

Measuring and Mitigating the Impacts of Light Pollution with EWM-TOPSIS Method

Summary

Light pollution is affecting our environment, biodiversity, biological clock, etc. Regarding this issue, we mainly need to solve three problems in our paper: establish a model to measure the light pollution, propose policies to reduce light pollution and evaluate the effectiveness of our policies.

First of all, we analyze the light pollution, and attribute it to night-light intensity. Then we select several indicators which are relevant to night-light intensity more or less, and got data from official web or database.

In order to build a model that can be applied to access the light pollution in all locations, we use selected indicators to reflect the night-light intensity to evaluate the light pollution. After determining the index system, we use the optimized **Entropy Weight Method(EWM)** to calculate the weights of indicators. Then, we use **Technique for Order of Preference by Similarity to Ideal Solution(TOPSIS)** to calculate the score of night-light intensity. We apply our model to four types of locations: urban communities, suburban communities, rural communities and protected land locations. In the application to 12 selected states, results are all in line with the reality.

Combining the results of our model and the reality of light pollution, we try to propose policies to reduce light pollution. Different policies varies greatly in different types of locations, so we take four types of locations into consideration and make three strategies in different aspects. The first one aims at technology to improve the efficiency of lighting, the second one aims at governor's regulations and the last one aims at improving residents' awareness of light pollution. Our policies aim to adjust selected indicators data, so it's operational and intuitive.

To evaluate the effectiveness of our policies, we select two positions: **California** and **New York** to implement our strategies. California is categorized as a suburban community and New York is categorized as an urban community. After exploring local situations, we made several tailored strategies relevant to the policies we addressed before. With our tailored strategy implementation, light pollution in both of them will be alleviated to some extend as shown in our model results.

Finally, we carry out a sensitivity analysis of the evaluation model, demonstrating the robustness of our models. We also write a flyer to the community officials and local groups in California to promote the strategy for the locals.

Keywords: Optimized Entropy Weight Method, TOPSIS, Light Pollution.

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1 Basic Introduction

1.1 Background

Light pollution is a term used to describe the excessive or inappropriate use of artificial light, which can take the form of light trespass, over-illumination, and light clutter. These phenomena are often visible as a glow in the night sky in large cities, but they can also occur in more remote areas. Light pollution affects our environment, health, and safety by altering our view of the night sky, delaying or accelerating plant maturation, disrupting wildlife migration patterns, and affecting our circadian rhythms. Excessive artificial light can lead to poor sleep quality and may contribute to physical and mental health problems, while glare from artificial lights can increase the risk of motor vehicle accidents.

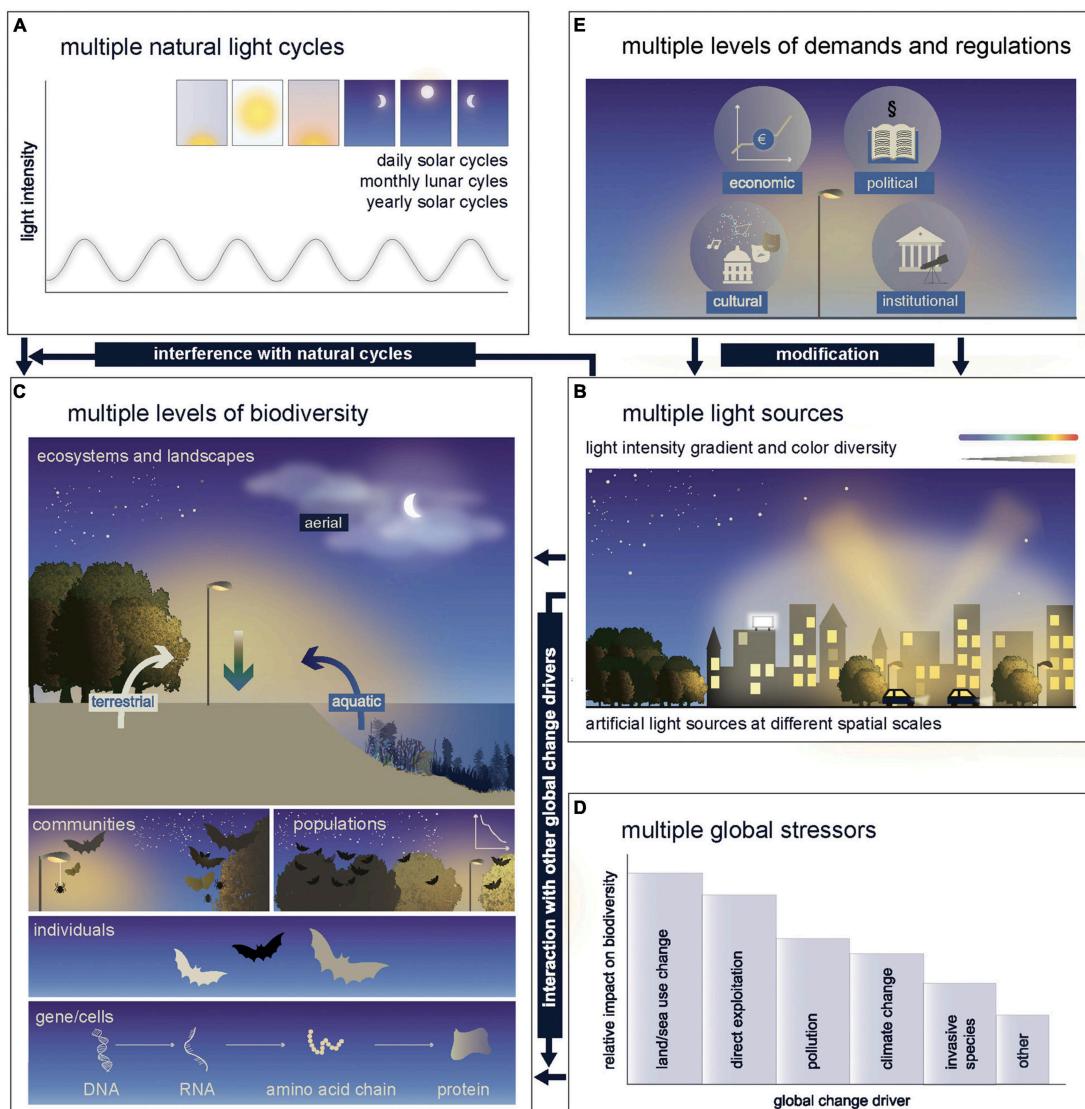


Figure 1: Artificial light at night: Potential sources, biodiversity impacts and responses are complex. Different natural light cycles (A) are affected by multiple forms of artificial light at night (B) at multiple levels of biodiversity in multiple realms (e.g. from bottom up: gene expression; phenotypes; population dynamics, e.g. decline; community composition; species dispersal and/or organismic fluxes across ecosystem boundaries and biomes) (C). Artificial light at night can interact with multiple global change stressors (D). Due to the potentially conflicting demands of artificial light at night a transition to a more sustainable use is extremely challenging and requires multiple levels of regulations (E) [1]

However, artificial light has both positive and negative impacts that can vary based on location. The effects of light pollution can depend on factors such as a location's level of development, population, biodiversity, geography, and climate. Therefore, assessing the extent of the effects and potential impacts of intervention strategies must be tailored to the specific location, and intervention strategies are needed to mitigate the negative effects of light pollution.

