Measurement and Curb of Light Pollution Risk Levels

Huiwen Liu [1, *], Ziyu Wang [2], Zhengzheng Huang [2]

[1] Department of International Economics and Trade, Lixin University of Accounting and Finance University Beijing, China, 201209

[2] School of Lixin University of Accounting and Finance, Shanghai, China, 201209

* Corresponding Author Email: stephenserein@gmail.com

Abstract. Nowadays, light pollution has become a serious environmental problem. However, there are no clear indicators to assess the level of light pollution risk in a certain area. Firstly, we took 31 provinces and cities in China as the research object, and collected the data of seven indicators that affect the risk level of light pollution, then weighted them using Analytic Hierarchy Process (AHP). Secondly, we used the Topsis method for quantitative calculation, and classified the light pollution risk level into five levels: heavy light pollution (score>0.05), high light pollution (0.04<score<0.05), moderate light pollution (0.03<score<0.04), mild light pollution (0.02<score<0.03), and no light pollution (score<0.02). Thirdly, we linked the light pollution risk level to the Comprehensive Development Level Index (CDCI) of each province and city, and divided the cities into four categories according to the CDCI. Then we used analogy analysis to measure the risk level of light pollution in four land types: protected land(score<0.02), rural area (0.02<score<0.03), suburban area (0.03<score<0.04) and urban area (score>0.04). Fourthly, we propose three intervention strategies to combat light pollution: strengthen urban planning and management, better the ecological design of nightscape lighting and improve the material of glass curtain wall. Finally, we test its rationality and feasibility. Our model can analyze the light pollution risk level of other countries or even continents. This is conducive to the government's future planning and resource control of the region.

Keywords: AHP; Topsis; Light pollution; Risk level.

1. Introduction

Light pollution has emerged as a new source of pollution due to the development of cities, the expansion of population and the increasing use of night lights8[1]. Its harm should not be underestimated. Whereas, there is no broadly applicable metric to identify the light pollution risk level of a location, and no concrete action on how to combat light pollution.

We built a mathematical model to measure the light pollution risk level of a location. Based on the historical data[2] about light pollution rick levels, such as population density, night light intensity and biodiversity, a evaluation model of light pollution risk level was established[3]. Then we used this model to measure the light pollution risk level of four diverse types of locations[4]. Based on this model, we propose three intervention strategies to approach light pollution and explain their potential impacts on the effects of light pollution in general.

2. Methods

2.1. Light Pollution Risk Level Model

2.1.1 Derermine indicator weight

We initially use AHP [5] to rank the importance of seven indicators to the level of light pollution risk. Firstly, establish a decreasing hierarchy and a judgment matrix. Determine the scale value of comparison between each element. The matrix between the target layer and the criterion layer is shown in the Table 1.

Table.1. Judgment matrix

O	C_1	C_2	C_3	C_4	C_5	C_6	C_7
C_1	1	1/2	6	3	1/2	5	6
C_2	2	1	6	3	1	6	3
C_3	1/6	1/6	1	1/5	1/6	1/3	3
C_4	1/3	1/3	5	1	1/3	3	6
C_5	2	1	6	3	1	6	3
C_6	1/6	1/6	3	1/3	1/6	1	5
C_7	1/6	1/5	1/3	1/6	1/5	1/5	1

Then, perform consistency tests on the above matrix by calculating consistency metrics CI and find the corresponding average random consistency metric RI according to the Table 2. find the maximum eigenvalues of the matrix and its corresponding eigenvectors, and normalize them to obtain the weights. Since weights are determined through AHP, we can use this auxiliary to Topsis.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

Table.2. Average random consistency metric RI

n	1	2	3	4	5	6	7	8
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41

2.1.2 Risk level score model

The preliminary issue is to classify the seven indicators. The higher the nocturnal illumination, the more light pollution, so it is maximum type. Other indicators of the same type are electricity, population density, GRP, carbon emissions and biodiversity. The higher the Gini index[6], the less the light pollution, and it is minimum type.

