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Comprehensive assessment and intervention strategies of urban light pollution in China based on AHP and entropy weight method

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Abstract. Rapid economic growth and urbanization have exacerbated light pollution, threatening ecosystems and human health. This study develops a robust evaluation system using the entropy weight method and analytic hierarchy process (AHP), ensuring objective index weighting and reliable results. By incorporating precise data such as the night light index (DN value), it provides a more accurate assessment of light pollution. The research identifies a decreasing trend in light pollution from major to smaller cities, highlighting the correlation with urban development levels. Based on these findings, the study recommends targeted strategies: promoting green lighting, optimizing urban planning, and enhancing light pollution prevention facilities. These measures aim to mitigate light pollution's impact, protecting human health and ecological balance. Effectively managing light pollution requires collaborative efforts from government, businesses, communities, and the public to create a healthier nocturnal environment.

Keywords: Light Pollution; Evaluation System; Entropy Weight Method; Analytic Hierarchy Process.

1. Introduction

1.1. Research background and overview

145 years ago, man invented the electric lamp, a small beam of light to illuminate the world. However, with the rapid development of economy and city, the wide application of light brings convenience at the same time, but also brings a new type of environmental pollution after waste gas, waste water, waste residue and noise pollution -- light pollution. This special environmental pollution source not only seriously threatens the ecological environment, but also has a lot of adverse effects on human health. For example, the sunlight reflected by the glass curtain wall has led to many car accidents and visual disorders, and the convergence of reflected light often leads to fire accidents. Sea turtles and migratory birds become disoriented when light pollution interferes with moonlight, while insects, attracted by artificial light, congregate until they die of exhaustion.

Martin Rees, the UK's Astronomer Royal, said light pollution had worsened rapidly in recent years. Since 2016, a third of humanity has been unable to see the Milky Way in all its glory. Light pollution is causing the night sky to gradually brighten at a rate of about 10 per cent a year, according to research by Christoph Kiba of the German Centre for Geosciences. Therefore, the establishment of an assessment of light pollution levels and the exploration of intervention strategies to reduce light pollution levels are of great practical importance.

1.2. Research objectives

The core purpose of this study is to build a comprehensive and systematic comprehensive evaluation system, aiming at accurately quantifying and scientifically evaluating the severity of light pollution phenomenon, and deeply analyzing its multi-dimensional impact on human health, ecosystem balance, economic development and social well-being [1]. In order to achieve this goal, the research will focus on selecting and in-depth analyzing a series of key indicators that will comprehensively cover different dimensions and levels of light pollution.

In terms of methodology, this study will use the data processing and decision analysis techniques of entropy weight method and analytic hierarchy process to determine the weights of each evaluation index, ensure the objectivity and accuracy of the evaluation results, and build an efficient and reliable evaluation model for accurate evaluation of light pollution in cities of different levels, so as to provide powerful data support and decision basis for policymakers.

In addition, this study will further explore and propose effective intervention strategies and specific action plans to solve the problem of light pollution. These programs will be based on in-depth analysis of the causes, impacts and status quo of the current light pollution problem, aiming to reduce the generation and transmission of light pollution through scientific and reasonable means, protect human health, maintain ecological balance, promote sustainable economic development and improve the overall well-being of society. At the same time, the research will also assess the potential impact of these interventions to provide comprehensive reference and guidance for practical applications.

1.3. Overview of the structure of the paper

This paper first discusses the prevalence and severity of light pollution, and emphasizes the necessity and goal of the research, namely to construct a model to comprehensively evaluate the degree of light pollution and its impact, and propose effective intervention strategies. In the model building part, the paper elaborates on the selection of indicators, data collection and model methods to ensure the accuracy and scientificity of the assessment. Subsequently, the model is applied to the risk assessment of light pollution in different urban areas, and corresponding intervention strategies are proposed. In the case study, the paper takes the samples of first-tier, second-tier, third-tier and fourth-tier cities as examples, uses the light pollution evaluation model proposed above and obtains corresponding scores and intervention strategies. Finally, the study results are discussed, suggestions for policy formulation are put forward, and the direction of future research is pointed out. On the whole, this study aims to comprehensively reflect the multifaceted effects of light pollution through a comprehensive assessment model, and provide practical tools and recommendations for policy makers to jointly promote the construction of a healthier and environmentally friendly night environment.