Light pollution is a serious problem with implications for wildlife, human health, scientific research, energy consumption, global warming, and the ageless pastime of observing the night sky. Pristinely dark skies are very scarce in the developed world and most of the world's population—and nearly all of those living in the EU or the US—live under skies with at least some light pollution[2].

For biodiversity studies, nocturnal light ideally would be measured in biologically relevant ways, based on thresholds and spectral sensitivities of the species, because different light sources interfere differently with the large diversity of sensory systems in nature[3].

1.2 Problem Restatement

- The indicators of the EWM-TOPSIS model should be determined, in other words, it is equal to build a broadly applicable metric for identifying the light pollution risk level.
- Apply the indicators and the related data to the EWM-TOPSIS model, then analyse the result in the four diverse types of locations.
- Design 3 possible strategies for addressing light pollution, and how the indicators change with the strategies.
- Select 2 locations, and implement the most effective intervention strategies for each of them. See how the indicators change and the impact of the chosen intervention strategy.
- Write a 1-page flyer to community officials or local groups in a specific location to promote the most-effective intervention strategy tailored for the location.

1.3 Our Works

First of all, we selected 12 states as evaluation objects and 9 indicators for the EWM-TOPSIS Model. Both benefit-attributed and cost-attributed indicators are taken into account. Then we use the Entropy Weight Method (EWM) to get the weight of indicators. After getting the weights, we use the TOPSIS method to determine the best option from a set of alternatives.

According to our model, we selected three aspects for policy making. We have tailored a government regulation policy for California and a combination of technology and residents' awareness policy for New York.

Finally, we use our model to evaluate the effectiveness of the policy. Considering various factors, we admit that change is difficult as our data shows.

The structure of our paper is as follows:

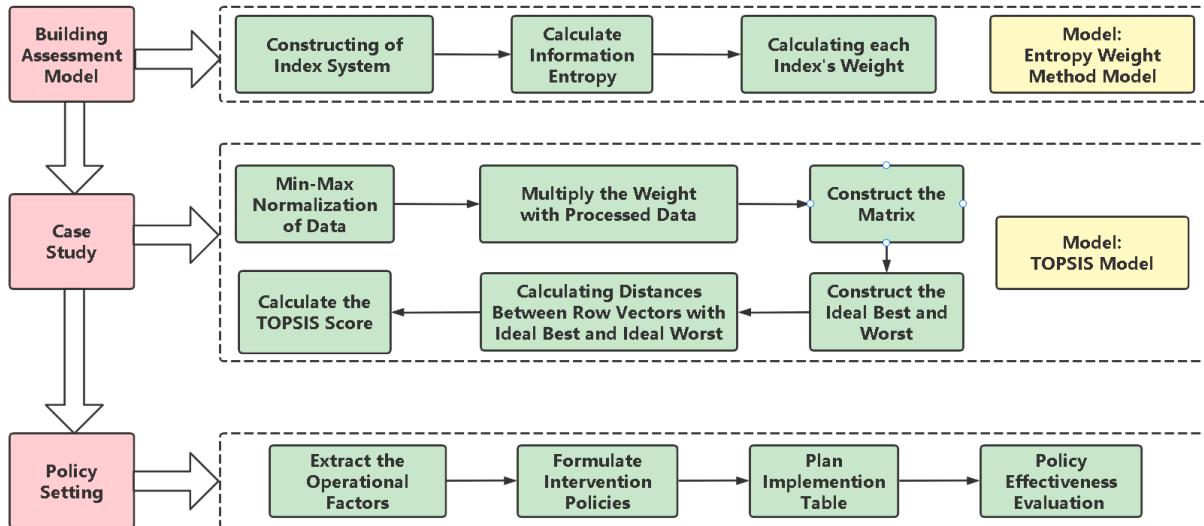


Figure 2: Our workflow.

2 Assumptions and Justifications

To simplify the problem, we make the following basic assumptions.

- Assume that all the light pollution is from night-time light, so we just need to consider night-time light intensity.

Justifications: According to the Wikipedia[4], the definition of light pollution is the presence of anthropogenic artificial light in otherwise dark conditions.

- Citizens will not reduce the basic consumption of living illumination for the purpose of reducing light pollution.

Justifications: To simplify the problem, we didn't take people's awareness of light pollution into account.

- Precipitation occurs in the day and night with equal probability and intensity.

Justifications: As we use year precipitation to evaluate the cloudiness of one location, and the light pollution occurs in the night-time, only rainy at night that the precipitation data is valid. So that the year precipitation can be comparable.

- Night-time light intensity is closely related with economics.

Justifications: According to fractional logit models[2], both population and GDP are significant explanatory variables, similar to other types of pollution.

- We ignored the differences of light colors.

Justifications: It's hard for us to get the using percentage of each light color.

3 Notations

Symbols used and their definitions are defined below(Table 1).

Table 1: Notations of symbols

Symbol	Description
a_{ij}	The value of the j-th indicator of the i-th city to be evaluated.
$A = (a_{ij})_{i \times j}$	Data matrix composed by a_{ij} .
p_{ij}	The proportion of the i-th evaluation objective to the j-th indicator.
e_j	The entropy value of the j-th indicator.
w_j	The weight of the j-th indicator.
b_{ij}	The data from a_{ij} after standard 0-1 transformation.
$B = (b_{ij})_{i \times j}$	The decision matrix composed by b_{ij} after processing.
$C = W * B$	The weighted-normalised decision matrix.
C_i	The i-th roll of the C matrix.
$C^* = [b_1^{max}, b_2^{max}, \dots, b_j^{max}]$	The positive ideal solution.
$C_0 = [b_1^{min}, b_2^{min}, \dots, b_j^{min}]$	The negative ideal solution.
s_i^*	The distance from C_i to the positive ideal solution.
s_i^0	The distance from C_i to the negative ideal solution.
f_i	The night-time light intensity of the i-th city.

4 The EWM-TOPSIS Model

4.1 Indicators of the Model

We selected 12 states in the USA as evaluation objects. As the night-time light intensity directly reflects the extent of light pollution, so it is regarded as the direct evaluation indicator, and we chose 9 indirect indicators as evaluation indicator variables to evaluate the night light level of the city. The value of the j-th index variable of the i-th city evaluated is a_{ij} , building a matrix $A = (a_{ij})_{12 \times 9}$.

The 12 states in the USA we selected are Massachusetts, New York, New Jersey, California, Pennsylvania, Washington, Nevada, Mississippi, Missouri, Wyoming, Montana, and Alaska. The first three states are taken as urban communities, the second three states are taken as suburban communities, the third three states are taken as rural communities, and the last three states are taken as protected land locations.

