit degree and the size of the correlation coefficient is shown in the following Table 1.

According to the above relationship criteria, we only need to prove that the absolute value of the correlation coefficient of the fitted curve is greater than 0.5, so that GDP can be considered to have a functional relationship with the number of night lights. However, in order to reduce the fit error and the subsequent calculation error, we should adopt the functional relationship with the correlative coefficient close to one as much as possible.

Table 1. Relation Criterion

Correlative Coefficient	Criterion
$-0.5 < R < 0.5$	Weak Correlation
$-1 < R < -0.5$ or $0.5 < R < 1$	Strong Correlation
$R = 0$	No Correlation
$R = 1$	Complete Correlation

According to the above analysis, we fit the scatter points with linear relation, exponential relation, power function relation and polynomial relation respectively. It is found that when the exponential function relation is used for fitting, the correlation coefficient is the largest and closet to one. The specific fitting results are shown in the figure below.

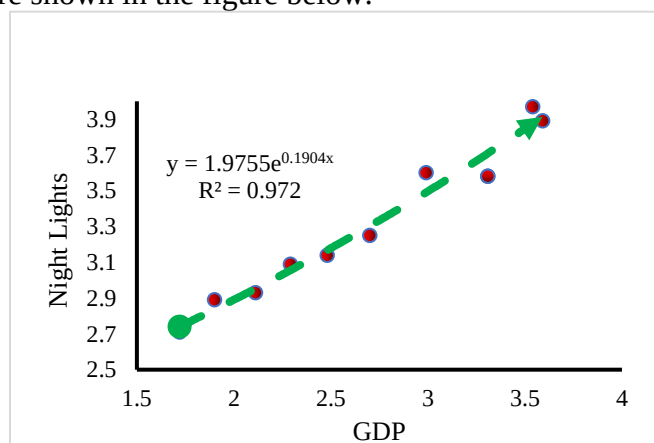


Fig. 2 Fitting results

According to the fitting curve in the figure above, we can get a functional relationship between the number of night lights and GDP as follows.

$$y_1 = 1.9755 * e^{0.1904 * x} \quad (2)$$

Where y_1 is the value of GDP and x is the number of night lights at the same year.

3. DEC model for light pollution Evaluation

3.1. Determination of Index

As for the assessment of light pollution risk, we mainly carried out from the two aspects of scoring and rating, and used TOPSIS method to carry out weight analysis of various indicators. Then according to the result of the score, the decision tree classification can be carried out to achieve grade classification. In our research, we model from the perspective of economy, population density, forest area, terrain, temperature and precipitation.

3.2. Calculation of Weights

In the process of weight calculation, due to insufficient data in some aspects, we choose TOPSIS method for calculation. Of course, in this process, some errors caused by subjective decisions will inevitably be caused, so we will carry out corresponding consistency test in the process of weight calculation.

Since the data of the obtained indicators belong to different types of numerical values, their units are different. It is worth noting that when dealing with indicators of different attributes(positive indicators and negative indicators), the processing methods are different. Since the indicators selected by our model are all positive indicators, only the standardize of positive indicators is discussed in this paper.

$$Z_i = \frac{a_i}{\sum_{i=1}^n a_i} \quad (3)$$

Where Z_i is the standardize value of each indicator and a_i refers to the initial measurement of each factor.

The judgement matrix containing all factors is listed, and the maximum eigenvalue is calculated. The relative importance parameters of each factor in the judgement matrix are determined according to the data over the years and some subjective inferences.

$$|\lambda * I - A| = 0 \quad (4)$$

Where I is the standard matrix, in this paper is the sixth order standard matrix.

$$A = \begin{bmatrix} m_{11} & \cdots & m_{16} \\ \vdots & \ddots & \vdots \\ m_{61} & \cdots & m_{66} \end{bmatrix} \quad (5)$$

Where A is a six-order matrix composed of the importance parameter values of each factor.

Different eigenvalues can be obtained from the calculation of formula 5 and formula 6, from which we choose the maximum value as λ_{max} , and use this value for subsequent operations.

In order to prove whether the proportion distribution containing our subjective inference is reasonable, a consistency test is needed, and the premise of the consistency test is to calculate the consistency proportion, which is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

$$CR = \frac{CI}{RI} \quad (7)$$

Where n is the number of indicators, numerically the same as the number of rows in the judgement matrix, RI is the average random consistency index, and different values of n can be obtained by looking up the table, CI is the parameter value of the final consistency ratio.

After calculating the consistent proportion CI , it needs to be tested. Only when the consistent proportion value is within a certain range, can the error be not large.

The CI calculated by us will be tested according to the process in the figure above until it passed the consistency test.

The judgement matrix that passes the consistency test is normalized by column as follows.

$$M_{ij} = \frac{m_{ij}}{\sum_{i,j=1}^n m_{ij}} \quad (8)$$

Where M_{ij} is the relative importance of each indicator after normalization, m_{ij} is the relative importance of each indicator before normalization.

Since the fluctuation value of each indicator is obtained after normalization by column, it is also necessary to calculate the average value by row, so that the weight of each indicator with relatively stable and small error can be obtained. The calculation formula is as follows.

$$P_j = \frac{M_{ij}}{\sum_{i=1}^n M_{ij}} \quad (9)$$

Where P_j is the weight of each indicator.

