| Problem Chosen | 2023 | Team Control Number |
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| E | MCM/ICM<br>Summary Sheet | 2318646 |

# Light Pollution Mesurement And Mitigation


**Summary**

Light pollution has been on the rise due to the increasing use of electric lighting, which has enabled people to carry out activities after dark, and to feel safe and comfortable in urban areas. Artificial light affects the natural rhythm of life and can have a profound impact.

For Task1 ,we developed the **Pollution-Capacity Model(PCM)** model that measures the risk level of light pollution based on the harm of light pollution (**Light Pollution Index or LPI**) and the ability to cope with light pollution (**Bearing Capacity Index or BCI**). The model uses weighted parameters and multicollinearity parameters to measure the effects of indexes and correlation between indexes. The PCM is a comprehensive approach that can be used to evaluate the level of light pollution in different locations and can be helpful for urban planning and conservation efforts.

For Task2, we use the newly developed model to a typical city in China(**Hohhot**) to find out the riskest areas in the city. The four types of locations were differentiated based on administrative division, population density, and development level measured by GDP, using **Fisher Linear Discriminant** as a differentiation model. The resulting differentiation of protected land, urban community, suburban community, and rural community is presented in **Figure.5**. The article also describes the calculation and results of applying the **Entropy Weight Method(EWM)** to acquire weight parameters of LPI and BCI of the communities. These parameters can be used to measure the level of risk in each community and inform decision-making processes.

For Task3, we come up we **3 strategies**. Strategy 1 focuses on **upgrading light sources** to reduce light pollution. Specific actions include using low-power LED bulbs, optimizing lighting systems, and adjusting the type of light source to reduce blue light emissions. Strategy 2 focuses on **energy optimizing strategy**, including implementing smarter lighting systems with motion sensors and timers to reduce unnecessary lighting, which can save energy and reduce light pollution. Strategy 3 focuses on **promoting education and awareness** about light pollution.

For Task4, we discusses **the most effective intervention strategy** for two different communities - the Genghis Khan Street Community as an urban community and the Chasuqi Community as a rural community. **Grey Prediction Model(GPM)** was used to predict the impact of each strategy, while The **Analytic Hierarchy Process(AHP)** was used to select the best strategy from the two locations. **Strategy 1** is the most-effective for the Genghis Khan Street Community and **Strategy 2** works most-effectively for the Chasuqi Community. The document further explains the impacts of each strategy on the location, which will significantly lower risk level(here only consider LPI) of the two locations by about $65\%$ for the Genghis Khan Street Community and $62\%$ for the Chasuqi Community.

For Task5, we select *urban* area and Strategy 1 to make a 1-page flyer call on everyone to start from the side, to upgrade light, and to reduce light pollution.



**Keywords**: Light Pollution; Pollution-Capacity Model; Entropy Weight Method; Fisher Linear Discriminant ; Grey Prediction Model

# Contents

# 1 Introduction

## 1.1 Problem Background

Light pollution refers to excessive or poor use of artificial light, which can lead to phenomena like light trespass, over-illumination, and light clutter. These issues can be observed as a glow in the sky after the sun sets in urban areas and can affect the environment, human health, quality of life, road safety, etc.

## 1.2 Restatement of the Problem

Through in-depth analy-sis and research on the background of the problem, combined with the specific constraints given, the restate of the problem can be expressed as follows:

- The first requirement is to create a metric that can measure the level of light pollution risk in different locations. The metric should be applicable to a wide range of locations, including those that are protected, rural, suburban, and urban. The metric should consider both human and non-human concerns.
- Apply our metric and interpret its results on the following four diverse types of locations: a protected land location, a rural community, a suburban community, and an urban community.
- Describe three possible intervention strategies to address light pollution. Discuss specific actions to implement each strategy and the potential impacts of these actions on the effects of light pollution in general.
- Choose two locations and use developed metric to determine which of intervention strategies is most effective for each of them. Discuss how the chosen intervention strategy impacts the risk level and some other impacts for the location.
- For one identified location and its most-effective intervention strategy, produce a 1-page flyer to promote the strategy for that location.

## 1.3 Our Work

The problem requires us to measure and mitigate light pollution. Our work mainly includes the following:

**1.** We developed a measurment the risk level of light pollution, taking both the harm of light pollution and the adaptation of environment into consideration.

**2.** We apply the newly developed model to a typical city in China(Hohhot) to find out the riskest areas in the city.

**3.** We come up with our 3 pratical strategies and disscussed their impacts.

**4.** We Choose two towns in Hohhot and use your metric to determine which of your-intervention strategies is most effective. 5. Finally, we made a fancy flyer to promote the Strategy.

In order to avoid complicated description, intuitively reflect our work process, the flow chart is shown Figure.1:

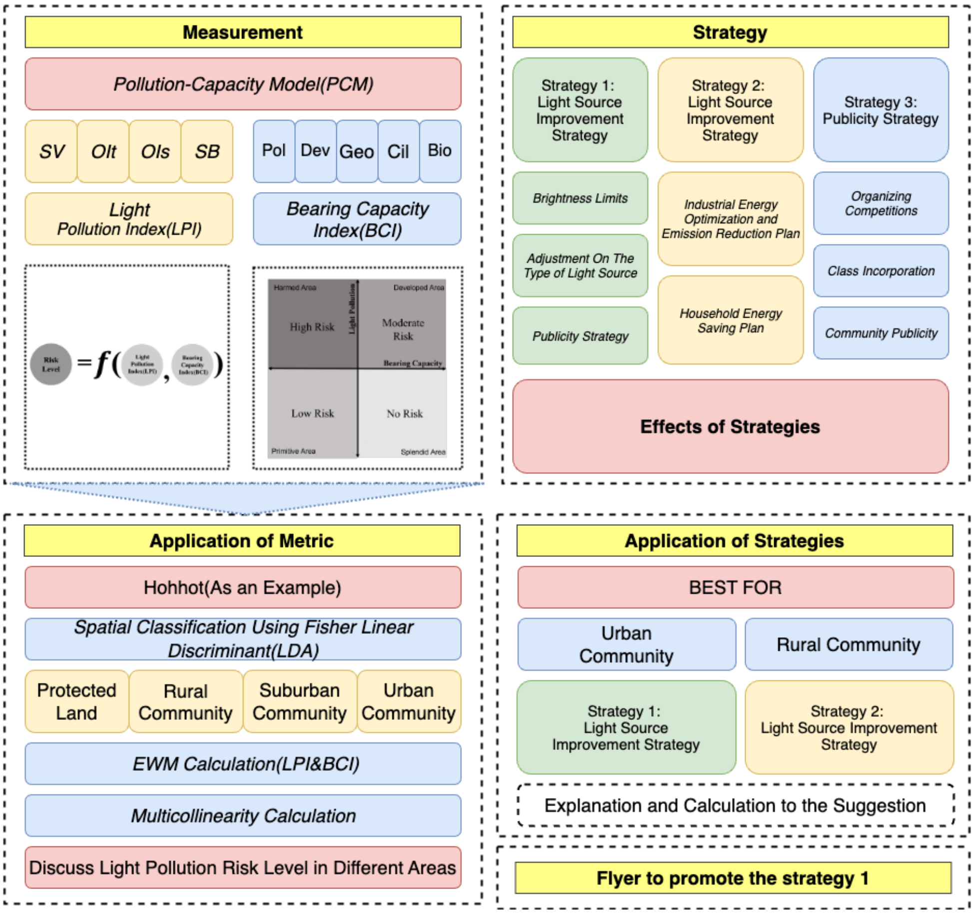



Figure 1: Flow Chart of Our Work

## 2 Assumptions& Explanations And Notations

Considering that practical problems always contain many complex factors, first of all, we need to make reasonable assumptions to simplify the model, and each hypothesis is closely followed by its corresponding explanation:

*Assumption* 1: **The impacts of light pollution are negative and need to be mitigated.**
*Explanation:* If not, there is no need to measure and develop strategies to mitigate light pollution.