The 9 indirect indicators we selected are population density, night-time electricity consumption, per capita GDP, regional industrial structure, regional average working hours, the last bus time of public transportation, night life index, year precipitation, limiting magnitude, etc. Among these indicators, only the limiting magnitude is an objective indicator and cannot be changed.

To explain the selection of indicators, We divide the indicators into two categories. One is the benefit-attributed indicators. The larger the data index, the higher the night-time light intensity. The other is the cost-attributed indicators. The smaller the data index, the higher the

night-time light intensity.

For the benefit-attributed indicators, there are 7 indicators which are listed below.

1. **Population density.** With the increase of population density in a region, the illumination demand of this region's public space also increases, thus increasing the night-time light intensity.
2. **Night-time electricity consumption.** A large part of night-time electricity consumption is used for lighting, so it can also reflect the night-time light intensity to a certain extent, which is a benefit data.
3. **GDP per capita.** GDP per capita reflects the degree of local development. The more developed and prosperous the region, the more shopping malls and high-rise buildings in prosperous areas. And we believe the LED lights in shopping malls and the glass curtain walls of high-rise buildings lead to an increase in night-time light intensity, which may lead to the light pollution.
4. **Regional industrial structure.** The demand for illumination in various industries is different. The primary industry has little demand for light. Some industries in the secondary industry have requirements for light, and the tertiary industry service industry is extremely dependent on light to attract customers. So the industrial structure also has an impact on the local night-time light intensity, and we believe that the more the proportion of the tertiary industry, the higher the night-time light intensity is.
5. **Nightlife index.** Nightlife is a collective term for entertainment that is available and generally more popular from the late evening into the early hours of the morning. As long as nightlife prevails, the lighting demand increases. The higher the nightlife index of a region, the higher the night-time light level, which belongs to the benefit data.
6. **Year precipitation.** The more rainy days, the more precipitation, which also means the thicker clouds, thus increasing the reflectivity of light.
7. **The last bus time of public transportation.** The operation guarantee condition of ground public transportation is lighting, so the lighting will naturally increase during the traffic operation time. And also to some extent, the last subway train time is connected with the night-time living. The later the last bus is, the higher the night-time lighting level will be, so it belongs to the benefit data.

For the cost-attributed indicators, there are 2 indicators which are listed below.

1. **The average working hours in the region.** The earlier people leave work, the earlier the end of the evening commute. So the demand for high-beam lights will become less, and the demand for night lighting time will become less, so it will affect the level of night-time lighting.

2. **Limit magnitude.** Limit magnitude refers to the darkest magnitude that can be observed through a telescope. The higher the limit magnitude that can be seen, the lower the brightness on the ground, that is equal to lower level of illumination at night, so it belongs to the cost data.

4.2 Data Collection

We got our data from these websites listed below:

Table 2: Data Sources

Data	Source
Population density	Census.gov [5]
Power consumption	U.S. Energy Information Administration (EIA) [6]
GDP per capita	Bureau of Economic Analysis (BEA)[7]
Regional industrial structure	Bureau of Economic Analysis (BEA)[7]
Average working hours in the region	Business.org [8]
The last bus time of public transportation	Google Map [9]
Nightlife index	Google Trends [10]
Limit magnitude	DarkMap [11]
Average Annual Precipitation	CurrentResults.com [12]

4.3 The Optimized Entropy Weight Method (EWM)

We use the Entropy Weight Method (EWM) to get the weight of indicators. The Entropy Weight Method is an objective weighting method, which uses the information entropy idea for reference. It is used to determine the relative weights of different criteria in a decision-making process. It determines the weight of the indicators by calculating the information entropy of the index, according to the impact of the relative change of the index on the overall system.

In other words, the weight of each indicator is given according to the difference degree of the indicator value, and the corresponding weight of each indicator is obtained. The indicator with relatively large change degree has larger weight.

The greater the entropy, the more chaotic the system is, the less information it carries and the less weight it has. Otherwise, the higher the entropy, the more orderly the system is, the more information it carries, and the greater the weight is.

The first step of the Entropy Weight Method is the standardization of measured values. The standardized value of the j-th index in the i-th sample is denoted as p_{ij} , and its calculation method is as follows:

$$p_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}, i = 1, 2, \dots, 9, j = 1, 2, \dots, 9$$

Secondly, in the EWM, the entropy value e_i of the j-th index is defined as:

$$e_j = -\frac{1}{\ln(9)} \sum_{i=1}^n p_{ij} \ln(p_{ij}), j = 1, 2, \dots, 9$$

The range of entropy value e_j is $[0, 1]$. The larger the e_j is, the greater the differentiation degree of index j is, and more information can be derived. Hence, higher weight should be given to the index.

Therefore, in the traditional EWM, the calculation method of weight is:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^m e_j}, j = 1, 2, \dots, 9$$

It can be seen from the above equation that when $e_j \rightarrow 1$, the difference in the entropy value of different evaluation indexes is small, but the difference in the entropy weight is large. Therefore, we use the following equation to calculate entropy weight instead of traditional equation.

$$w'_j = \frac{1 + e_j + \sum_{k=1}^n e_k}{\sum_{l=1}^n (1 - 2e_l + \sum_{k=1}^n e_k)}$$

In the above method, the different entropy weights for different indicators (e.g. p and q) become

$$\Delta w = 2\Delta e/C$$

where

$$\Delta e = e_p - e_q, C = \sum_{l=1}^n (1 - 2e_l + \sum_{k=1}^n e_k)$$

It indicates that the entropy value changes slightly, and its corresponding entropy weight also changes slightly. For the factor with equivalent useful information, the weight information is consistent with the corresponding entropy level.

Table 3: Weights of the Indicators Calculated from optimized EWM method

Indicators	Weights
All industry total	0.12709
All tertiary industry percentage	0.12376
Population Density	0.12742
Limiting Magnitude	0.12390
Last Bus Time	0.12436
Power Consumption per Capita per Month	0.12378
Annual Precipitation(in millimetre)	0.12411
Working hours per Week	0.12581
Nightlife index	0.12402

4.4 The TOPSIS Method

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision-making method that is used to determine the best option from a set of alternatives based on multiple criteria.

First of all, we use Min-Max normalization to process the data.

For the benefit-attributed data,

$$b_{ij} = \frac{a_{ij} - a_j^{\min}}{a_j^{\max} - a_j^{\min}}$$

And for the cost-attributed data,

$$b_{ij} = \frac{a_j^{\max} - a_{ij}}{a_j^{\max} - a_j^{\min}}$$

All these data form the normalized matrix B . We then multiply each value in a column with the corresponding weight given, and get weighted-normalised decision matrix, which

$$C = W * B$$

Secondly, calculating the positive ideal solution C^* and the negative ideal solution C_0 , which

$$\begin{aligned} C^* &= [b_1^{\max}, b_2^{\max}, \dots, b_9^{\max}] \\ C_0 &= [b_1^{\min}, b_2^{\min}, \dots, b_9^{\min}] \end{aligned}$$

Now we need to calculate Euclidean distance s_i^0 for elements in all rows from the positive ideal solution and the negative ideal solution.

$$s_i^0 = \sqrt{\sum_{i=1}^{12} (b_{ij} - C_i^*)^2}, j = 1, 2 \dots, 9$$

Here, s_i^* is the best distance calculated on the i-th row, where b_{ij} is element value and C_i^* is the ideal best for that column. Similarly, we can find s_i^0 , which is the worst distance calculated on the i-th row.

