

Research on solution strategy based on light pollution risk level assessment model

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Abstract. Global light pollution is darkening the stars in many parts of the world, even endangering humanity and the environment. Therefore, in order to mitigate the effects of light pollution and make the stars shine brightly in the sky, we do further research on the problem of light pollution. First, in order to determine the light pollution level in specific areas, we established the light pollution risk level assessment index system (LPRL). Based on the hierarchical analysis process (AHP) and the entropy weight method (EWM), we selected three first-level indicators. Next, we first estimated the LPRL for the four selected sites protecting land location, rural, suburban, and urban communities. Then, we proposed three reasonable and effective intervention strategies from the perspective of preventing light pollution sources, reducing light pollution hazards, and reducing light pollution transmission. Finally, we selected two sites in the suburbs of Shanghai and central Shanghai and identified their best intervention strategies by qualitative analysis.

Keywords: List LPRL; AHP; EWM; Pareto optimality; Linear Programming model.

1. Introduction

Global light pollution is dimming the starry skies in many parts of the world, and the situation is worsening. Light is one of the environmental elements necessary for human survival. However, inappropriate light radiation can also pollute the environment and endanger human health. With the industrialization and urbanization of society, Urban Lighting Projects are developing rapidly. Light pollution has become the fifth most extensive environmental pollution after air pollution, water pollution, noise pollution, and solid waste pollution. Its impacts on human health, astronomical observations, biodiversity, and various other aspects are enormous. Satellite images show that nighttime artificial light is spreading to more and more areas in the world at a rate of 2% per year ^[1].

In recent years, the amount of light pollution in cities has changed little. However, it has increased markedly in suburban and rural areas. The intensity of light pollution has increased significantly in all three types of areas, and light pollution spreads from cities to the surrounding ecological regions ^[2]. An index system is needed to evaluate light pollution in a region to determine the evaluation value of the light pollution level. However, academic studies on light pollution evaluation are still immature. Therefore, this paper establish a widely applicable system of the Light-pollution evaluation index and gives three intervention strategies to address light pollution.

2. Light-pollution Risk Level Assessment (LPRL)

The economic development, geographical location, climate, and ecosystem structure of each region differ, so the broad applicability of the metric is significant. In order to evaluate the light pollution risk level of each region, we combine Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM) to establish the Indicator System of Light-pollution Risk Level Assessment (LPRL).

2.1. Indicator selection

According to Light Pollution, Urbanization and Ecology [3], we determine the indicators from three perspectives: they are the source factors of light pollution, the ecological impact caused by light pollution, and the effect of natural environment on light pollution, respectively. We divided the evaluation system of light pollution risk level into three layers: target layer, indicator layer, and sub-indicator layer. The first layer is the Light-pollution Risk Level (LPRL). The second layer contains three first-level indicators: Social Development Level (SDL), Geography and Natural Climate (GNC), Ecological Environment Index (EEI). The third layer subdivides the indicator layer into eight sub-indicators, as shown in Figure 1.

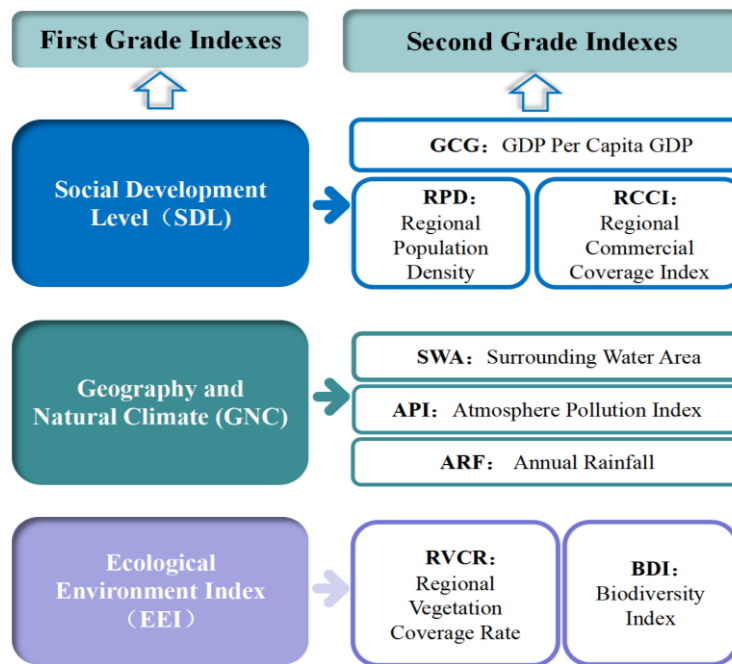


Fig. 1 The framework diagram of LPRL Indicator System

Social Development Level (SDL): GDP Per Capita (GCG), Regional Population Density (RPD), Regional Commercial Coverage Index (RCCI) [4].