*Assumption* 2: **The broadly applicable metric needs to be comprehensive and take into account various factors such as the location's level of development, population, biodiversity, geography, and climate.**
*Explanation:* In real world, there are plenty of indicators about light pollution that we need to consider, and our metric should be board enough, so we need to comprehensively take into account various factors.

*Assumption* 3: **The effectiveness of the intervention strategies depends on the location and its specific characteristics, and the potential impacts of the actions should be carefully considered.**
*Explanation:* Indicators of different locations vary from each other in reality, strategies should adjust measures to local conditions, and potential impacts should be in consideration.

Additional assumptions are made to simplify analysis for individual sections. These assumptions will be discussed at the appropriate locations.

Besides, some important mathematical notations used in this paper are listed in Table.1.

Table 1: Notations used in this paper

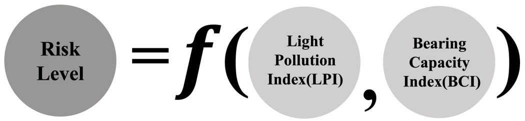
| Symbol | Description |
|---|---|
| $LPI$ | Light Pollution Index |
| $BCI$ | Bearing Capacity Index |
| $SB$ | Sky Brightness Index |
| $OI_t$ | An index to measure degree of traffic night luminance |
| $OI_s$ | An index to measure static sver-illumination |
| $SV$ | Scotopic Vision Capability |
| $Pol$ | Population |
| $Dev$ | local Development |
| $Bio$ | Biodiversity |
| $Geo$ | Geography |
| $Cli$ | Climate |

There are some variables that are not listed here and will be discussed in detail in each section.

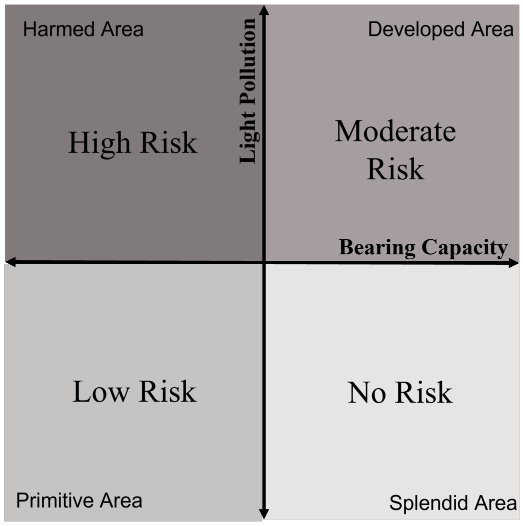
# 3 Task1: Pollution-Capacity Model(PCM)

## 3.1 Overview

As Wikipedia describes,"Risk involves uncertainty about the effects/implications of an activity with respect to something that humans value (such as health, well-being, wealth, property or the environment), often focusing on negative, undesirable consequences[1]." As a result, we can never consider **risk** with only the harm of light pollution or the bearing capacity of the location(or environment). So the risk level of light pollution is measured by **Light Pollution Index(LPI)**(which refers to the harm of light pollution) and **Bearing Capacity Index(BCI)**(which is the ability to cope the light pollution), the overview of the model lies in Figure.2(a). When LPI and BCI are both high, although the pollution is severe, the location can manage to stay stable. We call locations in this situation *developed*, such as NYC downtown and the center of Beijing, China. When LPI is high while BCI is low, the location can hardly cope light pollution, we call it *harmed*. And when LPI is low while BCI is high, we call it *ideal*, which shows its splendid ability to cope light pollution, for instance, some rural settlements with many people. We call it *primitive* when LPI and BCI are both low, and preserves can be a proper example. You can see this clearly in Figure.2(b). Generally, the process of development start from *primitive*, going along the way from *harmed*, *developed*. And it eventually reach *ideal*.




(a) PCM Overview




(b) Four Types of Light Pollution Risk

Figure 2: Pollution-Capacity Model(PCM)

## 3.2 LPI Measurement

To consider the two dimensions of light pollution risk level, we first measure **Light Pollution Index(LPI)**, which is a comprehensive index that takes into account a number of factors, including light source brightness(night luminance), color temperature, and starry sky brightness. LPI mainly considers three types of light pollution,**light trespass, over-illumination, and light clutter**. We measure the three types of light pollution with indexes of **Night Luminance, Sky Brightness and Scotopic Vision**. Considering different impacts of the indexes and correlation between indexes, we use weighted parameters$\alpha_i$ and **multicollinearity**(which often use correlation coefficient$\beta_{ij}$ as a parameter) to measure these effects of indexes. The general equation of **LPI** lies below:

$$LPI = \sum \alpha_i x_i + \sum \beta_{ij} x_i x_j \tag{1}$$

Where $x_i$ refers to an index of LPI and $\alpha_i$, $\beta_{ij}$ refers to weighted parameter and multicollinearity parameter in LPI. To better measure LPI, the indexes measured in detail will be presented as below.

### 3.2.1 Sky Brightness

Sky brightness measures how bright the sky is, which is a proper index to measure artificial light in the night sky. Ideally, we can see stars shining brightly in the night sky clearly. However, due to the light trespass, especially lights that emitt 80-90°above nadir and directly illuminate the night sky, we can rarely see stars anymore but only see even red and turbid sky. As a result, **Sky Brightness** is usually measured by starry vision, the number of different kinds of stars we can catch sight of. The equation shows as follows:

$$SB = \sum (t_i \times m_i) / \sum t_i \tag{2}$$

Where $m_i$ refers to the size of star i(which ranges from 4.0 to 8.0), and $t_i$ refers to the number of observed stars with the size of $m_i$. This is often called **Bortle Scale**[2] as a standard of Sky Brightness varying from 1 to 9, which is a discrete index that equals to $[SB]$(by Gauss Function). However, as other indexes measuring LPI are all continuous, we use continuous $SB$ as **Sky Brightness Index**. As $SB$ gets larger, air pollution gets more severe because you are more likely to only see bigger stars.