Finally, calculate the TOPSIS Score and Ranking. For $C_i, i = 1, 2, \dots, 12$, solve s_i^* , the distance to the positive ideal solution C^* , and s_i^0 , the distance to the negative ideal solution C_0

Now that we have s_i^* and s_i^0 . Then calculate the Topsis score for each row, and get the final score and ranking.

$$f_i = \frac{s_i^0}{s_i^* + s_i^0}$$

4.5 Application of the Model on the Four Locations

4.5.1 A Protected Land Location: Wyoming

For a protected land location, we choose Wyoming. Wyoming is a state in the Mountain West subregion of the Western United States. Almost half of the land in Wyoming is owned by the federal government, generally protected for public uses.

Wyoming is the least populous state despite being the 10th largest by area, with the second-lowest population density after Alaska. And it's population density is 5.9 men per km^2 . Since

the sparse population, its GDP is only 41510.2 million dollars per year. Without much demand for transportation, its local bus deadline is 5 p.m., which largely reduce its demand for road illumination. The nightlife index is only 37, which reason is closely related to the indicators above. This may account for the low power consumption, which is only 128.9 kWh.

Today, Wyoming's economy is largely based on tourism. So its tertiary industry percentage of GDP is similar to New York, which is one of the most prosperous city in the world. And the detailed data for tertiary industry percentage of GDP is 0.247. To support its tourism, people should work for more hours, so we can see its working hour is 40.3 hours per week.

Due to its geographical position, its annual precipitation is 390 millimeters. And with its vast land, the limiting magnitude in Wyoming is 8.3, which means you can see several faint planet.

According to the indicators we mentioned before, its night-light intensity score in our model is 0.18786, which ranks the lowest in our selected locations. This shows that our model's application for protected location is in line with the reality.

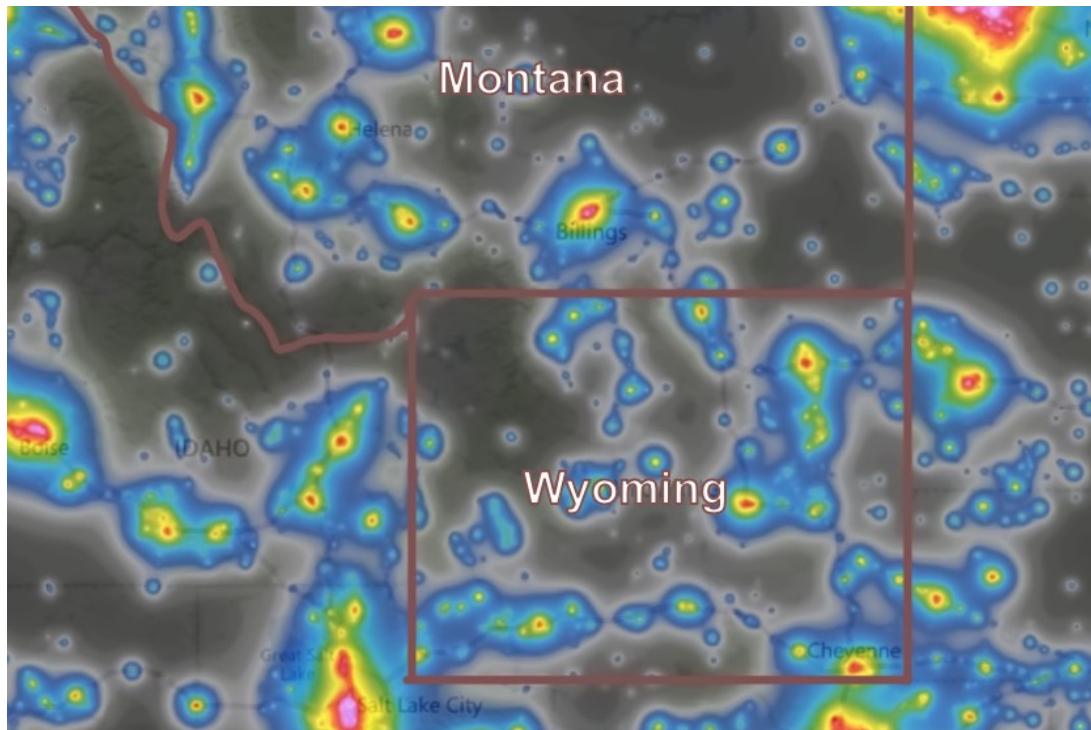


Figure 3: Night-time Light Intensity of Wyoming

4.5.2 A Rural Community: Nevada

For a rural community, we choose Nevada. Nevada is the 7th-most extensive, the 32nd-most populous, and the 9th-least densely populated of the US states. Its population density is 28.3 men per km^2 . And its working hour belongs to the average level in US.

As we all know, Las Vegas is located in Nevada. This may account for its night-life index of up to 70. Nevada's power consumption is 362.8 kWh per month, far more than protected locations, but similar to other locations.

Legalized gambling and lenient marriage and divorce laws transformed Nevada into a major tourist destination in the 20th century, which promote local economy. Its GDP is 194486.6 per year and its tertiary industry percentage of GDP is 0.284. The early deadline of bus is mainly because of tourism. Its local bus deadline is 3 p.m.

Nevada is the driest state, and its annual precipitation is 241 millimeters. Its limiting magnitude is 8.3, which means you can rarely see faint planet.

According to the indicators we mentioned before, its night-light intensity score in our model is 0.38081, which ranks above all the protected locations in our selected locations, but below all the more prosperous states. This shows that our model's application for rural community is in line with the reality.

4.5.3 A Suburban Community: California

Although California is full of modern metropolises such as Los Angeles and San Francisco, we categorize it as a suburban community, since most area of California is not cities but suburban areas and hilly areas.

California is the third-largest state by area, and more than this, it also has a high population density of 253.7 men per km^2 , resulting in the most populated state in the U.S.

Due to its huge population, the economy of California is no doubt the largest in the United States. Its GDP is 3373240.7 per year, far more than any other state, and it's night-life index is 65. It's working hour is 38.3 hours per week, similar to other states.

Sacramento is the state's capital, while Los Angeles is the most populous city in the state and the second most populous city in the country. So it has the highest power consumption among suburban communities, which values 394.2. And it also has the latest deadline of local bus, which is 11:30 p.m.

California has a Mediterranean climate, depending on latitude, elevation, and proximity to the Pacific Coast. Its terrain varies widely from hot desert to alpine tundra. The average annual precipitation is 563 millimeters. And its limiting magnitude is 6, which means it's hard for you to see the stars by eyes.