Geography and Natural Climate (GNC): Surrounding Water Area (SWA), Atmosphere Pollution Index (API), Annual Rainfall (ARF).

Ecological Environment Index (EEI): Regional Vegetation Coverage Rate (RVCR), Biodiversity Index (BDI) [5].

2.2. Data standardization

Data are from multiple databases, including the National Bureau of Statistics of China [6], and we obtained data from 254 regions for the last five years. To improve the accuracy of the results, the regions we selected are supported by complete and reliable data.

Due to the different nature of each evaluation indicator, a direct analysis with raw indicator values will highlight the role of indicators with higher values in the comprehensive analysis and relatively weaken the role of indicators with lower value levels. We analyze the selected indicators and divide them into positive and negative ones. Larger values of positive indicators indicate more severe light pollution, and larger values of negative indicators indicate less light pollution. Therefore, we standardize the data.

The positive indicator normalization formula is:

$$a_{ij} = \frac{x_{ij} - \min\{x_{1j}, \dots, x_{nj}\}}{\max\{x_{1j}, \dots, x_{nj}\} - \min\{x_{1j}, \dots, x_{nj}\}} \quad (1)$$

The negative indicator normalization formula is:

$$a_{ij} = \frac{\max\{x_{1j}, \dots, x_{nj}\} - x_{ij}}{\max\{x_{1j}, \dots, x_{nj}\} - \min\{x_{1j}, \dots, x_{nj}\}} \quad (2)$$

where x_{ij} and a_{ij} denote the original and normalized values of the j -th term of the i -th program.

2.3. Weight determination

Steps 1. Calculate the weight of the j -th indicator for the i -th region.

$$w_{ij} = \frac{a_{ij}}{\sum_{i=1}^m a_{ij}} \quad (3)$$

Steps 2. Based on self-information and entropy, the entropy value of each evaluation index is calculated and obtained.

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n w_{ij} \ln w_{ij} \quad (4)$$

Steps 3. Then based on the information entropy, we further calculate the weights of each evaluation index previously defined.

$$\omega_j = \frac{g_i}{\sum_{j=1}^m g_i}, j = 1, 2, \dots, n \quad (5)$$

Where g_i is the coefficient of variation; ω_j is the weight of the j -th evaluation index.

Steps 4. We derive the risk level evaluation score for the i th system based on the weighted risk level evaluation formula.

$$LPRL_i = \sum_{j=1}^m L_{ij} \omega_j \quad (6)$$

In addition, we also used Analytic Hierarchy Process (AHP) to make up for the shortcomings of the entropy method because the model may have a significant dependence on the sample. And we need to consider the cross-sectional influence between indicators.

Finally, we assign values to each indicator as described above. Results for these weights are given as follows. The level of social development (0.518), geographical and natural climate (0.172), and ecological environment index (0.31) are the first level indicators. The second-level indicators are shown in Figure 2 below.