#### 3.2.2 Night Luminance

Over-illumination, the excessive use of light, not only causes great energy waste, but also affects our circadian rhythms badly. Usually, we use **Night Luminance** to measure it. Here, Night Luminance can be sorted into three kinds, traffic, public, and private. Traffic Night Luminance comes from vehicles and can be seen as linear dynamic light. To measure this, we select traffic flow data(note it as $TF$) and average over-illumination data$\hat{\delta}$[3] of each vehicle to indirectly estimate degree of traffic Night Luminance.

$$OI_t = \hat{\delta} \times TF \tag{3}$$

Public and private Night Luminance are usually static, which means they are not moving, and most of public Night Luminance comes from street lights and landscape lights. The data we can approach is NPP-VIIRS[4] night light data, which contains both public and private data. As a result, we consider static Night Luminance together as $NL_s$. We can see from Figure.3 that not all the Night Luminance is over-illumination, there is useful light. So here we measure static over-illumination by:

$$OI_s = \hat{\alpha} \times NL_s \tag{4}$$

Where $\hat{\alpha}$ refers to the percentage of over-illumination in night luminance.

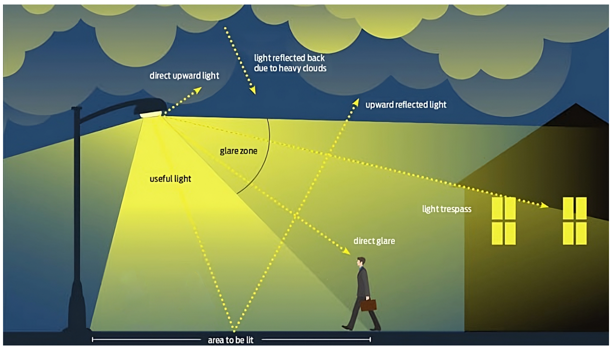



Figure 3: Light Pollution and Luminance

#### 3.2.3 Scotopic Vision

Light clutter, excessive groupings of lights, leading to generate confusion, distraction from obstacles, even potential accidents[5]. For example, when you drive on a night road with colorful neon light, you may get distracted and lose the sight of a barrier which then causes an accident. To measure the harm of light clutter, **Scotopic Vision** is selected as an indicator measuring how clearly we can see at night(it can also measure effects of Glare, which means excessive brightness that decreases ones ability to see). The better Scotopic Vision is, the smaller LPI is. Scotopic Vision efficiently measures the effects light pollution do on human-being health and society health. Usually, Scotopic Vision data comes from experiments and it is really hard to acquire the data of a huge region of places. And there are evidence showing that light pollution does damage to eyes, causing cataract and dry eye for people of different ages[6]. Therefore, we choose morbidity $M$ of cataract and dry eye in the location as our indicator for scotopic vision $SV$. Higher $SV$ refers to higher LPI.

$$SV = \hat{\beta} \times M \tag{5}$$

In conclusion, considering different function of these indexes and multicollinearity among them, we generate the equation of LPI as:

$$LPI = \sum \alpha_i x_i + \sum \beta_{ij} x_i x_j + \epsilon \tag{6}$$

Where $x_i$ refers to $SB, OI_t, OI_s, SV$, $\alpha_i$ refers to weighted parameters of these indexes and $\beta_{ij}$ refers to correlation coefficient measuring multicollinearity. $\epsilon$ is a random diturbing term.

## 3.3 BCI Measurement

**Bearing Capacity Index(BCI)** measures the ability of the location to cope light pollution, which contains artifial and natural conditions. The further discussion comes as follows.

### 3.3.1 Artificial Condition

Seeing in **PCM Overview**, there are four types of situation under light pollution,*primitive, harmed, developed, ideal*. While LPI is high, due to different BCI, there are two situations, *harmed* and *developed*. Let's take urban areas as an example for *developed* and villages beside lighting factories as an example for *harmed*. As population increases and development becomes higher, BCI increases significantly. Population and development of a location, which are two main factors for BCI, work as positive indicators for it. We note them as $Pol$ for Population and $Dev$ for development.

### 3.3.2 Natural Condition

More widely, natural conditions efficiently and thoroughfully contribute to BCI measurement. Considering the mass of natural conditions, we select some main indicators to as thoroughfully as possibly measure natural conditions in BCI. And other possible indicators will be discussed as a random disturbing term in BCI equation. The followings are the chosen indicators:

- **Biodiverity $Bio$:** As we all know, biodiversity of preserves are much larger than urban areas, BCI goes the opposite way. Actually, human-being can bear light pollution much more than wildlife. In urban areas, light luminance keeps high for decades, animals cannot bear the lights have already left. Low biodiversity actually reflects the result of *"natural" selection* and BCI of this kind of area is really high. However, preserve is not accustomed to light pollution, which means its low BCI positive effects. As a result, biodiversity is a negtive indicator of BCI. To better measure BCI, we use the negtive value of biodiversity, which is noted as $Bio$.

- **Geography** $Geo$**:** Mainly considering latitude and altitude, we can see geography a positive indicator of BCI. As latitude and altitude increases, the night sky gets darker, which is more difficult to be affected by light pollution[5].
- **Climate** $Cli$**:** Climate is a complicated index, so we only consider cloud cover and air quality. More clouds and worse air quality(we call this worse climate) means huger difficulty to mitigate light pollution as there are more reflection, refraction, diffraction of light. So we difine climate $Cli$ as a negtive indicator of BCI.

In conclusion, BCI equation is expressed as:

$$BCI = \sum \widetilde{\alpha_i}\widetilde{x_i} + \sum \widetilde{\beta_{ij}}\widetilde{x_i}\widetilde{x_j} + \eta \tag{7}$$

Where $\widetilde{x_i}$ refers to indicators of BCI(including $Pol$, $Dev$, $Bio$, $Geo$, $Cli$), $\widetilde{\alpha_i}$ refers to weighted parameters of these indicators and $\widetilde{\beta_{ij}}$ refers to correlation coefficient measuring multicollinearity. $\eta$ is a random diturbing term.

## 3.4 Conclusion: Applicable Metric

In the last two parts, we built up the two dimensions of risk level in PCM, which we can see from below. In the overview of PCM, we introduced four types of locations with different risk levels, *primitive, harmed, developed, ideal*. But what is the applicable metric to divide the four types? Or in another word, how to quantificationally identify the locations? To set up the metric, we need to first calculate LPI and BCI, then analyze these data and acquire the critical point that help to classify locations with different risk levels.

$$LPI = \sum \alpha_i x_i + \sum \beta_{ij} x_i x_j + \epsilon$$

$$BCI = \sum \widetilde{\alpha_i}\widetilde{x_i} + \sum \widetilde{\beta_{ij}}\widetilde{x_i}\widetilde{x_j} + \eta$$

**4.1.1 Calculation**

**(1)Entropy Weight Method(EWM)**

In order to calculate weight parameters that present different effects of different indexes, we select **Entropy Weight Method(EWM)**, which is a method efficiently and objectedly setting weight parameters by measuring value dispersion. Generally, in this method, m indicators and n samples are set in the evaluation, and the measured value of the $i^{th}$ indicator in the $j^{th}$ sample is recorded as $x_{ij}$.