The specific modeling process is:

Firstly, the original data matrix will be unified as the same type.

$$minimum\ type = maximum\ type - x \tag{2}$$

Secondly, to achieve normalization of the normalized matrix in order to eliminate the effect of measurement.

$$X = \begin{bmatrix} x_{1\,1} & x_{1\,2} & \cdots & x_{1\,7} \\ x_{2\,1} & x_{2\,2} & \cdots & x_{2\,7} \\ \vdots & \vdots & \ddots & \vdots \\ x_{31\,1} & x_{31\,2} & \cdots & x_{31\,7} \end{bmatrix} \tag{3}$$

The normalized matrix is denoted Y, and each element of Y is given by:

$$Y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^{n} x_{ij}^{\ 2}} \tag{4}$$

$$Y = \begin{bmatrix} y_{1\,1} & y_{1\,2} & \cdots & y_{1\,7} \\ y_{2\,1} & y_{2\,2} & \cdots & y_{2\,7} \\ \vdots & \vdots & \ddots & \vdots \\ y_{31\,1} & y_{31\,2} & \cdots & y_{31\,7} \end{bmatrix} \tag{5}$$

Thirdly, considering the weights that are calculated, the weights derived from AHP can optimize the Topsis model.

$$Z_{ij} = y_{ij} \times w_j \tag{6}$$

Fourthly, for purpose of finding the optimal and the most inferior solutions among the limited solutions, the distance to the optimal and the most inferior one of each evaluation object are calculated respectively to obtain the relative proximity of each evaluation object to the optimal solution.

$$Z = \begin{bmatrix} z_{1\,1} & z_{1\,2} & \cdots & z_{1\,7} \\ z_{2\,1} & z_{2\,2} & \cdots & z_{2\,7} \\ \vdots & \vdots & \ddots & \vdots \\ z_{31\,1} & z_{31\,2} & \cdots & z_{31\,7} \end{bmatrix} \tag{7}$$

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

$$\begin{aligned} Z^+ &= (Z_1^+, Z_2^+, \cdots, Z_7^+) \\ &= (\max\{z_{1\,1}, z_{2\,1}, \cdots, z_{31\,1}\}, \max\{z_{1\,2}, z_{2\,2}, \cdots, z_{31\,2}\}, \cdots, \max\{z_{1\,7}, z_{2\,7}, \cdots, z_{31\,7}\}) \end{aligned} \tag{8}$$

$$\begin{aligned} Z^- &= (Z_1^-, Z_2^-, \cdots, Z_7^-) \\ &= (\min\{z_{1\,1}, z_{2\,1}, \cdots, z_{31\,1}\}, \min\{z_{1\,2}, z_{2\,2}, \cdots, z_{31\,2}\}, \cdots, \min\{z_{1\,7}, z_{2\,7}, \cdots, z_{31\,7}\}) \end{aligned} \tag{9}$$

Define the distance between the i(i=1,2,...,31)th evaluation object and the maximum value as D^+, and the minmum value as D^-:

$$D_i^+ = \sqrt{\sum_{j=1}^{7} (Z_j^+ - z_{ij})^2} \tag{10}$$

$$D_i^- = \sqrt{\sum_{j=1}^{7} (Z_j^- - z_{ij})^2} \tag{12}$$

Then, it is possible to calculate the unnormalized score of the i(i=1,2,...,31)th evaluation object as S_i:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{13}$$

The scores can be normalized as the following:

$$\widetilde{S}_i = S_i / \sum_{i=1}^{31} S_i \tag{14}$$

2.2. Measurement of Four Diverse Types of Locations

The CDIC of China's provinces in 2021 is found from the Chinese Academy of Sciences. The full score of index is 100. By analogy analysis, the division and proportion of the four types of locations mentioned above can be determined by the development of a province or city[7]. We divide 31 provinces into four levels according to this index.