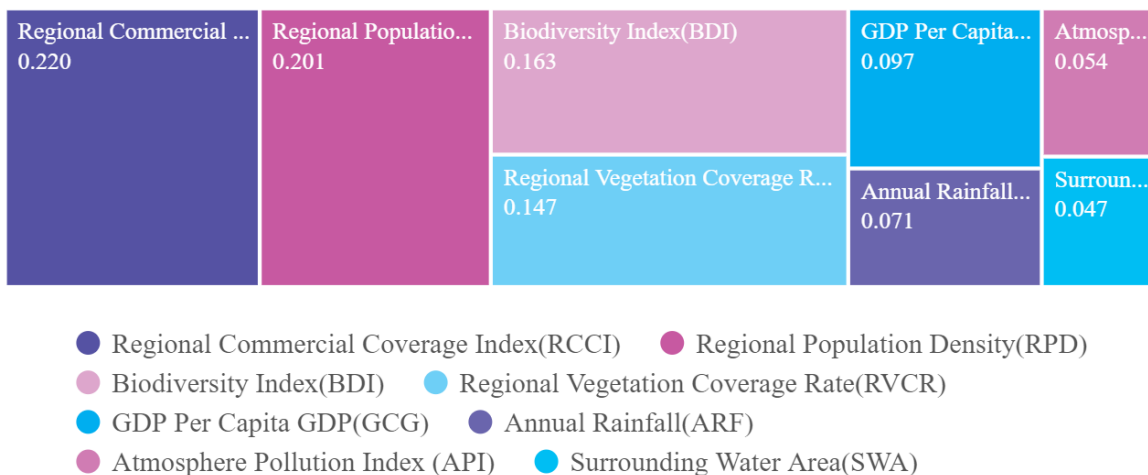


Fig. 2 Area map of second-level indicators indicator weights

3. Application of LPRL to four different regions

Different regions' Social Development Level, Geography and Natural Climate, and Ecological Environment Index have apparent differences. We divide the different regions into four levels according to the three indicators and made a rough assessment of the light pollution risk level, we can roughly understand that the risk level of light pollution in four areas may be Protected land location, Rural community, Suburban community, Urban community. Then we compare the LPRL scores of the four areas three times, and we can determine the level of light pollution risk in each area and the impact of essential indicators on them.

We establish the Regional Commercial Coverage Index (RCCI) model based on the research of Wang Fang and Gao Xiaolu [5] with the following formula.

$$RCCI = \frac{\sum_{i=1}^n \frac{a_i}{a_{mean}}}{S_j} \quad (7)$$

Where RCCI is the degree of commercial aggregation in region j; n is the sum of the number of retail outlets in region j; a_i is the average area of commercial outlets; a_{mean} is the weighted middle area of commercial outlets.

We quote the formula of Shannon-Wiener biodiversity index [4], by which we calculated the BDI values with the following formula.

$$BDI = -\sum_{i=1}^S \frac{n_i}{N} \log \frac{n_i}{N} \quad (8)$$

Where BDI is the species diversity index; S is the total number of species in the sample; n_i is the number of individuals of species i; N is the total number of individuals.

Standardize and normalize the obtained values, and thus

$$LPRL = RCCI\omega_3 + BDI\omega_8 + Q \quad (9)$$

Where ω_3 is the indicator weight of RCCI; ω_8 is the indicator weight of BDI; Q is the sum of the scores of the other six indicators.

Substituting the values in the Table 1, we get the following results.

$$LPRL_{(U)} = RCCI_{(U)}\omega_3 + BDI_{(U)}\omega_8 + Q_{(U)} = 0.854$$

$$LPRL_{(S)} = RCCI_{(S)}\omega_3 + BDI_{(S)}\omega_8 + Q_{(S)} = 0.677$$

$$LPRL_{(P)} = RCCI_{(P)}\omega_3 + BDI_{(P)}\omega_8 + Q_{(P)} = 0.124$$

$$LPRL_{(R)} = RCCI_{(R)}\omega_3 + BDI_{(R)}\omega_8 + Q_{(R)} = 0.397$$

Table 1: Important indicator data for the four regions

Index	GDP Per Capita GDP	Regional Population Density	Surrounding Water Area	AAtmosphere Pollution	Annual Rainfall
Unit	dollars	Person/square kilometer	Square kilometer	-	millimeter
Xishuangbanna Nature Reserve	3368.40	67.00	286.00	23.00	1500.00
Tongguan Town,Sichuan Province	3149.30	631.00	128.30	35.00	1200.00
Shanghai suburb	7834.80	1372.00	132.50	69.00	1166.10
Shanghai Municipality	13050.40	3923.00	56.80	82.00	1082.30

From this, we conclude that: urban communities with higher commercial coverage have higher levels of light pollution risk than suburban communities. And the level of light pollution risk in protected land locations is lower than in rural communities.