The first step of EWM is **standardization** of measured values. The standardized value of the ith index in the $j^{th}$ sample is denoted as $p_{ij}$, and its calculation method is as follows:

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}$$

The second step is **Defining entropy value**. the entropy value $E_i$ of the $i^{th}$ index is defined as

$$E_i = -\frac{\sum_{j=1}^{n}(p_{ij}\dot{\ln}p_{ij})}{\ln n}$$

In the actual evaluation using the EWM, $p_{ij} \ldots \ln p_{ij}$ is generally set when $p_{ij} = 0$ for the convenience of calculation.

The range of entropy value $E_i$ is [0, 1]. The larger the $E_i$ is, the greater the differentiation degree of index $i$ is, and more information can be derived. Hence, higher weight should be given to the index. Therefore, in the EWM, the calculation method of **weight** $\alpha_i$ is

$$\alpha_i = \frac{1 - E_i}{\sum_{i=1}^{m} (1 - E_i)}$$

Weight parameters varies from place to place, specific results will be presented in Task 2.

**(2)Multicollinearity Parameter**

Multicollinearity parameter measures the situation that indexes in LPI or BCI are not independent and they have some correlation between each other. For instance, as static night luminance $OI_s$ increases, light trepass also increases, which leads to more difficultly seeing stars(higher $sb$). As a result, we use correlation coefficient to measure multicollinearity Parameter.

$$\beta_{ij} = E[(x_i - E(x_i))(x_j - E(x_j))]$$

Where E is the sigh of expectation and $x_i$ is indexes we discussed before.

## 3.5 Classification Method & Applicable Metric

As discussed before, the four tupes of locations with different risk levels, *primitive*, *harmed*, *developed*, *ideal*, will be classified in this section. Based on calculation results of PCI and BCI(shown as below), we need to figure out the exact value that divide these types. And this process does not run at the same time. As you can see in Figure.4, we firstly divide locations by LPI, whether LPI is more than 0.5(**which is a reference value made no sense**) or not, we then consider BCI. If $LPI > 0.5$ and $BCI < 0.5$, it refers to *harmed* area, which faces really high risk. If PCI and BCI are both larger than 0.5, the location is *developed area* with moderate risk. *primitive* area and *ideal* area is classified with the same value 0.5.

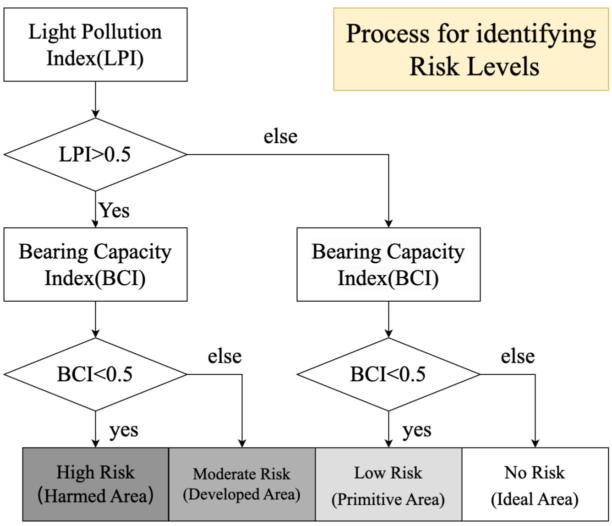



Figure 4: Classification Method & Applicable Metric

# 4 Task 2: Risk Level Metric Application

## 4.1 Research Object Selection & Type Differentiation

**(1)Research Object Selection**

For the purpose to apply metric in Task 1, we select Hohhot, China as our research object, for its medium size, clear differentiation of the four types of locations, and proper artificial and natural conditions.

**(2)Type Differentiation**

To differentiate communities of Hohhot into the four types(including *protected land*, *rural community*, *suburban community* and *urban community*), we look up relative government policies and acquire population, position, and GDP data of communities in Hohhot. And our differentiation is based on administritive division of Hohhot. Here are the brief steps of location type diffeentiation.

***Step* 1:** **Protected Land:** We pull out protected land by relative laws and principles. Here, a nature reserve(as the protected land) means an area set aside according to law for special protection and management of land, land water bodies or sea areas where representative natural ecosystems, rare and endangered species of wild animals and plants are concentrated, and natural relics of special significance are located[7]. As a result, we pull out based on relative laws and policies, and the result will be shown in Figure.5.

***Step* 2:** **Urban Community:** Urban Community is one of the most crowded places of the region. So we pull it out with the data of population density. A community with more than 200 people per square kilometer[8] is defined as urban community. The result will be shown in Figure.5.

***Step* 3:** **Suburban Community & Rural Community:** As we know, population ,access to urban community and development level(measured by GDP) are the factors to consider. Here, we use Fisher Linear Discriminant(or Linear Discriminant AnalysisLDA) as diffentiation model.

**(3)Fisher Linear Discriminant(LDA)**

**Fisher Linear Discriminant(or Linear Discriminant AnalysisLDA)**, a statistic method aim to find a linear combination of features that characterizes or separates two or more classes of objects or events[9]. The main thoughts of LDA is to lower variation in the same sort as possible, and to increase means of different sorts as possible. Finally, the sorts will be differentiated clearly.

Here, we set the population of suburban community and rural community as $G_A$ and $G_B$, which are measured by the data of China from National Bureau of Statistics of China. Besides, we set indexes of each sample(community) as $X_1$(population) , $X_2$(distence to urban community), $X_3$(GDP). Distance $X_2$ is measued from the central point of the community to the central point of urban community. The **differentiation index** $Z$ is constructed by linear combination

$$Z = C_1X_1 + C_2X_2 + C_3X + 3$$

Where $C_1, C_2, C_3$ are weight of $X_1, X_2, X_3$.

Then, it comes to **criterion equation** construction. From the thought of LDA, we know the criterion is positive with means between different sorts and negtive within a sort. As a result, we difine the **criterion index**$\lambda$ as

$$\begin{cases} \lambda = \frac{|\overline{Z_A} - \overline{A_B}|}{S_A^2 + S_B^2} \\ max\lambda \end{cases}$$

Where $\overline{Z_A}$ and $\overline{A_B}$ are means of $G_A, G_B$, $S_A^2, S_B^2$ are variations of $G_A, G_B$. The linear combination $Z$ will acquire its discriminant coefficient $\hat{C}_1, \hat{C}_2, \hat{C}_3$ with $max\lambda$.