After the calculation of the above steps, we can summarize all parameter values of the light pollution degree evaluation model as shown in the following table.

Table 2. Parameter values(DEC Model)

Primary index	Weight(%)	Secondary index	Weight(%)
Development degree	$\alpha = 53.9$	GDP	$a_1 = 80$
		Density of population	$a_2 = 20$
Ecological environment	$\beta = 29.7$	Forestry area	$e_1 = 40$
		Landform	$e_2 = 60$
Climate condition	$\lambda = 16.4$	Temperature	$c_1 = 30$
		Precipitation	$c_2 = 70$

Based on the Table 2, we can list all the relationships in the evaluation model and apply them to the site - specific analysis.

$$D = a_1 * y_1 + a_2 * y_2 \quad (10)$$

$$E = b_1 * E_1 + b_2 * E_2 \quad (11)$$

$$C = c_1 * C_1 + c_2 * C_2 \quad (12)$$

$$X = \alpha * D + \beta * E + \gamma * C \quad (13)$$

Where α is the weight of development degree, β is the weight of ecological environment, λ is the weight of climate condition, a_1 is the weight of GDP, a_2 is the weight of density of population, b_1 is the weight of forestry area, b_2 is the weight of landform, c_1 is the weight of temperature, c_2 is the weight of precipitation.

3.3. Risk Classification

Since the values of each influencing factor are different in different regions, taking all factors into consideration, the risk scores of some regions are ultimately the same, so we decide to classify the scores.

We mainly divide the model into four levels: stable, critical, dangerous and alert. The corresponding score ranges are 0 to 40, 40 to 60, 60 to 80 and 80 to 100.

It is worth emphasizing that there are vary few cities with high regional scores and vary low regional scores, because most of these areas do not meet the conditions of regional balance, so most of the areas score between 80 and 40 points[6].

4. Results

4.1. Model Evaluation

Based on our model, we can roughly classify light pollution into four levels: stable, critical, dangerous and alert. We applied the light pollution evaluation model to urban communities, suburban communities, rural communities and protected lands, and calculated their light pollution degree scores respectively, and divided them into different grades.

4.1.1 A protected land location

Protected land can be understood as a nature reserve in another way. In order to analyze the evaluation of light pollution degree of this land, we need to analyze the characteristics of this land from three perspectives of DEC model.

Firstly, the development of natural reserves is primarily influenced by forest conservation rather than economic factors. The ecological environment in natural reserves is typically excellent, with forest coverage often exceeding 80%. Variations in terrain and climatic conditions can have a significant impact on light pollution levels, but overall, light pollution in natural reserves tends to be low.

In summary, the level of light pollution in natural reserves generally remains in a relatively low and stable state, although it may reach critical levels in some popular tourist destinations.

4.1.2 A rural community

Rural communities are primarily based on agriculture and animal husbandry, with their development status largely influenced by GDP disparities. Some communities experience rapid industrial growth due to the influence of nearby urban areas. With lower population densities, their impact on light pollution is minimal.

Terrain factors outweigh forest coverage, with most communities situated in plain areas. Most rural areas have minimal industrial activity, resulting in lower environmental pollution. However, due to limited forest cover, temperatures and precipitation may deviate from regional norms.

Based on this analysis, the majority of rural communities face a critical level of light pollution, although a few economically developed ones are at risk due to the radiation effect of surrounding urban areas.

4.1.3 A suburban community

More and more people are choosing to live in suburban areas rather than city centers. However, this trend also exacerbates light pollution in suburban areas.

When considering the ecological environment, the impact of forest area can be basically ignored. In terms of the influence of climate conditions on the level of light pollution, we first consider that the current suburban areas, with their well-developed infrastructure, have a climate impact second only to that of cities and we believe that temperature and precipitation have equal importance in affecting the level of light pollution.

According to our model analysis, the level of light pollution in suburban communities falls into the category of danger, except for a few economically developed suburban communities which fall into the alert category.

4.1.4 A urban community

With the continuous advancement of urbanization, the scale and population of cities are constantly expanding, leading to a relatively severe level of light pollution in urban communities. In terms of ecological environment, the impact of forest area can be temporarily ignored. The influence of topography is a greater determinant of the level of light pollution in urban communities.

The climate regulation effect is a significant deviation between the temperature and precipitation in urban communities and the standard temperature and precipitation, resulting in higher comprehensive light pollution scores in urban communities.

In summary, urban communities are both the main source and primary victims of light pollution. Therefore, for most urban communities, their level of light pollution is at the alert level.

4.2. Testing of Models

4.2.1 Sensitivity analysis of DLP Model

The parameter determination of the fitting curve in the DLP Model is calculated according to the data over the years, but the data over the years are not continuous values, and the data is rounded according to the subjective analysis, so certain errors will be caused in the fitting process, so it is necessary to analyze the sensitivity of the DLP Model.

$$\Delta = \frac{\Delta y}{y_1} \quad (14)$$

$$\Delta y = y'_1 - y_1 \quad (15)$$

$$\Delta \leq 5\% \quad (16)$$

Where Δ is the relative error rate. Δy is the relative error (the difference between the change value of the model and the initial value). y'_1 is the change value of the model. We increase or

decrease the parameters in the model by 5%, respectively calculate the corresponding model values, and analyze the relative error rate, if the relative error rate is controlled within 5%, the sensitivity analysis is passed.