According to the indicators we mentioned before, its night-light intensity score in our model is 0.59146, highest in the suburban locations, but lower than Massachusetts and New York. It clearly reflects the high density of the suburban regions of California, and the result is in line with the reality.

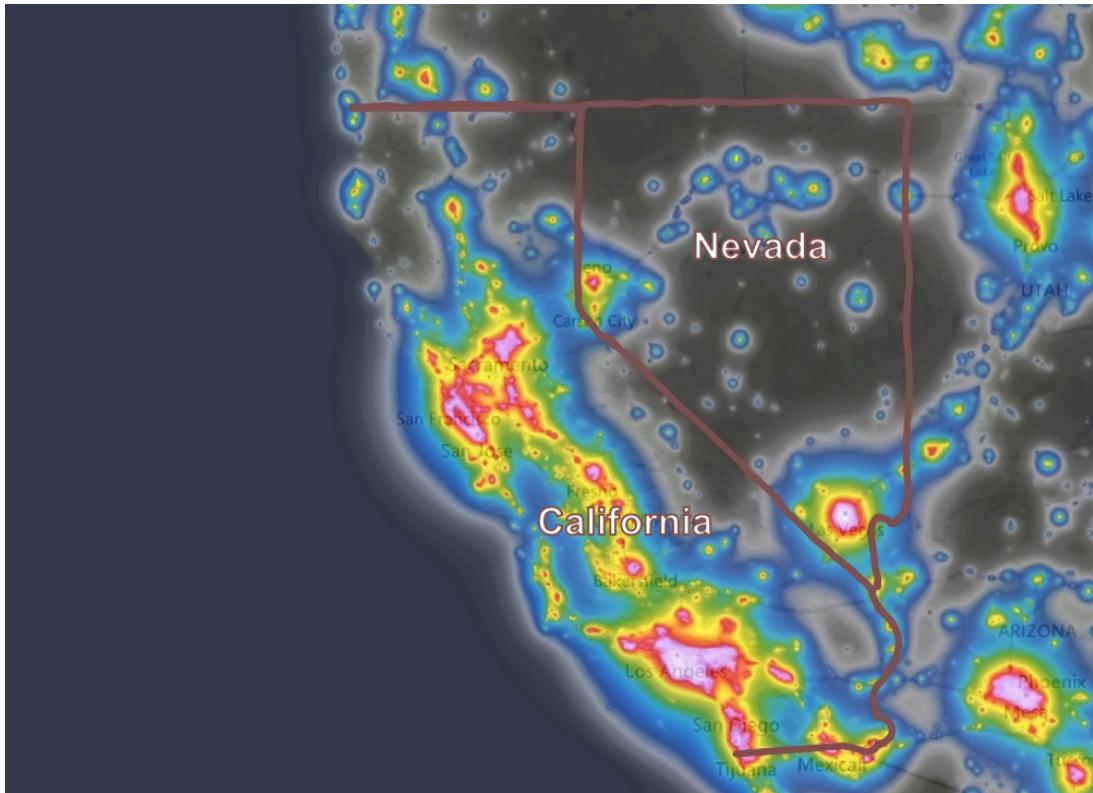


Figure 4: Night-time Light Intensity of California and Nevada

4.5.4 An Urban Community: New York

New York State is a highly developed state with a world famous international metropolis, New York. State of New York was one of the original Thirteen Colonies forming the United States. With a total area of 54,556 square miles ($141,300 \text{ km}^2$), New York is the 27th-largest U.S. state by area. But also, it is the fourth-most-populous state in the United States as of 2021, with 20.2 million people.

Due to its great importance in USA's and international economy, it's GDP is 1901296.5 million dollars per year. And in serving its highly developed service industry, it's local bus deadline is 1 a.m, and the nightlife index is 83, ranks the top of the chosen locations. And this leads to a huge power consumption, which is 412.8 kWh.

Since New York is famous for its economy, its tertiary industry percentage is the highest among the chosen locations. And it seems that people in New York States enjoys their life, as their average working hour is 38.4 hours per week.

New York State has a temperate continental humid climate, with an annual precipitation 1062 millimeters. And with its well-explored land, the limiting magnitude in New York State is 4, which means you can seldom see faint planets.

According to the model, New York State night-light intensity score is 0.69031, which ranks the highest in all, in line with the reality.

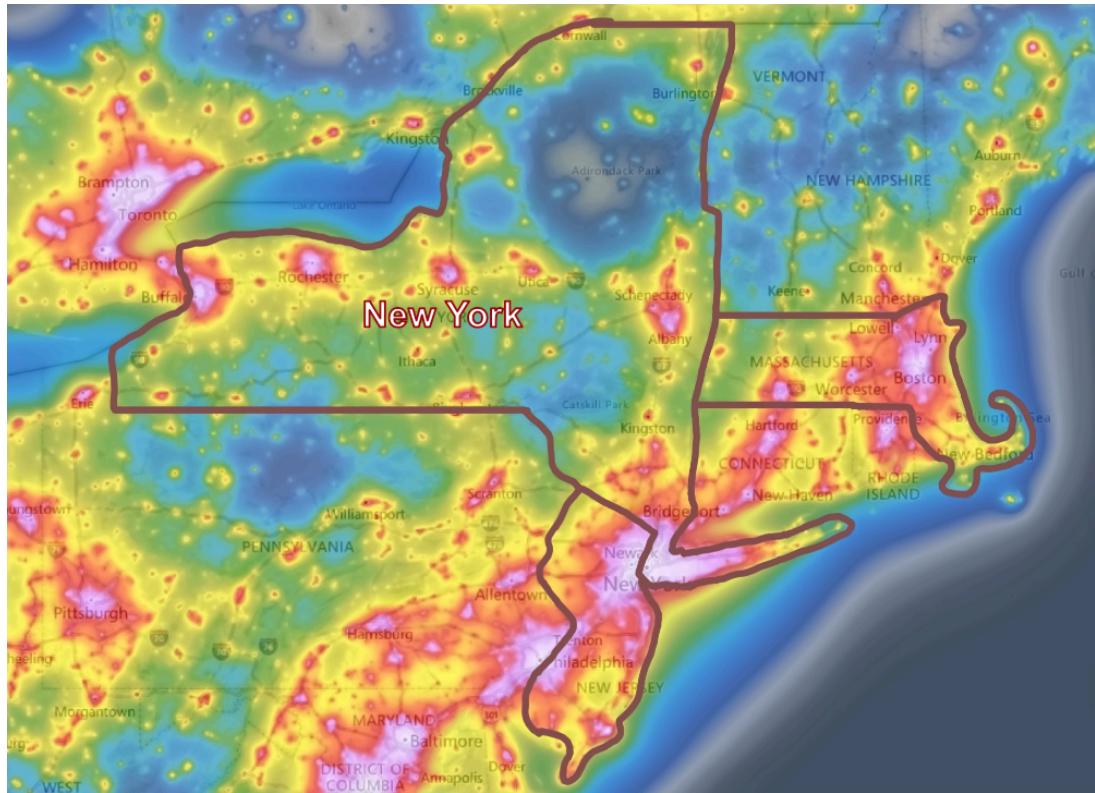


Figure 5: Night-time Light Intensity of New York State

4.5.5 Result of the TOPSIS Score and Ranking

The result of the TOPSIS Score and relative ranking are listed in the chart below. And we drew a map to get a better looking.