With its discriminant coefficient, we calculate differentiation index $Z_i$ of each community one by one(i=1, 2, . . . , n) in the linear combination. Also, the **discriminant critical value** $Z_c$ equals

$$Z_c = \frac{\overline{Z_A} + \overline{A_B}}{2}$$

Finally, we compare each $Z_i$(i=1, 2, . . . , n) with $Z_c$ and differentiate suburban community and rural community. The standard lies as follows:

$$\begin{cases} Z_i \geq Z_c, & community \quad i \quad is \quad a \quad suburban \quad community \\ Z_i < Z_c, & community \quad i \quad is \quad a \quad rural \quad community \end{cases}$$

The differentiation result lies as follows in Figure.5

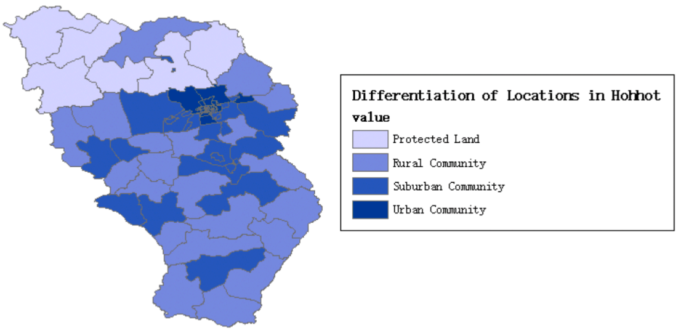



Figure 5: Differentiation of Four Types of Locations

## 4.2 Application: Calculation & Results

### 4.2.1 EWM Calculation and Results

Applying EWM in the last section, we can acquire weight parameter of LPI and BCI of the communities. Here, part of the data is presented in Figure.6. We can easily see that the most weighted indexes are $OI_t$ for LPI and $Pol$ for BCI.

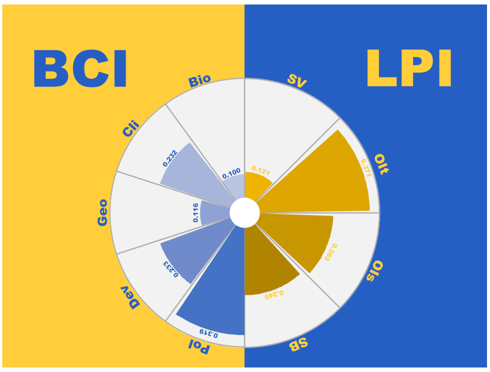
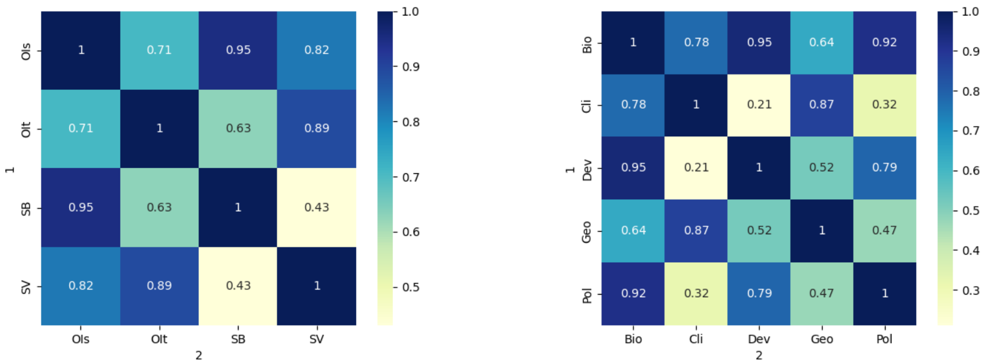



Figure 6: General Information of Hohhot

### 4.2.2 Multicollinearity Calculation and Results

Similarly, multicollinearity parameter is calculated with the method in the last section, correlation coefficient. Due to the mass of data, we only choose a group of representative data showing here with heatmap in Figure.7.




(a) multicollinearity parameter of LPI (b) multicollinearity parameter of BCI

Figure 7: A Group of Multicollinearity Parameter

### 4.2.3 Results of Light Pollution Risk Level

With weight parameter and multicollinearity parameter results, we can calculate LPI and BCI of each community. To simplify calculation, we consider indexes with high multicollinearity parameter(correlation coefficient) as one index. As a result, we only consider $OI_s$, $OI_t$, $SV$ calculating LPI and $Pol$, $Dev$, $Cli$ calculating BCI. After calculating PCI and BCI of each community, we **standardize** the results to better compare and analyze the data.

In PCM, we developed a metric to calssify locations into four types with risk level(which can be seen in Figure.4). However, the criterion value did not come out because it needs specific data. Here, we select average data of indexes of China[8] and current national standard of China[10] to calculate the criterion data(standardized):

$$\begin{cases} LPI = 0.63 \\ BCI = 0.49 \end{cases}$$

Generally, we first compare average risk levels of the four types of locations differentiated in the last part. The result is presented in radar Figure.8.

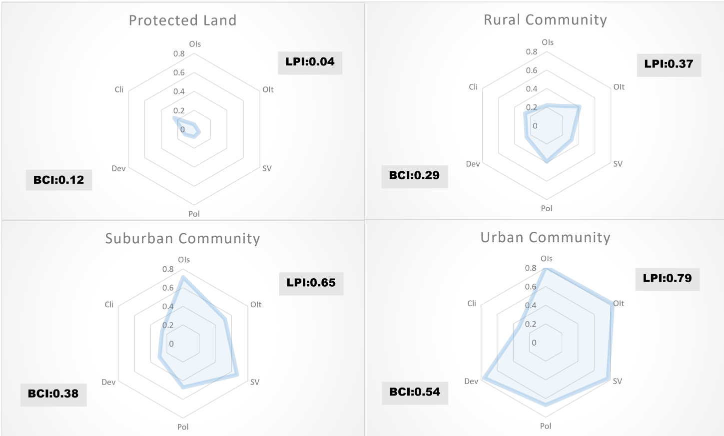



Figure 8: General Comparation of Risk Level in Four Types of Locations

As we can see, it is obvious that average LPI and BCI both obey the trend going up from *protected land*, along *rural community*, *suburban community*, and finally to *urban community*. Compared with criterion value, we can roughly put *protected land* and *rural community* into *primitive*, *suburban community* into *harmed* and *urban community* into *developed*. Also, $Cli$ is quite similar due to the size of Hohhot. Main indexes influencing LPI and BCI are $OI_s$, $OI_t$, $Pol$, $Dev$. Here is one thing interesting, $OI_s$ of *suburban community* is much larger than our common sense, which may owe to the development of transport industry, suburban community becomes freight hub.

However, as LPI of *rural community* and *suburban community* are close to the criterion value. So as BCI of *suburban community* and *urban community*. We can hardly simply be satified with the result. Furtherly, we measure exact risk level with PCM of every community in Hohhot, and divide them into the four types(*primitive, harmed, developed, ideal*), which is shown in Figure.9.

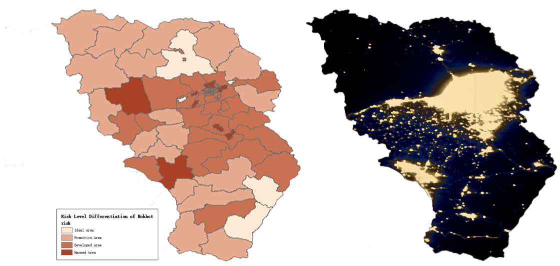


Figure 9: Risk Level And Night Light of Hohhot

In Figure.9, we can clearly see the four sorts of locations with different risk levels, *primitive, harmed, developed, ideal*. And the gradation of color shows risk level, the deeper the color is, the higher risk level of that location is. Generally, risk level matches night light of Hohhot, brighter places usually means higher risk levels. For example, we can see the urban communities(shown in Figure.5) with really bright lights are mainly *developed* areas. However, in some places, things are different. For example, Daqingshan Community, the only *ideal* area in the upper half part of the picture(the north of Hohhot), keeps ideal while surrounding a community with really bright night light. Actually, there is a preserve in Daqingshan Community covers a huge area, Daqingshan National Forest Park[11]. Mass of actions have been taken to thoroufully protect the preserve, which leads to *ideal* situation of light pollution here.