We analyzed the LPRL scores for rural and suburban areas. Based on the analysis of the results, it is clear that there are significant differences between suburban and rural areas. None of them are part of the city center, and the differences in population density are insignificant. The main difference is due to the significant weighted indicators, including Regional Vegetation Coverage Rate (RVCR) and Biodiversity Index (BDI). Based on the data in Table 1, we obtained $RVC(R) = 43.9$ and $RVC(S) = 20.1$. In the above analysis, we calculated the non-standardized biodiversity indices for both, where $EEI(R) = 3.7$ and $EEI(S) = 1.5$. It can be seen that the significant differences in light pollution risk levels between suburban and rural areas are mainly due to Regional Vegetation Coverage Rate (RVCR) and Biodiversity Index (BDI). We chose Urban community in Shanghai and Nanhui district, a suburb of Shanghai, for our analysis.

In summary, the initial rough estimate is verified correctly, and the evaluation result of light pollution risk level is: Protected land location < Rural community < Suburban community < Urban community.

4. Three strategies for solving light pollution

The causes of light pollution are multifaceted, as well as the intervention strategies to control light pollution. We propose three reasonable and effective intervention strategies from the perspectives of preventing the source of light pollution, reducing the harm of light pollution, and reducing the spread of light pollution.

4.1. Establishment of the green community system

We learned from Green Communities ^[7] that the green community system refers to introducing green ecological systems into the communities where human beings live, increasing the vegetation coverage of the communities, providing sustainable living conditions for human beings, and getting rid of light pollution on human.

Building a green community system can significantly increase Regional Vegetation Coverage Rate (RVCR), reduce the Atmosphere Pollution Index (API), increase the Biodiversity Index (BDI), and provide conditions for harmonious coexistence between people and nature. In general, it can effectively reduce the harm of light pollution to people, plants, and animals from the process of light pollution transmission.

4.2. Vehicle Light Pollution Control

Major roads in major cities have a high traffic volume at night, and gathering the high beam from headlights causes a lot of light pollution. That can also cause driver glare and cause danger. We introduce the concept of vehicle light pollution control to reduce light pollution by controlling the light of headlights on crucial roads.

Controlling the use of lights in vehicles reduces the primary source of urban light pollution, improves the technology of headlights, and reduces the possible harm to humans due to glare. The spread of light pollution is controlled while improving the safety of people driving at night.

4.3. Decentralizing commercial centers

The over-concentration of commercial areas is the city's most significant source of light pollution. Large shopping malls, giant billboards, and multiple neon lights reflecting off tall glass buildings can produce tremendous glare.

Decentralizing commercial centers can reduce the Regional Commercial Coverage Index (RCCI), the Regional Population Density (RPD) in a particular district and the traffic flow on the roads around

the current commercial centers, and reduces the Biodiversity Index (BDI). Overall, it reasonably reduces light pollution from the perspective of the source of light pollution generation.

5. Application of intervention strategies

5.1. Strategy selection for Nanhui District, a suburb of Shanghai

The vegetation coverage in Nanhui District is low, while a large area for green communities strategy B construction meets the requirements. We establish a green community system. The vegetation coverage of Nanhui District can be improved significantly. At the same time, there are some hidden dangers. For example, completing the green community system will lead to a large influx of people. It causes a local increase in population density. So next, we analyze how much strategy B can improve the light pollution in Nanhui District, Shanghai.

According to the literature [8], we assume that for every 20% increase in vegetation cover, there will be a 5% increase in population density. After calculation, we can see that RVCR is a negative indicator, and RPD is a positive indicator. So we divided it into two groups and calculated LPRL (increase) and LPRL (decrease) separately.

$$LPRL_{(R)} = 67.7$$

$$LPRL_{(new)} = LPRL_{(R)} + (LPRL_{(increase)} - LPRL_{(decrease)}) = 46.8 < 67.77 \quad (10)$$

It can be seen that strategy B is very suitable for Shanghai suburbs. Therefore, strategy B reduces the risk level of light pollution in this area by greatly improving the vegetation coverage rate and limiting the transmission of light pollution.

5.2. Strategy selection for the urban community in Shanghai

The urban area of Shanghai has high commercial concentration and population density, low vegetation cover and species diversity. The leading cause of light pollution is the over-concentration of commercial centers. By comparison, we find that the impact of light pollution caused by road vehicles is relatively small, so we choose from strategy B and strategy C. Due to the greater degree of light pollution in the urban area, strategy B increases population density while increasing vegetation coverage. We cannot directly analyze which strategy is more effective. Therefore, we use a linear programming model to analyze different strategies, change the values of different indicators, and compare them with the derived optimal solutions to select which strategy.