Table 4: Result of the TOPSIS Score and Ranking

Types of Locations	States	Score	Ranking
Urban Communities	New York	0.69031	1
	Massachusetts	0.60754	2
	New Jersey	0.59492	3
Suburban Communities	California	0.59146	4
	Pennsylvania	0.48859	5
	Washington	0.40662	6
Rural Communities	Missouri	0.40527	7
	Nevada	0.38081	8
	Mississippi	0.36775	9
Protected Land Locations	Montana	0.34936	10
	Alaska	0.21363	11
	Wyoming	0.18786	12

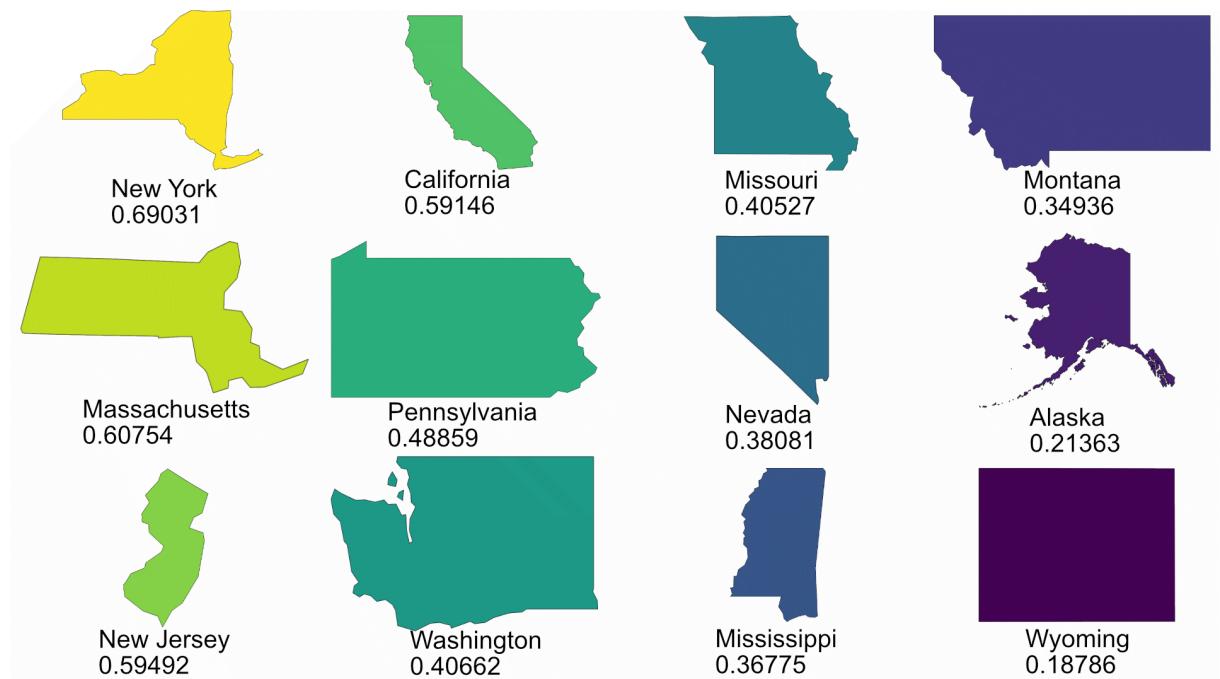


Figure 6: Result of the TOPSIS Score and Ranking

5 Strategy Making and Implementation

5.1 Strategies for Addressing Light Pollution

According to the problem 3, to address light pollution, we designed three possible intervention strategies as follows.

5.1.1 Lighting Design and Technology Innovations

Lighting design and technology play a crucial role in reducing light pollution. Poor lighting design and the use of outdated lighting products can result in excessive glare, sky glow, and light trespass, which can disrupt ecosystems and interfere with human sleep cycles. Our goal is to promote research and development of new lighting technologies that are designed to minimize light pollution while still meeting lighting needs. Here are some actions that can be taken into account.

- 1. Develop and implement smart lighting technologies that reduce light pollution and save energy.**
 - Install sensors that adjust lighting levels based on natural lighting conditions, such as sunlight and moonlight.**
 - Install motion sensors and timers to reduce the amount of unnecessary outdoor lighting.**
 - Develop and deploy smart city technologies that optimize lighting efficiency and minimize light pollution in public spaces.**

2. Use directional lighting that illuminates only the areas that need to be lit, rather than casting light in all directions.

Directional lighting can be used in landscape lighting to highlight specific features, such as trees or statues, while minimizing light pollution and unwanted glare. This creates a more visually appealing and sustainable lighting solution for outdoor spaces.

- **Use lighting fixtures that direct light downward, reducing sky glow and light trespass.**
- **Use shielding to direct light only where it is needed.**

3. Avoid blue-rich white light sources at night.

Blue-rich white light sources are also known to increase glare and compromise human vision, especially in the aging eye. These lights create potential road safety problems for motorists and pedestrians alike.

These actions not only help protect the environment, but also save energy and reduce the cost of outdoor lighting.

We hope these regulations and policies can make influence to these indicators:

- **Power Consumption per Capita per Month.** Using the state-of-art lighting designs and technologies, power consumption can be reduced for sure.
- **All tertiary industry percentage.** The emphasis on lighting design and technology researches can bring up the secondary industry percentage while slightly reduce the percentage of tertiary industry.

5.1.2 Government Regulations and Policies

Government regulations and policies can help reduce light pollution in a more compulsory way, and lead a environment-friendly social trend. Among the policies listed below, the dark-sky-areas-related plans take a big part, and also are easier and better for government to realize the idea to some extent.

1. **Establish lighting standards that require businesses and homeowners to use lighting fixtures that minimize light pollution.**
2. **Develop and enforce outdoor lighting regulations that reduce glare, sky glow, and light trespass.**
3. **Encourage the use of energy-efficient lighting through tax credits and rebates.**
4. **Establish and designate dark-sky areas that are free of artificial light pollution.**

Dark-sky areas are becoming less and less because of human expansion. The dark-sky-area plan can be regarded as one of the most practical and considerable plans in consideration of human development and urbanization.

There are many actions can be taken for the dark-sky area plan. For example,

- **Implement and enforce regulations that prohibit outdoor lighting in designated dark-sky areas.**
- **Encourage the use of low-intensity lighting in dark-sky areas to minimize light pollution while still providing visibility.**
- **Work with community leaders, landowners, local organizations, and stakeholders to establish dark-sky areas and develop sustainable tourism opportunities around them.**

We hope these regulations and policies can make influence to these indicators:

- **Limiting Magnitude.** As time goes on, with the regulations and policies taken place, the limit magnitude can certainly witness a significant improvement.
- **Population Density.** With more and more dark-sky areas open to the public, we hope it will promote rural area travelling, while decreasing population density.
- **Working hours per Week.** Same as the population density, people can possibly have more time of leisure and enjoy the beautiful night sky.