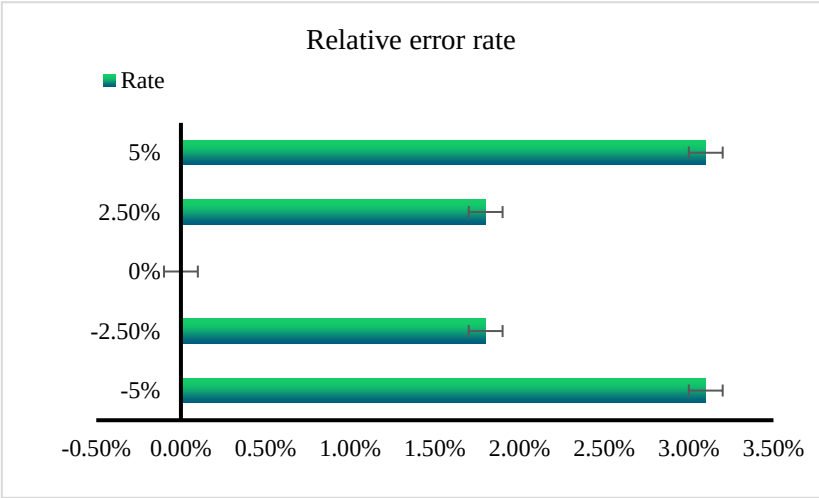


Fig. 3 Relative error rate (DLP Model)

We take the data of Beijing in 2020 as the calculation target for verification, and the specific results are shown in the Figure 3:

It is not difficult to see from the figure above that the relative error rate of the DLP Model is always controlled within 5%, so the value of the parameter has passed the sensitivity analysis, that is, the fitting curve of the model is reasonable.

4.2.2 Sensitivity analysis of DEC Model

The sensitivity analysis method of this model is consistent with that of the above model. We change the weight of each influencing factor within the range of plus or minus 5%, and calculate the relative change of its corresponding light pollution degree value.

Due to the large number of parameter values in the DEC Model, we adopted the method of control variables to carry out a case - by - case analysis, that is, to determine the values of the remaining parameters and analyze the relative error values of the results. If the relative error of the three parameter values is controlled within 5%, the model has passed the sensitivity analysis.

The specific calculation results are as Figure 4.

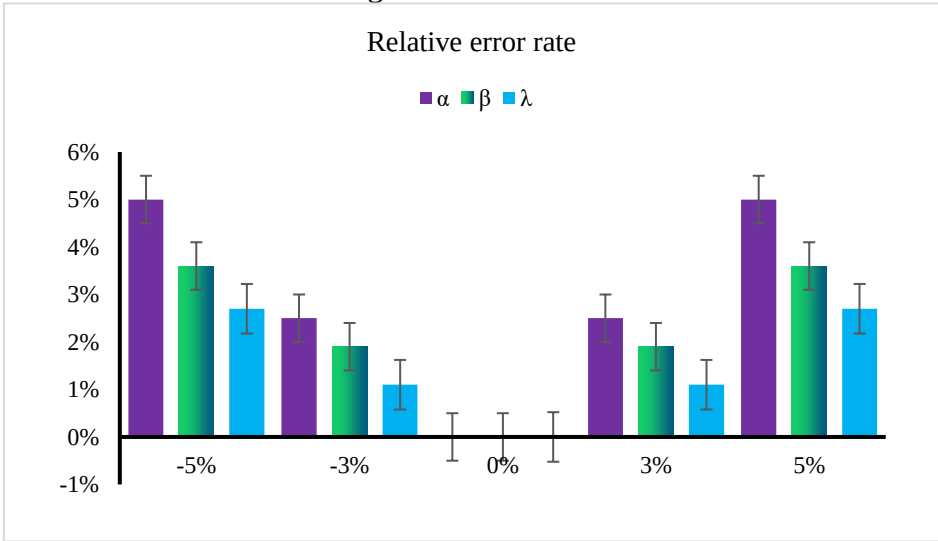


Fig. 4 Relative error rate (DEC Model)

It is not difficult to see from the figure above that the relative errors of the three weight parameters are controlled within 5%, so both models pass the sensitivity analysis.

5. Summary

The DEL and DLP models based on time series proposed in this paper comprehensively consider all factors and establish a comprehensive evaluation model of light pollution from three perspectives: development level, ecological environment, and climatic conditions. It is worth mentioning that our model not only uses the AHP model after sensitivity analysis and consistency testing but also establishes the relationship between indicators and evaluation objects, representing influencing factors through quantitative indicators of evaluation objects.

However, our model applies some approximate analysis methods when evaluating light pollution, which may lead to situations contrary to reality in extreme cases. In future research, we will consider analysis methods that are closer to the distribution of real data.

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