In strategy B (and the same in strategy C), when we build a large number of green ecosystems, we will certainly use a large number of societal resources. At the same time, it will lead to an increase in population density in the region and a decrease in the equity of the social part. The purpose of implementing the strategy is to maximize social welfare. We compare each green community to a commodity and consider the social resources, human resources, and the pressure to increase population density required to build a green community as costs. We introduce the concept of Pareto optimality in economics and use this formula to maximize social welfare.

$$MRT_{XY} = MRS_{XY} \quad (11)$$

Since the two strategies do not significantly impact other indicators, and the weights of other indicators are small, here we only substitute RPD, GCG, RCCI, BDI, and RVCR. A new risk score, Z, is calculated using their original weights. We obtain the following numerical model.

$$\min Z = \sum_{i=1, j \neq 2}^3 \omega_{1j} x_{1j} + \omega_2 x_{12} - \sum_{j=1}^2 \omega_{3j} x_{3j}$$

$$\begin{cases} 0.5x_{13} - x_{32} \geq 1, \\ |y_2 - y_1| < 50000 \\ x_{11} \leq 14000, x_{31} \leq 85 \\ x_{1i}, x_{3j} > 0, (i = 1, \dots, 3) (j = 1, 2) \end{cases} \quad (12)$$

Where y_1 represents the original population size, y_2 represents the current population size. ω_2 is the new weight for RCCI.

The minimum value of the weighted sum of indicators is our objective function, and the optimization range of each indicator is our constraint. For example, $x_{31} \leq 85$ means that RVCR should not exceed eighty-five percent; RCCI and BDI conform to the limit of $0.5x_{13} - x_{32} \geq 1$, the consensus of international experts on urban equilibrium. We use new weights ω_2 because the only target of optimization is the city, and RCCI significantly impacts the city, so we set a new weight.

6. Sensitivity Analysis

In this section, we conducted a sensitivity analysis based on the parameters of the LPRL model. It can be determined that Regional Commercial Coverage Index (RCCI) has the most significant effect on the model, followed by Regional Population Density (RPD), Biodiversity Index (BDI), Regional Vegetation Coverage Rate (RVCR), and GDP Per Capita (GCG). The sensitivity analysis is shown in Figure 3.

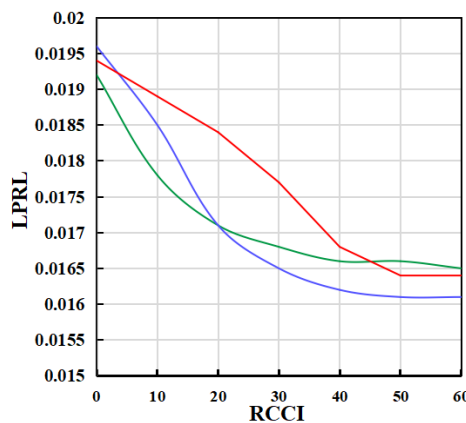


Fig. 3 Sensitivity analysis graph of LPRL

The other parameters are held constant for the light pollution risk level, and the light pollution risk level fluctuates by approximately +1.9% and -1.6% when the business concentration index fluctuates by $\pm 1\%$. The fluctuations of our selected parameters have less than $\pm 2.0\%$ change on the model output value, so the model stability is high.

7. Strengths and Weaknesses

7.1. Strengths

1) Our LPRL model uses EWM and AHP to combine subjective and objective with complementary strengths. We adopted a combined AHP and EWM methods to assess the risk level of light pollution. To a certain extent, the method not only reduces the subjectivity of AHP but also compensates for the possible disadvantages of the entropy weighting method, which is highly dependent on samples and cannot consider the cross-influence between indicators.

2) The model has a solid and reliable mathematical foundation. The optimization model satisfies the extreme or maximum value of the function. This type of problem is called an optimization problem, and it is the best model for solving optimization problems.

7.2. Weaknesses

1) Our model requires cross-calculations, which may lead to inaccurate results. For example, there is some crossover between Regional Vegetation Coverage Rate (RVCR) Biodiversity Index (BDI), which may lead to incorrect results.

2) We chose one explanation for biodiversity: biodiversity as an absorber of harmful light waves can reduce light pollution. However, we did not consider another explanation: biodiversity as an affected species is positively associated with the risk of light pollution.

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