5.1.3 Promoting Responsible Lighting Practices

Promoting responsible lighting practices raises awareness about the negative impacts of excessive lighting and encourages individuals and organizations to take action and develop awarenesses of sustainable action series. Through these actions, we hope it can help create more sustainable and livable communities for all.

1. **Implement lighting ordinances and regulations for outdoor lighting to reduce unnecessary and excessive lighting.**
2. **Promote the use of energy-efficient lighting technologies such as LED lights that reduce energy consumption and light pollution.**
3. **Encourage homeowners and businesses to turn off non-essential lighting during late-night hours to reduce light pollution.**
4. **Propagandize and educate the public on responsible lighting practices and the negative impacts of light pollution, and develop awarenesses of action.**

We hope these regulations and policies can make influence to these indicators:

- **Nightlife index** We hope the consciousness of action can be turned into less night-time illumination for nightlife. People can spend more time in less illuminated activities at home or outside.
- **Working hours per Week** Work more at daylight time and reduce the working hours in general.
- **Last Bus Time** As the working hours have been moved up, we expect the last bus time can be moved up as well.

5.2 Tailored Strategy Implementation

We chose California and New York for the following tailored strategy making, for California represents the biggest suburban area and New York represents the metropolis.

5.2.1 California: Government Regulations and Policies

California has a extremely diverse geography ranges from the Pacific Coast and metropolitan areas in the west to the Sierra Nevada mountains in the east. Although the San Francisco Bay Area and the Greater Los Angeles Area are widely seen as the centers of California, and it also has a high intensity of night-time light, California still has a large area which are perfect for developing dark-sky parks and conservation areas. California also has the largest number of national parks in the United States.

It is suitable for local governments implementing regulations and polices. Here are our tailored strategies for California and our expected result changes in the indicators.

1. **Take the advantage of large amount of national parks, develop dark-sky conservation areas and high-quality dark-sky national park tourism.**
2. **Enforce outdoor lighting regulations that prohibit strong lighting around the conservation areas.**
3. **Encourage the use of energy-efficient lighting through tax credits and rebates.**

We assume the indicators changes as follows

- **Limiting Magnitude.** Increase from 6 to 7.
- **Population Density.** Decrease from 253.7 to 252.
- **Working hours per Week.** Decrease from 38.3 to 37.7.

And the score decreased from 0.59146 to 0.58023, which stands for a great improvement.

5.2.2 New York: Technology Innovations and Practice Promotions

New York's Gross domestic product (GDP) in 2022-Q2 was US\$2.0 trillion. If the State of New York were an independent nation, it would rank as the 11th largest economy in the world. With its sound financial base, it's easy for New York State to implement technology innovation and practice promotion actions.

Here are our tailored strategies for New York State and our expected result changes in the indicators.

1. **Design glass curtain wall of the skyscrapers in New York properly to direct light downward, reducing sky glow and light trespass.**

2. **Install motion sensors and timers to reduce the amount of unnecessary outdoor lighting.**
3. **Encourage homeowners and businesses to turn off non-essential lighting during late-night hours to reduce light pollution.**

We assume the indicators changes as follows

- **Power Consumption per Capita per Month.** Decrease from 412.8 to 400.
- **All tertiary industry percentage.** Decrease from 0.387 to 0.36.
- **Nightlife index.** Decrease from 83 to 70.

And the score decreased from 0.69032 to 0.68076, which stands for a good improvement while not affecting normal production and living activities.

6 Sensitivity Analysis

We chose California to test the sensitivity of our model. We selected two indicators, regional industrial structure and limit magnitude, which are cost-based and benefit-based, to test the sensitivity of our model.

1. Regional industrial structure

California's regional industrial structure is 0.2229. We have studied the change of California's light-light intensity when the regional industrial structure changes from 0.20 to 0.25. From the chart, we can see that the night-light intensity of California is 0.59146 at this time. When the regional industrial structure changes to 0.20, the night-light intensity decreases to 0.58000, and the relative change rate is 1.94%. The relative change rate from 0.2229 to 0.20 is 10.3%, and the ratio of the two relative change rates is 0.188. When the regional industrial structure changes to 0.25, the night-light intensity increases to 0.60490, and the relative change rate is 2.27%. The relative change rate from 0.2229 to 0.25 is 12.2%, and the ratio of the two relative change rates is 0.186. Therefore, we can see that our model will not deviate greatly due to the deviation of the regional industrial structure.

And we can see continuous night-time light intensity changes with regional industrial structure as the following figure.

2. Limit magnitude

California's limit magnitude is 6. We have studied the change of California's light-light intensity when the limit magnitude changes from 5 to 7. From the chart, we can see that the night-light intensity of California is 0.59146 at this time. When the limit magnitude changes to 5, the night-light intensity decreases to 0.59908, and the relative change rate is 1.29%. The relative change rate from 6 to 5 is 16.7%, and the ratio of the two relative change rates is 0.08. When the limit magnitude changes to 7, the night-light intensity increases to 0.58320, and the relative change rate is 1.40%. The relative change rate from 6 to 7 is 16.7%, and the ratio of

the two relative change rates is 0.08. Therefore, we can see that our model will not have a large deviation due to the deviation of Limit Magnitude.

And we can see continuous night-time light intensity changes with limit magnitude as the following figure.