# 5 Task 3: Discussion of Possible Strategies And Their Potential Impacts

As it is unveiled in the last section that light pollution has strong relationship with night lights, which comes from lighting sets at most. Strategy about lighting set must be an efficient way dealing with light pollution. However, other strategies can also be developed and applied to light pollution. To develop strategies dealing with light pollution, **ecological, economical, social, and intergenerational** impacts and sustainability must be involved(details to be considered in the four aspects are shown in Figure.10). Here, with regard of all these, three possible strategies are discussed, including their thoughts, specific actions and effects.


Figure 10: A Model of Sustainable Night For Everyone

## 5.1 Strategy 1: Light Source Improvement Strategy

Night lights contribute to light pollution dominantly. Starting from lighting sets is definitely a great idea. And due to the speed of light, we can hardly do with its transmit. As a result, we develop a strategy focusing on light source(upgrade lights), which is the most direct way dealing with light pollution. Here are three aspects of Strategy 1.

- **Brightness Limits**
- **Adjustment On The Type of Light Source**
- **Shade Adjustment**

### 5.1.1 Brightness Limits

Traditionally, incandescent light bulb is wildely used in daily life, providing comfortable light for us. However, not only do incandescent light bulb offers **over-illuminational** light, it also **wastes** too much energy.

So the **first specific action** can be achieved by using **low power or low brightness output** bulbs or lamps, such as LED bulbs. Compared to traditional incandescent bulbs, these bulbs are usually more energy efficient and more environmentally friendly. **In addition**, you can choose to **optimize the lighting system**, such as **directional** lighting or lighting **attenuation** system, these systems can reduce the scattering of light and leakage, thereby reducing light pollution.

Low-intensity lighting can not only **reduce light pollution**, but also **save energy** and reduce energy costs. This is the main **positive effect** of brightness limits.

At the same time, brightness limits may have some **negative effects**. For example, lower light brightness will lead to reduced visibility of traffic roads, and may also affect the driver's mental condition, and thus improve the accident rate. The following is a random sample of Hohhot's urban, suburban, rural, and protected areas road accident rate and light intensity, according to the intensity of light intensity to make the following graph (Figure.11), which shows a trend that traffic accident rate increases with intensity too low or too high.

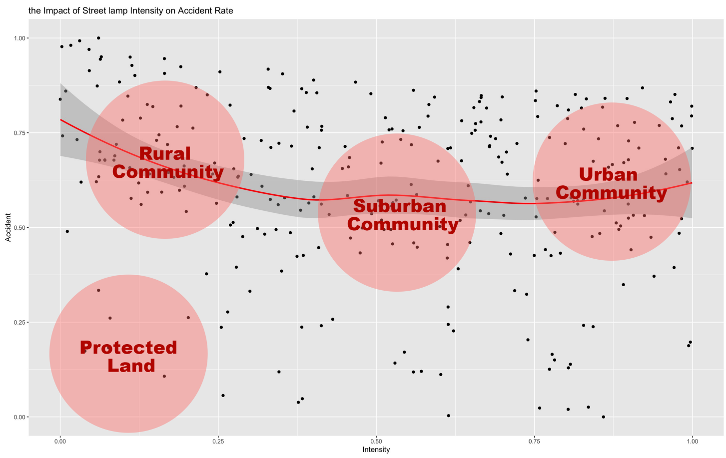



Figure 11: Intensity-Trafffic Accident Curve

### 5.1.2 Adjustment On The Type of Light Source

Short wave light(blue light) is a significant reason of eye disease, cancer, and damage to wildlife. Also, blue light is more likely to cause light pollution than green or red light. Blue light is more likely to be scattered in the atmosphere, which you can tell from the blue sky during the day. As a result, it is a good choice to **use low blue light source**.

Cutting the use of blue light can lower the risk of insomnia, mania and cancer, etc, mainly by preventing circadian rhythms from being disturbed. Besides, blue light really does harm to wildlife, mainly affecting animal rhythms as well as migration.

For example, light pollution can disrupt the migration patterns of nocturnal birds and newly hatched sea turtles[12]. In summary, adjusting to a low blue light source has a more significant **positive effect** on human and animal health. It is also a way of reducing **light clutter**.

At the same time, the adjustment of light source type may have some **negative impact** on commercial activities, especially in some large shopping malls or commercial centers with bright color lights attracting customers and increasing consumption. Adjusting light source affects the attraction of these shopping malls and commercial centers, leading the cut-down of consumption. There is realistic correlation between light source color richness and consumption obtained from a sample of milk tea stores in Beijing(Figure.12)(where data is more abundant to analyze).

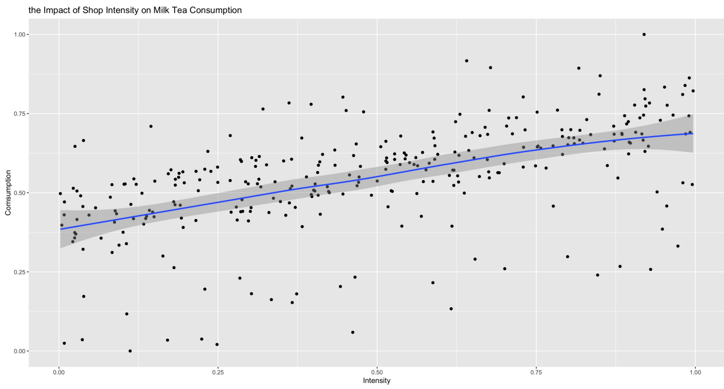



Figure 12: Light-Consumption Curve of Milk Tea Shop

### 5.1.3 Shade Adjustment

**Shade adjustment** can be seen as one of the cheapest way of dealing with light pollution, for the low cost of material and easy operation of installing shades. But it benefits significantly. Installation of shade, can control the direction of light dispersion of lamps and lanterns, and prevent the light towards the area that does not need to be illuminated. In short, shade adjustment provides a way preventing **light trepass**.

Here is a brief model optimizing shade for street lights. Our goal here is to acquire the minimum length of the shade(which we assume as a bar), and the best angle to install the shade considering the lowest cost on material. The following is our objective function.

$$\begin{cases} min l \\ \theta = \theta(l) \end{cases}$$

Besides the objective function, constraint condition describes light trepass of different length $l$ and angle $\theta$ of the shade.

$$l = \pi \times (\sin\theta)^2$$

By calculation, the ideal length $l$ is $0.34m$.

In addition, housing window materials can also be improved to reduce light transmission rate, especially the transmission rate of blue light, the potential positive impact is mainly mainly can enhance the privacy and security of the home, and can also reduce the impact on the outside of the house.