2. Literature Review

2.1. Research status and development trend at home and abroad

In the world, the problem of light pollution has aroused wide attention and carried out in-depth research. Especially in the measurement technology of light pollution, related policies and legislation, remarkable results have been achieved [2-3].

In recent years, scholars such as Zhao F, Deng L and A Laforge have further improved and perfected the quantitative model of light pollution degree by applying various technical means [4-7]. These improvements make the measurement results more accurate and provide more reliable data support for the assessment and management of light pollution. In addition, several researchers have developed models to predict future light pollution levels and their potential environmental impacts [8][9]. These models not only provide early warning for the prevention and control of the deterioration of light pollution, but also translate the research results into specific prevention and control practices, providing a scientific basis for environmental protection work.

At the regional level, researchers in South Africa, South Korea and other countries and regions have actively engaged in the field measurement and assessment of light pollution degree [10][11]. Through regional case analysis and data accumulation, not only promote the localization and refinement of light pollution research, but also provide rich case references for global cooperation on light pollution prevention and control.

In order to achieve more effective light pollution prevention and control and continuous improvement of environmental quality in the future, we need to further deepen the research of light pollution evaluation system and monitoring technology, and broaden the field of light pollution research.

2.2. Possible contributions

This paper proposes a multi-dimensional, data-driven light pollution assessment and optimization model. This study fills the gaps of existing models in real-time data analysis, comprehensive weight determination, and public participation mechanism. By combining DMSP/OLS technology, this paper improves the accuracy of data acquisition and the adaptability of the model. At the same time, using the goal planning and the economic-social-ecological model as reference, this paper formulated a set of intervention strategies that considered both environmental protection and social development.

3. Model construction

3.1. Index selection and description

Based on the impact of light pollution, the evaluation index selection of light pollution degree is divided into four core dimensions: human health, ecosystem, economic impact and social impact. On this basis, compared with the general model, this paper introduces the night light index data (DN value) as a key indicator to measure light pollution itself, thus enriching the quantitative dimension of the evaluation system. DN value is derived from DMSP/OLS global remote sensing image database. This dataset includes cloudless observation frequency image, average light image and stable light image with removal of occasional noise interference. The latter is particularly critical. It reflects the spatial distribution of average light intensity at night during the year, accurately covering cities, towns and areas with persistent light source. Its pixel value (DN value) varies between 0 and 63, becoming an effective tool to characterize the intensity of human activities and the level of light pollution, showing great value and application potential in urban macro research.

For the remaining four dimensions, we combined literature review and screening to extract 7 most representative secondary indicators to build the model.

3.2. Hypotheses

Hypothesis 1: Only the widely applicable evaluation criteria for light pollution under objective circumstances are considered, and geographical environment and climate and other factors are not considered.

Hypothesis 2: Ignoring the locality and non-residue of light pollution, assuming the uniform distribution of light pollution in the region and only considering the degree of light pollution at the measurement time.

Hypothesis 3: Specific lighting parameters such as lighting method, casting direction and type of luminaire are ignored

3.3. Light pollution impact model

3.3.1. Determine index weights.

Based on the above classification of the impact degree of light pollution, the five main aspects of the impact on human beings, the impact on society, the impact on ecology, the impact on economy and the intensity of light pollution itself are taken as a layer category. Table 1 shows the corresponding, description and data source of the specific indicators of the second layer.

Table 1. Descriptions of indicators

Objection	Indicators	Description	Unit	Source
Human	DR	Death rate	%	https://www.stats.gov.cn/
	LE	Life expectancy at birth	Years	https://data.worldbank.org/
Economy	GDP	GDP	Hundred million yuan	https://data.worldbank.org/
	UUR	Urban unemployment rate	%	https://www.stats.gov.cn/
Ecology	FCR	Forest coverage rate	%	http://www.forestry.gov.cn/
Society	PR	Prosecution rate of people's procuratorates	%	https://www.stats.gov.cn/
Light pollution degree	DN	DN value	——	DMSP/OLS

3.3.2. Entropy weight method.

The entropy weight method is an objective weight determination method based on the information entropy of indicators.

First of all, for the data of different indicators, this paper standardizes it to eliminate the dimensional influence between different indicators and ensure that the indicators are compared on the same basis.