2.3. Three intervention strategies to address light pollution

2.3.1 Strengthen urban planning and management

The layout of buildings in some cities is not reasonable, and there are too many glass curtain walls. The strong light reflected when the light illuminates the wall is not only harmful to human health, such as affecting the quality of sleep, causing neurasthenia, it also has adverse effects on surrounding animals, changing the physiological behavior of them, and even they can be burned to death by the heat around the bright light. Specifically, when planning the main roads of the city, the light environment planning of the street front should be considered first, and possibly reduce the concentrated distribution of glass curtain wall. Since green plants can turn reflected light into diffuse reflection, light pollution is reduced. Therefore, we can strengthen the planning and design of urban green space landscape, expand the green space area, implement greening project, build three-dimensional greening. Increased greenery gives animals places to live and protects local biodiversity [8].

2.3.2 Better the ecological design of nightscape lighting

The main function of night light is illumination, followed by beautification. Excessive lighting not only affects daily life, but even destroys the ecological environment. Nightscape lighting should be designed according to the needs, and fully consider the ecological environmental factors. Cities can divide regional brightness levels according to their own regional planning, and scientifically control the duration, period and mode of lighting, which is conducive to the brightness control and energy saving of urban lighting. For urban landscape lighting, in addition to reduce its brightness, it can also appropriately advance the light-off time of some ornamental architectures. At the same time, the number, size and appearance of colored lights such as commercial street lights and neon advertisements should be uniformly planned to prevent excessive use. This can also save electricity and reduce carbon emissions to a certain extent [9].

2.3.3 Improve the material of glass curtain wall

How to prevent light pollution caused by glass curtain wall? The architectural team can install double glazing inside the glass curtain wall, and paste black light-absorbing material on the inner glass, which can absorb a lot of light and avoid light reflection. At the same time, low radiation glass can be selected to avoid harsh mirror reflection. Low-radiation glass has good thermal insulation effect, reduces the heat energy transferred to the outdoors, and can lower energy consumption. It has less side effect on surrounding animals, so it protects biodiversity.

3. Results

3.1. Light Pollution Risk Level Model Result

From the Table 3, we can see that Gini Coefficient ranks first, which means disparity of income distribution of the population counts. Electricity is also cruial to light pollution [10].

Table.3. Weights

Criterion layer (C_j)	Weights (w_j)
Nocturnal Illumination (C_1)	0.214 (w_1)
Electricity (C_2)	0.266 (w_2)
Population Density (C_3)	0.039 (w_3)
GRP (C_4)	0.125 (w_4)
Gini Coefficient (C_5)	0.266 (w_5)
Carbon Emission (C_6)	0.061 (w_6)
Biodiversity (C_7)	0.027 (w_7)

We use MATLAB software to process the raw data. Partial results obtained after forwarding and normalization are shown in the Table 4.

Table.4. Normalization results for the six provinces and cities

Province Name	Nocturnal Illumination	Electricity	Population Density	GRP	Gini coefficient	Carbon Emission	Biodiversity
Beijing	0.372	0.067	0.287	0.154	0.133	0.038	0.076
Tianjin	0.267	0.053	0.284	0.060	0.110	0.067	0.025
Hebei	0.084	0.232	0.086	0.154	0.192	0.385	0.113
Shanxi	0.089	0.141	0.051	0.086	0.192	0.238	0.093
Inner Mongolia	0.078	0.214	0.005	0.078	0.225	0.334	0.126
Liaoning	0.101	0.139	0.064	0.105	0.218	0.224	0.110

Afterwards, the weights derived from the AHP model are used to optimize the normalized model that has been derived to get the eventual risk level.