## 5.2 Strategy 2: Energy Optimization Strategy

Energy Optimization Strategy offers another view of dealing with light pollution, which makes a more far-reaching difference but is more difficult to take action. Here, two plans on energy optimization are developed, **Industrial Energy Optimization and Emission Reduction Plan, Household Energy Saving Plan**.

### 5.2.1 Industrial Energy Optimization and Emission Reduction Plan

Economic development, especially industrial development, influencing light pollution obviously, especially in the natural gas energy extraction and combustion process, where a large number of flares are produced[14]. Thus, it is a need to optimize industrial energy and reduce emission. For example, actively expanding the mining of wind and solar energy, changing the form of open burning such as coal, have a **positive impact** in reducing the risk of light pollution.

### 5.2.2 Household Energy Saving Plan

Household light source is an important source of light pollution. And at the same time it is one of the sources of light pollution most closely related to human health. Restrictions on household light sources, especially government regulations and regulatory restrictions, can play a more obvious role, but the adoption of this measure will cause some potential negative effects. Taking into account high degree of privacy and privacy of family, household light source Restrictions may cause a greater threat on the freedom of residents and quality of life. This refers to **social equality** that we must consider.

## 5.3 Strategy 3: Publicity Strategy

Except for Light Source Improvement Strategy and Energy Optimization Strategy, Publicity Strategy seems to be the most abstract strategy, because there is no specific metrics to measure how good the Publicity Strategy is. However, this is probably the most interesting and profound strategy that leads to **intergenerational influence**.

- **Organizing Competitions:** Competition offers opportunity for the public to participate in light pollution publicity actively, and leave an impression of light protection in their mind.
- **Class Incorporateion:** This combine light pollution publicity with education, which leads to profound impacts by generations.
- **Community Publicity:** It will bring the awareness of light pollution reduction to the neighborhood efficiently.

In conclusion, we developed 3 possible strategies based on **ecological, economical, social, and intergenerational** impacts and sustainability and their specific actions, then analyzed their potential impacts.

# 6 Task 4: Further Discussion on Strategies of Specific Locations

To further discuss strategies of specific locations, we first select two identified locations considering their representativeness. As a result, we choose **Genghis Khan Street Community** as an example of *urban* community and *developed* area, and **Chasuqi Community** as an example of *rural* community and *harmed* area.

## 6.1 Most-effective Intervention Strategy

Here, Due to the impacts of strategies play the same role to LPI and BCI, we only consider the change of LPI as the impact of strategies. To select the best strategy from the two locations, we first use **Grey Prediction Model(GPM)** to predict impacts of each strategy, and then we select **The Analytic Hierarchy Process(AHP)** to comprehensively consider the effects of strategies for the locations.

### 6.1.1 Grey Prediction Model(GPM)

Grey Prediction Model(GPM)[15] is usually a combination of multiple sets of data. After a series of fitting of these different data, a general prediction of the future direction can be made. By analyzing the relationship between the strategy implementation and LPI, we generate and process a series of indicators affecting the light pollution risk, so as to find out the rule of the light pollution risk system, generate a data series with strong regularity, and then make the corresponding **differential equation model** to predict the change of LPI after the strategy implementation.

The following assumptions are made: Strategy 1 mainly affects LPI through the influence of $OI_s$ (influence parameter is $a$); Strategy 2 mainly affects LPI through the influence of $OI_t$ and $Dev$ (influence parameter is $b_1$, $b_2$); Strategy 3 mainly affects LPI through the influence of $Pol$ and $Dev$ (influence parameter is $c_1$, $c_2$). Based on the above assumptions, The three strategies are predicted according to the time change.

We set initial(LPI of the first 10 seasons with strategy implementing) LPI of Genghis Khan Street Community as $X^{(0)} = [X^{(0)}(1), X^{(0)}(2), \ldots, X^{(0)}(9), X^{(0)}(10)]$. And this for Chasuqi Community is noted as $Y^{(0)} = [Y^{(0)}(1), Y^{(0)}(2), \ldots, Y^{(0)}(9), Y^{(0)}(10)]$. When strategy is implemented, predicted LPI in 10 seasons is calculated as
$X^{(1)} = [X^{(1)}(1), X^{(1)}(2), \ldots, X^{(1)}(9), X^{(1)}(10)]$. $X^{(0)}(1)$ is LPI when new strategy starts to work and provides no change, and strategy influence parameter works to generate the other 9 LPI.

Process of GPM comes as follows:

***Step* 1: Data Test:** To test if the data can be applied in GPM, we need to take **step-by-step test** and **smoothness test**. For step-by-step test, the standard is $\theta/in(0.7564, 1.3367)$. Until data mathches the standard, criterion $\theta^{(i)}$ is repeating linear transformation. The following is the eventual result of step-by-step test of Genghis Khan Street Community, which accords with the standard $\theta\ /in\ (0.7564, 1.3367)$(data of Chasuqi Community also does).

Table 2: Results of Step-by-step Test of Genghis Khan Street Community

| Criterion | $\theta^{(1)}$ | $\theta^{(2)}$ | $\theta^{(3)}$ | $\theta^{(4)}$ | $\theta^{(5)}$ | ... | $\theta^{(9)}$ | $\theta^{(10)}$ |
|---|---|---|---|---|---|---|---|---|
| Value | 1.0415 | 1.0398 | 0.9352 | 1.2781 | 0.8764 | ... | 1.0932 | 1.2737 |

Also, data of selected locations passed smoothness test, which means $X^{(0)}$ is a Quasi-smooth sequence and $X^{(1)}$ is in accord with Quasi-exponential law. They obey the following differentiating equation

$$\frac{dX^{(1)}}{dt} + \alpha X^{(1)} = \mu$$

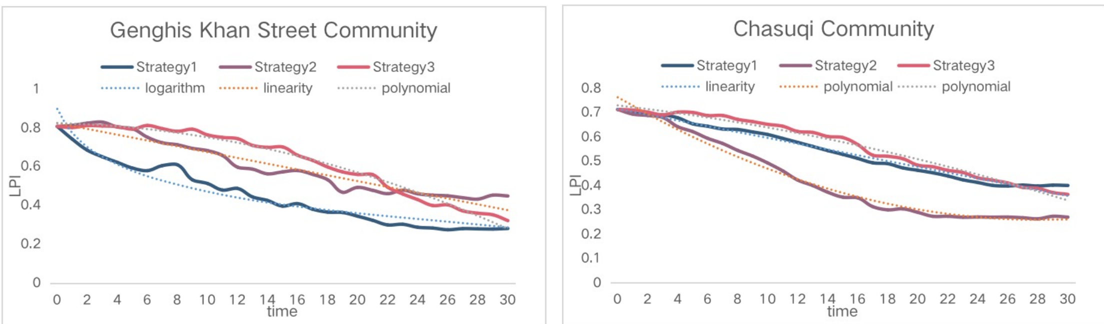
Where $\alpha$ and $\mu$ are the solution of the equation. As a result, $X^{(0)}$ can be used for GPM(GM(1,1)).