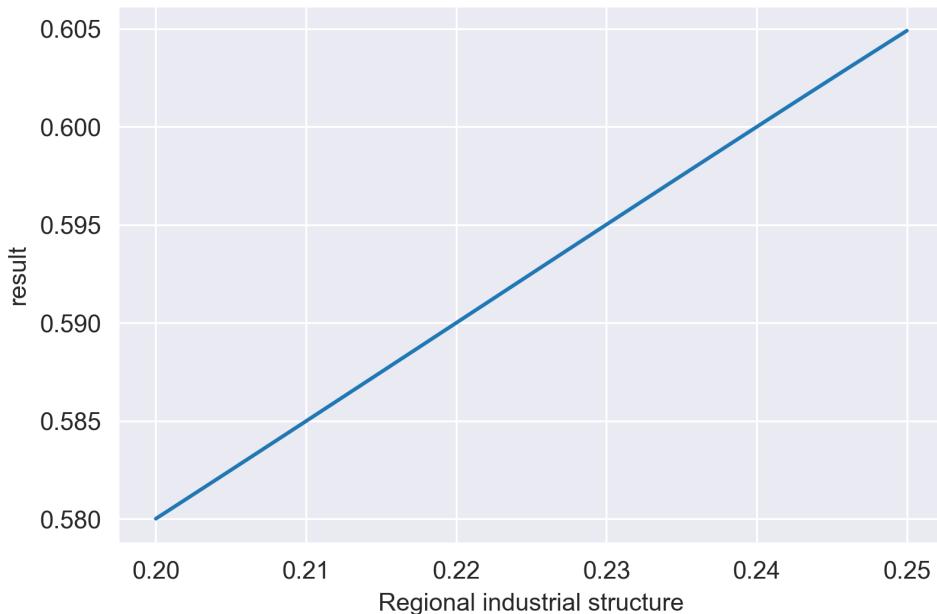


Figure 7: Night-time Light Intensity Changes With Regional Industrial Structure

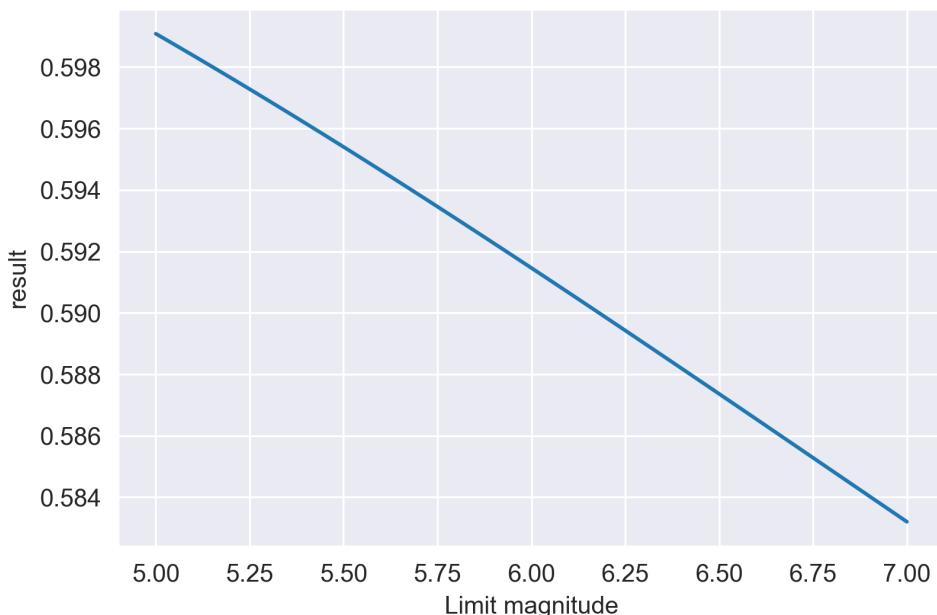


Figure 8: Night-time Light Intensity Changes With Limit Magnitude

7 Strengths and Weaknesses

7.1 Strengths

- The selection of evaluation indicators is scientific and comprehensive. We get the data from The U.S. Bureau of Economic Analysis and other scientific databases. We also make necessary modifications to better address our purpose, including involving the education context and adjust specific indicators.
- It's convenient for governor to propose strategy based on our model. Since our indicators are specific and operational, governors can propose targeted strategies.
- We used optimized EWM to calculate the weight instead of traditional EWM, which overcomes shortcoming of unrealistic weights.
- Comprehensive application of multiple methods. We use relatively objective methods - EWM to identify the weights of the multiple indicators. Then, we use TOPSIS to calculate night-light intensity of each location. The combination of multiple methods has constructed a scientific evaluation system.
- The evaluation model is robust. We did a sensitivity analysis on the night-light intensity. We made several indicators fluctuate in a small range and found that the list of locations' night-light intensity did not change significantly, indicating that our evaluation model has high stability. Weaknesses:

7.2 Weaknesses

- The model does not consider differences between light colors. Based on several researches of light pollution, specific use of light color can reduce light pollution in some extend.
- We didn't get the specific data of how much consumption is on lighting, so we use another index to instead. But the indicator of Power Consumption per Capita per Month just reflects residents' usage on lighting in some extend.

8 Conclusion

In this paper, we proposed a detailed model in order to analyze the light pollution objectively. We selected 9 indicators to establish our optimized EWM-TOPSIS method and it is realistic in our 12 selected locations, and we make some strategies based on our indicators. Our strategies aims at three aspects: technology, regulation and residents' awareness. Moreover, we address our strategies into two states and show significant effect.

In the future, with development of technology, comprehensive regulation and awareness of light pollution, the light pollution will become controllable.

9 Flyer

Touch the stars

Join Us! Reducing Light Pollution in California!

Did you know that California has long been suffered from light pollution? Not only does this ruin the beauty of the night sky, but it also harms our wildlife and wastes energy.

But there's something we can do about it! Join us in reducing light pollution and preserving the natural wonder of California !

What is Light Pollution?

Light pollution is the excessive use of artificial light that interferes with natural darkness. This includes streetlights, buildings, and other sources of light that shine upward into the sky.

Why is Light Pollution a Problem?

Light pollution has a negative impact on the environment, wildlife, and human health. It can disrupt the sleep patterns of animals and humans, affect migratory patterns, and even alter ecosystems.

How to Reduce Light Pollution:

- Turn off unnecessary lights when not in use.
- Use more energy-efficient lighting such as LEDs to save power.
- Avoid using blue-rich white light sources at night.
- Take part in high-quality dark-sky national park tourism, enjoy the beautiful night sky!

Visit our website to learn more about reducing light pollution and ways you can get involved in our efforts !

References

- [1] Höller F, Bolliger J, Davies T W, et al. 11 Pressing Research Questions on How Light Pollution Affects Biodiversity [J/OL]. *Frontiers in Ecology and Evolution*, 2021, 9. <https://www.frontiersin.org/articles/10.3389/fevo.2021.767177>.
- [2] Gallaway T, Olsen R N, Mitchell D M. The economics of global light pollution [J/OL]. *Ecological Economics*, 2010, 69 (3): 658–665. <https://www.sciencedirect.com/science/article/pii/S0921800909004121>.
- [3] Davies T W, Bennie J, Inger R, et al. Artificial light pollution: are shifting spectral signatures changing the balance of species interactions? [J]. *Global change biology*, 2013, 19 (5): 1417–1423.
- [4] Light pollution - Wikipedia. https://en.wikipedia.org/w/index.php?title=Light_pollution&oldid=1138318392.
- [5] Bureau U C. Historical Population Density Data (1910-2020). <https://www.census.gov/data/tables/time-series/dec/density-data-text.html>.
- [6] U.S. Energy Information Administration. <https://www.eia.gov/electricity/data.php>.
- [7] Bureau of Economic Analysis, U.S. Department of Commerce. <https://www.bea.gov/data/gdp/gdp-state>.
- [8] The Most Overworked States in the US, 2020. <https://www.business.org/hr-workforce-management/most-overworked-states>.
- [9] Google Map. <https://www.google.com/maps/>.
- [10] Google Trends - Nightlife. <https://trends.google.com/trends/explore?geo=US&q=nightlife>.
- [11] DarkMap. <https://darkmap.cn/>.
- [12] Average Annual Precipitation by State. <https://www.currentresults.com/Weather/US/average-annual-state-precipitation.php>.