Suppose x is some value in X group of data, and Max represents the largest data in X group. Min identifies the smallest data in that group, defining the range DV=MAX-MIN

For the "benefit attribute" type, where the larger the data type, the better, we normalize using the following formula:

$$x = (x - MIN)/DV \tag{1}$$

For the "cost attribute" type, where the smaller the data type, the better, we normalize using the following formula:

$$x = (MAX - x)/DV \tag{2}$$

The coefficient of difference reflects the extent to which the indicators differ between different samples. The greater the difference coefficient, the greater the variability of the index and the more information. Then, the entropy of each indicator is calculated based on the difference coefficient, and the smaller the entropy, the more information the indicator provides.

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} yij} \tag{3}$$

$$e_j = -k \sum_{i=1}^{m} P_{ij} \ln P_{ij}, k > 0, 0 < e_{ij} < 1 \tag{4}$$

Determine the entropy weight, or initial weight, of each indicator based on its entropy, as shown in the table 2 below

Table 2. Weight coefficient

indicator	Information entropy value	Information utility value	Weight coefficient
DR	0.8854	0.1146	13.61%
LE	0.9805	0.0195	2.32%
GDP	0.7844	0.2156	25.61%
UUR	0.9175	0.0825	9.80%
FCR	0.8461	0.1539	18.29%
PR	0.9022	0.0978	11.63%
DN value	0.8423	0.1577	18.74%

3.3.3. Analytic Hierarchy Process.

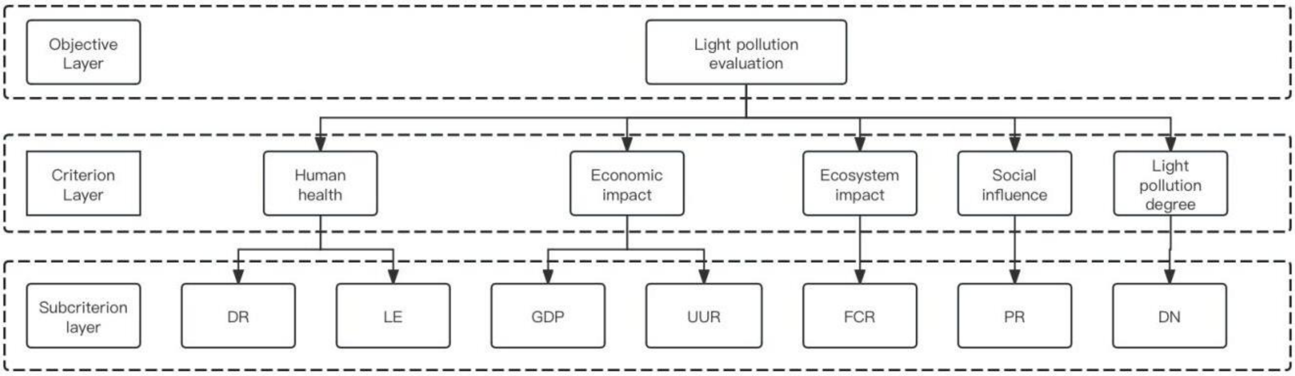

Figure 1. Hierarchy diagram

The Analytic Hierarchy Process (figure 1) is a subjective weight determination method based on expert judgment. Construct a hierarchical structure model as shown in the figure above, and divide the evaluation indicators into levels according to the influencing factors and sub-indicators. The decision-making model is divided into three levels: the uppermost layer is the target layer, that is, the impact index system to measure the degree of light pollution; The bottom layer is the sub-criterion layer, namely seven indicators. The middle layer is the guideline layer, which includes five categories: human health, economic impact, ecological impact, social impact and light pollution degree.

Construct judgement matrix O-C; Compare the importance of five factors in standard layer C to get the judgment matrix: Judgment matrix of target layer and criterion layer is shown in table 3.

Table 3. Judgment matrix of target layer and criterion layer

	Human health	Economical impact	Ecosystem impact	Social influence	Light pollution degree
Human health	1	6	4	2	1/3
Economic impact	1/6	1	1/2	1/3	1/8
Ecosystem impact	1/4	2	1	1/2	1/6
Social influence	1/2	3	2	1	1/5
Light pollution degree	3	8	6	5	1

As can be seen from the above table, aiming at a total of 5 factors including Human health, Economical impact, Ecosystem impact, social influence and Light pollution degree, we construct a 5-order judgment matrix and conduct AHP hierarchical method research. Feature vector is obtained by and integrated method for (1.209, 0.227, 0.373, 0.623, 2.569), and a total of five corresponding weights are respectively: 24.175%, 4.543%, 7.457%, 12.453%, 51.372%.