***Step* 2: Prediction Model:** the main model comes as follows:

$$\begin{cases} X^{(\hat{k}+1)} = [X^{(0)}(1) - \frac{\hat{\mu}}{\hat{\alpha}}] \exp -\hat{\alpha} k + \frac{\hat{\mu}}{\alpha}, & k = 1, 2, \ldots, 10 \\ X^{(\hat{0})}(k) = X^{(\hat{1})}(k) - X^{(1)}(\hat{k} - 1), & k = 2, 3, \ldots, 10 \end{cases}$$

Finally, the prediction results come out(in Figure.13).

***Step* 3: Residual Analysis:** this is to test if the error is acceptable, and all the residual here is lower than **0.1**, which means the error is acceptable.




(a) GPM Result of Genghis Khan Street Community

(b) GPM Result of Chasuqi Community)

Figure 13: Result of GPM

The article discusses the impact of implementing Strategies 1, 2, and 3 on light pollution in urban and rural communities over time. The study finds that Strategy 1 significantly reduced urban light pollution, while rural light pollution was affected to a lesser extent. Strategy 2 had a greater impact on household and industrial lighting in urban areas, and a significant decrease in rural light pollution was observed. Strategy 3 focused on publicity and education, and while it initially had a noticeable effect on both urban and rural light pollution, the long-term impact was subtle, with a significant decline in light pollution observed over time.

### 6.1.2 The Analytic Hierarchy Process(AHP)

The Analytic Hierarchy Process(AHP) is implemented to conprehensively consider LPI, economics(ecm), society(soc), eco-system(eco), and impacts of strategies(ios). AHP converts a complex multi-objective decision problem to a comprehensive sustainable development system Through hierarchical single-order ranking and total order ranking calculated by the fuzzy quantization method of qualitative indicators, the best control strategy of light pollution is determined.

The core of AHP is its scoring matrix, where its scores come from expert grading. Here the scoring matrix writes in the following tablet:

Table 3: scoring matrix

| | ECM | SOC | ECO | IOS | LPI |
|---|---|---|---|---|---|
| **ECM** | **1** | **2** | **1/4** | **1/4** | **1/5** |
| **SOC** | **1/2** | **1** | **1/3** | **1/5** | **1/3** |
| **ECO** | **4** | **3** | **1** | **3** | **1** |
| **IOS** | **4** | **5** | **1/3** | **1** | **1/4** |
| **LPI** | **5** | **3** | **1** | **4** | **1** |

Here we note an element in row $i$ and column $j$ as $a_{ij}$, so the weight can be measured as

$$\omega_i = \frac{1}{5}\sum_{j=1}^{5}\frac{a_{ij}}{\sum_{k=1}^{5} a_{kj}}$$

And the the **Comprehensive Strategy Score** is

$$S = \sum \omega_i s_i$$

Where $s_i$ is standardized value of the five we consider. After calculation, Comprehensive Strategy Score of each strategy of the two location are presented in the Table.4. From the CSS results, we can tell the most-effective strategy for Genghis Khan Street Community(urban) **Strategy 1**, and **Strategy 2** for Chasuqi Community(rural).

Table 4: Comprehensive Strategy Score Results

| | Genghis Khan Street Community | | | Chasuqi Community | | |
|---|---|---|---|---|---|---|
| | Strategy1 | Strategy2 | Strategy3 | Strategy1 | Strategy2 | Strategy3 |
| **ECM** | **3** | **2** | **1** | **2** | **2** | 1 |
| **SOC** | **2** | **1** | **5** | **1** | **1** | 4 |
| **ECO** | **3** | **5** | **2** | **3** | **5** | 3 |
| **IOS** | **5** | **3** | **1** | **4** | **5** | 2 |
| **LPI** | **0.281** | **0.449** | **0.321** | **0.399** | **0.269** | **0.363** |
| **CSS** | **0.879** | **0.764** | **0.632** | **0.621** | **0.735** | **0.598** |

## 6.2 Potential Impact of Selected Strategy For Locations

For Genghis Khan Street Community(urban), the most effective strategy to prevent light pollution is strategy 1, which includes diversified types of light sources, high brightness of light sources, and more public light sources (such as street lamps and buildings). Strategy 1 is to adjust light source types, use low-blue light devices, reduce light source intensity, and improve light source occlusion. The most effective effect is to target the main source of light pollution in urban areas.

For Chasuqi Community(rural), the most effective strategy to prevent light pollution is strategy 2. The sources of light pollution in rural areas are simple, mainly household light sources and flare light sources generated by fuel combustion in the field, while Strategy 2 focuses on household light sources and energy combustion to reduce the generation of household and fuel light sources, which just targets the treatment of the main sources of light pollution in rural areas. The influence effect is the most effective.

## 6.3 Sensitivity Analysis

In Task 4, Based on the grey prediction model, we simulated the change of LPI over time after the implementation of the light source improvement strategy. In this model, we assume that the light source improvement strategy mainly affects OIs, and the degree of influence is expressed by the trimming parameter a.To test the robustness of the model, we apply a change to the trimming parameter and check whether the adjustment of parameter a will have a great impact on the change of LPI.

As shown in, the proposed model is very robust to change points when a is greater than or equal to , which implies the value we selected is reasonable.

# 7 Srengths And Weakness

## 7.1 Strengths:

- The study employs a multi-dimensional approach that takes into account a range of factors that contribute to light pollution and its associated risks. By examining multiple variables and their relationships, the study is able to provide a more comprehensive understanding of the complex nature of the problem.
- The cross-disciplinary approach of the study is a major strength, as it draws on insights from multiple fields in order to develop a more nuanced understanding of the issue. By incorporating perspectives from ecology, sociology, statistics, ge-

Table 5: Results of Sensitivity Analysis

| Influence of a on change point detection | | | | | | |
|---|---|---|---|---|---|---|
| | | | | a | | |
| Value | 1% | 2% | 5% | 7% | 10% | 12% |
| LPI after 5 units of time | 0.6797 | 0.6234 | 0.5932 | 0.5689 | 0.5432 | 0.5198 |
| LPI after 10 units of time | 0.6423 | 0.6067 | 0.5135 | 0.4931 | 0.4794 | 0.4231 |
| LPI after 15 units of time | 0.5987 | 0.5543 | 0.3969 | 0.3578 | 0.3321 | 0.3019 |
| LPI after 20 units of time | 0.5478 | 0.4734 | 0.3446 | 0.3298 | 0.3109 | 0.2987 |
| LPI after 30 units of time | 0.5034 | 0.4567 | 0.2813 | 0.2783 | 0.2617 | 0.2561 |

ographic information science, and other disciplines, the study is able to develop a more comprehensive and integrated understanding of the phenomenon being studied.

- An additional strength of the study is its consideration of the broader societal and environmental implications of light pollution. By exploring the potential impacts on human health, wildlife, and the natural environment, the study highlights the need for a more holistic approach to addressing the problem.

## 7.2 Weakness:

- The data used in this study is relatively simple, which may not fully capture the complexity of the phenomenon being studied.
- The model employed in this study is also relatively simple, which may not accurately reflect the true relationship between the variables of interest.
- The applicability of the findings to policy making may be limited, as the study focuses on a specific context and may not be generalizable to other settings or populations.

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