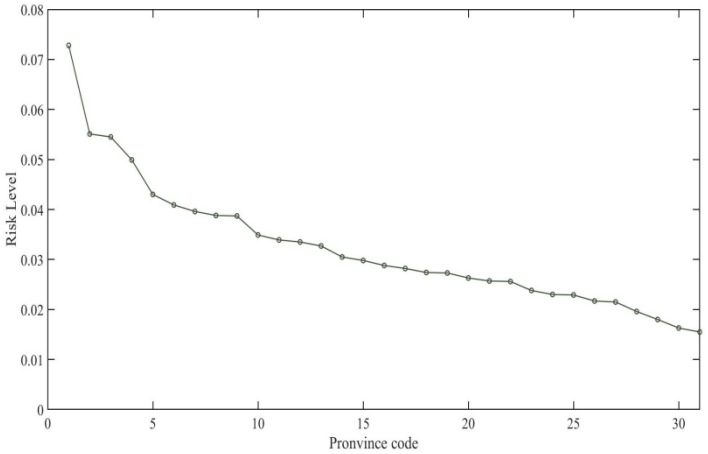


Figure 1: Light pollution level score

From the Figure 1 and the Table 5, we divide light pollution risk levels into five levels: risk level 5 is heavy light pollution, risk level 4 is high light pollution, risk level 3 is moderate light pollution, risk level 2 is mild light pollution, and risk level 1 is no light pollution.

Table.5. Five groups of light pollution risk levels

Score	Risk level	Province name
0.05+	5	Shanghai Guangdong Jiangsu
0.04-0.05	4	Shandong Zhejiang Beijing
0.03-0.04	3	Hebei Sichuan Yunnan Inner Mongolia Henan Fujian Tianjin
0.02-0.03	2	Hubei Liaoning Anhui Shanxi Hunan Xinjiang Guangxi Chongqing Shaanxi Jiangxi Heilongjiang Guizhou Hainan Jilin
0-0.02	1	Ninxia Tibet Gansu Qinghai

3.2. Four tiers of provinces and cities

To distinguish the CDIC and the light pollution risk level index, S Value is used below to represent the light pollution risk level index shown in the Figure 2.

3.2.1 First tier provinces and cities: index score > 85 (figure a)

As the provinces with the highest level of urbanization, the first tier of provinces has the highest proportion of urban area. The mean and median of S Value are 0.0528 and 0.06365, showing a left-skewed distribution. It can be concluded that the light pollution in first tier provinces is the most serious. In particular, Shanghai should pay more attention to light pollution, whose S Value exceeds 0.07, the highest in China.

3.2.2 Second tier provinces and cities: index score > 72.5 (figure b)

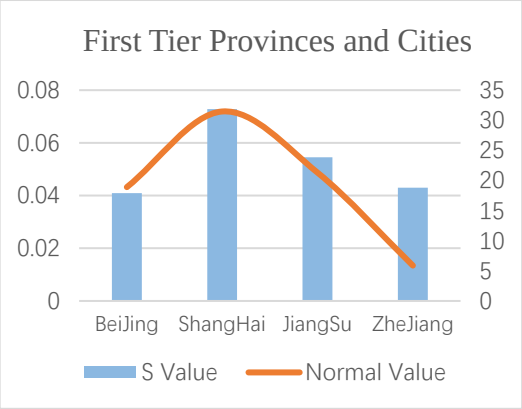
As provinces with a high level of urbanization, the proportion of urban area decreases, while the proportion of suburban and rural area increases. The mean and median of S Value are 0.0346 and 0.0394. It can be concluded that the light pollution of the second tier provinces and cities is weaker than that of the first tier provinces and cities, but due to the unbalanced development of each province and city, there is a range of 0.0313.

3.2.3 Third tier provinces and cities: index score > 70 (figure c)

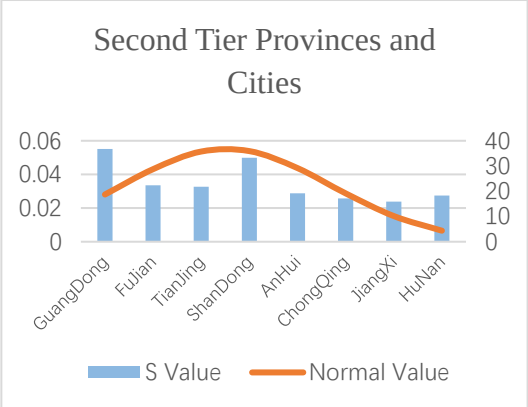
As provinces with average urbanization level, the proportion of urban area continues to decrease, suburban and rural area increases again, and the proportion of protected land increases significantly. The mean and median of S Value are 0.0309 and 0.02645. It can be concluded that the light pollution of the third tier provinces is weaker than that of the second tier provinces.