The consistency test is carried out, and the maximum eigenvalue of the O-C matrix is t=5.087

$$\mathrm{CI} = \frac{\mathrm{t-n}}{\mathrm{n-1}} \tag{5}$$

The maximum eigenroot value is used to calculate CI=0.022, and the CI value is used for the following consistency test.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{Ri}} \tag{6}$$

CR = 0.020

Under normal circumstances, the smaller the CR value, the better the consistency of the judgment matrix, under normal circumstances, the CR value is less than 0.1, the judgment matrix meets the consistency test; If the CR value is greater than 0.1, it indicates that there is no consistency, and the judgment matrix should be analyzed again after appropriate adjustment. The table for the RI value is 1.120, so the calculated CR value is 0.020<0.1, so the judgment matrix meets the consistency test, and the calculated weight is consistent.

In the same way, the importance of each index in the sub-criterion layer and the five criteria in the criterion layer are compared, and the seventh-order judgment matrix is formed respectively, and its weight value and maximum characteristic value are obtained. After calculation, the judgment matrix of the seven indexes also passed the consistency test.

The weight of the criterion and its total weight are summarized in the following table 4.

Table 4. Weight summary

	Human health	Economical impact	Ecosystem impact	Social influence	Light pollution degree	Total weight
Criterion weight	24.18%	4.54%	7.46%	12.45%	51.37%	——
DR	26.76%	3.43%	4.31%	11.37%	4.77%	10.81%
LE	26.76%	2.51%	4.31%	19.15%	11.04%	14.96%
GDP	10.87%	37.40%	15.10%	11.37%	4.68%	9.27%
UUR	10.87%	9.30%	10.71%	4.22%	4.96%	6.92%
FCR	3.39%	5.46%	39.94%	2.24%	15.29%	12.18%
PR	2.78%	14.35%	2.64%	28.91%	4.76%	7.57%
DN	18.59%	27.55%	23.00%	22.75%	54.50%	38.29%
CI	0.052	0.056	0.107	0.086	0.04	——
CR	0.038	0.041	0.078	0.063	0.029	——

Get the evaluation system based on the score:

$$\mathrm{Y} = 10.81\%\mathrm{DR} + 14.96\%\mathrm{LE} + 9.27\%\mathrm{GDP} + 6.92\%\mathrm{UUR} + 12.18\%\mathrm{FCR} + 7.57\%\mathrm{PR} + 38.29\%\mathrm{DN} \tag{7}$$

The greater the Y, the higher the light pollution.

3.3.4. Combinatorial weighting method.

The entropy weight method (objective) and analytic hierarchy process (subjective) are combined to establish a comprehensive evaluation index system to obtain a more comprehensive and accurate index weight. In this paper, the linear weighting method is used, that is, the weights obtained by the two methods are combined according to a certain proportion. The proportion of synthesis is determined according to the actual situation and expert opinions. Here, the actual situation is considered to be more important, so the entropy weight method and analytic hierarchy process are assigned 0.7 and 0.3 weights respectively. The weights of output indicators are as follows.

$$Y = 12.77\%DN + 6.11\%LE + 20.71\%GDP + 8.94\%UUR + 16.46\%FCR + 10.41\%PR + 24.61\%DN \quad (8)$$

According to the "evaluation system" obtained by the combinatorial weighting method, we evaluate the typical representative cities of first-tier cities, second-tier cities, third-tier cities and fourth-tier cities.

Due to Death rate, Life expectancy at birth, GDP, Urban unemployment rate, Forest coverage rate and Prosecution rate of people's The procurates have strong randomness and chance in the data, and are greatly affected by factors such as the size of the city. Here, variation DN value is selected as the representative to determine the light pollution level, and the rest index data is approximately replaced by the national average.

Multiply the weight by the corresponding evaluation index to get the city's score. Assessment of light pollution in sample cities is shown in table 5.

Table 5. Assessment of light pollution in sample cities

Level	city	DN value	score	average
First-tier city	Shenzhen	19.93	209924.4667	209922.6611
	Peking	9.08	209921.7965	
	Guangzhou	8.77	209921.7202	
New first-tier cities	Chengdu	6.27	209921.1049	209921.1985
	Hangzhou	6.56	209921.1763	
	Wuhan (capital of Hubei Province)	7.12	209921.3141	
Second-tier city	Kunming	4.18	209920.5906	209920.7588
	Changsha	5.01	209920.7949	
	Zhengzhou	5.4	209920.8908	
Third-tier city	Yangzhou (in Jiangsu Province)	3.62	209920.4528	209920.2977
	Lanzhou (capital of Gansu Province)	2.98	209920.2953	
	Luoyang	2.37	209920.1452	
Fourth-tier city	Changde	2.77	209920.2436	209920.0295
	Jinzhou	1.85	209920.0172	
	Danton	1.08	209919.8277	

Based on the random selection of typical city representatives and their average scores, it is possible to speculate that the light pollution level gradually decreases from first-tier cities to fourth-tier cities.

4. Intervention strategies, specific actions and potential impacts

Green lighting, sound urban layout planning, and the establishment of light pollution prevention and control facilities have become indispensable key elements in exploring strategies to address light pollution. As an innovative environmental protection concept, the core of green lighting is to reduce excessive lighting, light intrusion and light clutter by optimizing light source design. Specifically, this strategy promotes the use of energy-efficient lighting products such as low-pressure sodium lamps and light-emitting diodes (leds), aiming to control light pollution at the source. In practical applications, by installing a hood for the light source, designing a periodic luminous mode and using natural light simulation technology, green lighting can not only effectively reduce the light intensity and reduce the spread of harmful light, but also promote energy saving and emission reduction while improving the beauty of urban night scenery, and help urban sustainable development.

On the other hand, rational urban layout planning plays a crucial role in reducing the risk of light pollution. According to the development status of different cities, planners need to consider the layout of residential areas, industrial production areas and transportation networks to minimize light pollution. In high GDP cities, zoning should be used to reduce the risk of light pollution in high-density residential areas, while optimizing the lighting design of street lamps and car lights. In industrial areas, priority should be given to suburbs with low population density, and species diversity protection should be taken into account to avoid the adverse effects of light pollution on wildlife. In addition, the layout of trunk roads in transport planning needs to be optimized to reduce the number of roads passing through densely populated areas, and light insulation facilities should be placed on both sides of roads to further reduce the risk of light pollution. The implementation of these measures can not only significantly reduce the interference of light pollution on residents' lives in the short term, but also maintain ecological balance and promote the harmonious coexistence of the overall urban environment in the long term.

Finally, the establishment of light pollution prevention and control facilities is an effective means to block the transmission path of light pollution and reduce its negative impact. Measures such as building green Spaces around residential areas, promoting the use of opaque materials and setting up anti-light barriers can effectively weaken or block the spread of harmful light. The setting of these facilities not only directly reduces the negative impact of light pollution on residents' lives, improves the comfort of living, but also improves the ecological environment and promotes the growth of plants and the greening of the city. At the same time, these actions also enhance residents' awareness and participation in light pollution prevention and control, laying a solid foundation for the formation of a good atmosphere for the whole society to jointly prevent and control light pollution.

5. Conclusion

This paper reveals a significant correlation between the degree of light pollution and the city level, clearly showing that the level of light pollution shows a gradual decline as the city level decreases from the first line to the fourth line. By constructing a comprehensive evaluation system, this paper can accurately quantify and evaluate the light pollution situation faced by cities at different levels, laying a foundation for subsequent control work.

On this basis, this paper puts forward a series of intervention strategies aimed at alleviating light pollution, including but not limited to promoting green lighting technology, optimizing urban spatial layout planning, and establishing and improving light pollution prevention and control facilities system. These strategies not only aim to directly reduce the risk and impact of light pollution, but also promote the harmonious symbiosis of ecological environment and the sustainable development of the city at a deeper level, reflecting the modern urban development concept of harmonious coexistence of man and nature.

It is worth noting that the implementation of these interventions must comprehensively weigh the feasibility of technological innovation, the cost-effectiveness of economic input, and the wide acceptance and impact at the social level to ensure that the intervention strategy is scientific, rational and sustainable. Only in this way, while effectively controlling light pollution, can article achieve a win-win situation of economic, environmental and social benefits, and jointly move towards a brighter, green and healthy future of urban development.

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