3.2.4 Forth tier provinces and cities: index score < 70 (figure d)

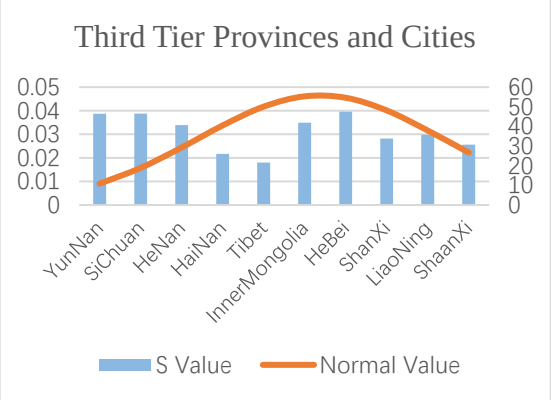
As provinces with low level of urbanization, the fourth tier provinces have a low proportion of urban area, a moderate proportion of suburban rural area, and a high proportion of protected land. The mean and median of S Value are 0.0225 and 0.0263. It can be concluded that the light pollution in the fourth-tier provinces and cities is the weakest.



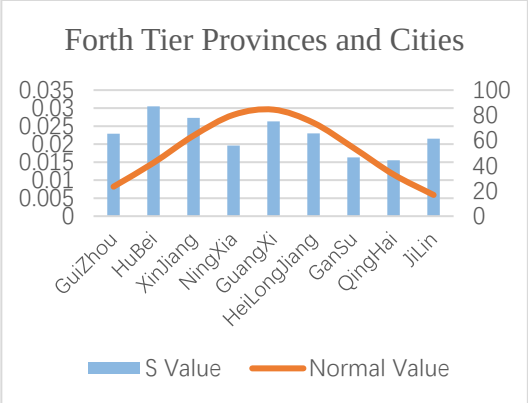
(a)First tier provinces and cities



(b)Second tier provinces and cities



(c)First tier provinces and cities



(d)Forth tier provinces and cities

Figure 2: Four tiers of provinces and cities

3.2.5 Measurement of four diverse types of locations

Four different types of locations are like four tiers of cities with different levels of development. The light pollution index in urban area was the highest, exceeding 0.04, and some even exceeded 0.07. Because of its high lighting density, high level of industrialization, energy consumption and carbon emissions, it is a highly light polluted area. Followed by suburban area has light pollution index between 0.03 and 0.04. It has a slightly lower level of modernization than the urban area, so its level of light pollution risk is moderate. The third is the rural area with light pollution index between 0.02 and 0.03. It has a low level of light pollution risk due to its good ecological environment without excessive artificial light. The lowest light pollution index is protected land, less than 0.02, which has almost no interference from artificial light and protects biodiversity [11].The above is shown in the Table 6.

Table 6: Four types of locations and their light pollution level scores

Types of locations	Scores
urban area	>0.04
suburban area	0.03—0.04
rural area	0.02—0.03
protected land	<0.02

4. Discussion

4.1. Sensitivity Analysis

In model we apply AHP to decide the weights of seven indicators. To testify the sensitivity, the weight of three random indicators is reduced by 5% The boxplot for the two cases are as follows. With the decrease of three indicators' weights, there was a 12.7% decline in the upper quartile and 0.56 % decline in the lower quartile. This means the lower quartile can be negligible and general light pollution level significantly decreases. The result of sensitivity test shown in the Figure 3 is consistent with the actual situation, which also proves the rationality of our model.

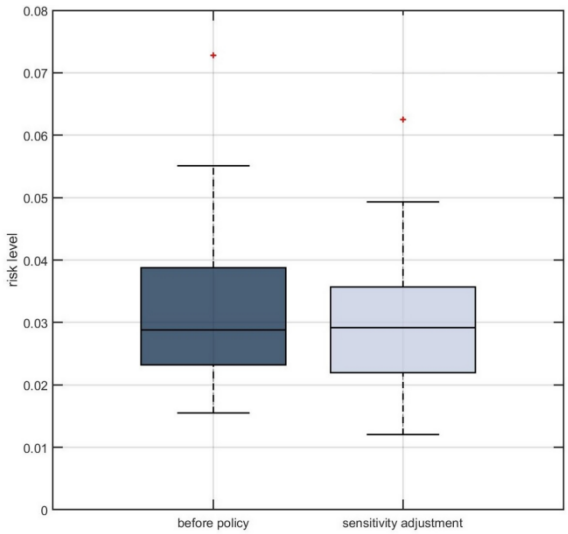


Figure 3: Box plot of sensitivity analysis

4.2. Strengths

AHP qualitatively transforms the difficulty to quantify light pollution risk level into the comparison of the importance of seven indicators, and its systematic analysis method effectively avoids the subjective judgment of decision makers.

TOPSIS avoids the subjectivity of data and does not need the objective function, so it can better describe the comprehensive influence strength of the seven indicators on the light pollution risk level.

Our model is suitable for measuring light pollution risk levels in both small cities and countries.

4.3. Weaknesses

The analysis of effects on intervention strategies in different locations can be more accurate if we have more complete data.

5. Conclusion

This paper takes provinces in China as the research object, with the intention that the model can be widely used in provinces around the world. The AHP method was used to add weights to the seven light pollution impact factors, and the TOPSIS method was used to score the light pollution risk level of each province and city in China. Then we divided China's provinces into four categories according to the comprehensive development level index of provinces, and then analyzed them by category. We obtained the light pollution risk levels of four different types of locations by analogy. After that, we proposed three strategies to reduce light pollution. Finally, we performed a sensitivity analysis of the model to prove its feasibility.

References

[1] Ciach, M., & Fröhlich, A. (2019). Ungulates in the city: light pollution and open habitats predict the probability of roe deer occurring in an urban environment. Urban Ecosystems, 22, 513-523

[2] Li, X., Zhou, Y., Zhao, M., & Zhao, X. (2020). A harmonized global nighttime light dataset 1992–2018. Scientific data, 7(1), 168

[3] Guo, L., Luo, J., Yuan, M., Huang, Y., Shen, H., & Li, T. (2019). The influence of urban planning factors on PM2. 5 pollution exposure and implications: A case study in China based on remote sensing, LBS, and GIS data. Science of The Total Environment, 659, 1585-1596

[4] Xiang, W., & Tan, M. (2017). Changes in light pollution and the causing factors in china's protected areas, 1992–2012. Remote Sensing, 9(10), 1026

[5] Fatemi, M., Rezaei-Moghaddam, K., Karami, E., Hayati, D., & Wackernagel, M. (2021). An integrated approach of Ecological Footprint (EF) and Analytical Hierarchy Process (AHP) in human ecology: A base for planning toward sustainability. Plos one, 16(4), e0250167

[6] Brakman, S., Hu, S., & Van Marrewijk, C. (2021). Urban development in China: On the sorting of skills. The Journal of International Trade & Economic Development, 30(6), 793-817

[7] Zhao, H., & Zhang, X. (2017). Planning for Urban Environmental Pollution Governance Under Urban-Rural Integration in China. Nature Environment and Pollution Technology, 16(1), 99

[8] J.(2019). Pollution lumineuse : l'État se met en règle en régulant l'éclairage nocturne. Environnement & technique,388,10

[9] Sordello, R. (2017). Pistes méthodologiques pour prendre en compte la pollution lumineuse dans les réseaux écologiques. VertigO-la revue électronique en sciences de l'environnement, 17(3)

[10] ALAIN BRENAC,J.(2018). L'Association francaise de l'eclairage met en garde contre les effets nocifs de la pollution lumineuse nocturne , Revue de l'electricite et de l'electronique,5

[11] Qu, C., Tie, B., Wanbo, Z., & Wei, L. (2014, September). Research on reliability evaluation and sensitivity analysis of domain software based on AHP method. In 2014 IEEE Workshop on Advanced Research and Technology in Industry Applications (WARTIA) (pp. 502-505). IEEE