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Article

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Posted Date: October 17th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7241526/v1

Additional Declarations: No competing interests reported.

Analysis of Urban Nighttime Light Attenuation Characteristics Based on Dark Sky Conservation Areas

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Abstract: The widespread use of nighttime lighting has led to the continuous expansion of the areas influenced by artificial light, resulting in a rapid depletion of natural night sky resources unaffected by artificial light interference. This paper reviews the development of dark sky protection movements worldwide, summarizes key organizations and types of initiatives in dark sky conservation and analyzes the current distribution and quantity of designated dark sky places across various regions. To study the attenuation characteristics of artificial nighttime light from urban areas to surrounding environment under ideal conditions, research selects concentric circle pattern for on-site monitoring from the city center of Jinzhong, to Taihang Conservation Area for Dark and Starry Sky. It is found that the area affected by nighttime light pollution from the city center far exceeds urban area. The degree of exposure to nighttime light pollution is decreasing continuously as the distance from the city center increases. In Taihang Conversation Area, which is 68km away from the city center, the magnitude brightness value reaches 21mag/arcsecond² and can be regarded as unaffected by artificial light. The study can provide data reference for the development of urban light pollution policy and further light pollution prevention in protected areas.

Keywords: Dark sky protection, light pollution, urban nighttime environment, night sky brightness

Introduction

Dark sky resources refer to the natural night sky free from nighttime artificial light pollution. Natural darkness is crucial for preserving biodiversity and ecological integrity, conducting astronomical observations and scientific research, safeguarding night sky cultural heritage, and promoting sustainable urban development[1]. The emergence of artificial light has allowed us to utilize the night more efficiently, extending the time available for work and leisure. However, with rapid urbanization, unrestricted lighting planning has led to the continuous expansion of artificial light at night, spreading into natural areas[2]. Light pollution caused by artificial nighttime illumination leads to a continuous increase in skyglow, making unpolluted night skies a rare resource[3]. This has affected the whole natural world including human beings. To limit the impacts of light pollution and raise public awareness, DarkSky International, previously known as International Dark-Sky Association (IDA), first launched the International Dark Nights Places (IDSP) program. Over the years, the association has accumulated significant experience and provided valuable references in light pollution prevention[4], outdoor lighting planning and management[5], and the operation of astronomical tourism[6].

In the 1970s, the International Astronomical Union (IAU) conference addressed the growing concern over the increase in nighttime sky brightness due to widespread artificial light usage[7]. DarkSky International defines light pollution as the pollution caused by artificial light sources that alter outdoor light levels and deviate from naturally occurring light levels, leading to glare, skyglow, light trespass, and clutter[8]. With the publication of the New World Atlas of Artificial Sky Brightness, it was discovered that over 80% of the world's population and over 99% of the populations in 2016 in the United States and Europe, were living under light-polluted skies, with more than a third of the population unable to see the Milky Way[9]. The expansion of the use of artificial light has rapidly diminished the natural night sky[10]. Not only can stars not be observed in urban skies, but even suburban areas far from cities are affected by excessive urban lighting, causing the night sky to be too bright[11]**.** The U.S. National Park Service has systematically surveyed the night sky quality of about 100 parks since 2001, finding that almost every measured park has some degree of light pollution (Service 1988). Kyba et al. analyzed DMSP satellite radiation measurement data from 2012 to 2016, showing that artificial outdoor lighting increased by an average of 2.2% per year[12]. It can be said that the Earth's nights are getting brighter, and the overall brightening of the night sky caused by artificial light is affecting the entire natural world, including humans.

At the same time, more studies have shown that light pollution caused by excessive lighting can cause harm to astronomical observation[13], resource consumption[14], human health and safety[15,16] ecological environment[17] and other aspects. In astronomy, since the last century, observatories have had to relocate due to light pollution interference, such as the Greenwich Observatory, the Purple Mountain Observatory in Nanjing, and the Sheshan Observatory in Shanghai. Currently, to prevent light pollution, the observatories would make strict regulations to control nighttime lighting in surrounding areas, ensuring good astronomical observation conditions. In terms of energy, the current global share of indoor and outdoor electricity consumption is about 17-20%[18]. Excessive lighting increases electricity use and carbon dioxide emissions, causing energy waste and contributing to global climate change. Long-term exposure to bright artificial lighting at night (disrupting circadian rhythms) can negatively impact human physical and mental health, increasing the risks of insomnia[19], obesity[20], cancer[21], and more. Since organisms on Earth are accustomed to living on a 24-hour circadian rhythm, the expanded range of nighttime artificial light may have adverse effects on biosphere organisms, including plants[22], invertebrates[23], birds[24,25] and others, thus causing disturbances to biodiversity and ecosystem balance[26].

The influence of nighttime lighting continues to expand, challenging the ecosystems of protected areas. Gaston et al. used calibrated global satellite nighttime light data to analyze the dark sky of the protected and unprotected areas on 6 continents (excluding Antarctica) [27]. Liangxian et al. used nighttime light data from 1992 to 2013 to analyze 7 types of protected areas worldwide, finding that nighttime light values in all protected areas and their surrounding buffer zones showed an increasing trend[10]. Benyan Jiang et al. used nighttime light remote sensing data from 2000 to 2018 in Guangdong Province's protected areas, to analyze the correlation between light pollution and human activities and the sensitive distance of light pollution[28]. However, most studies on nighttime light pollution in protected areas use nighttime remote sensing data, and ground-based measurements were not used. In reality, skyglow can amplify the impact of artificial light and can disrupt natural ecosystems through various mechanisms[29]. Therefore, this study selects the measured skyglow data along the route from the center of Jincheng City in Shanxi Province to Taihang Conservation Area for Dark and Starry Sky, analyzes the characteristics of night light attenuation under natural conditions, and explores the sensitive areas and protection scope of light pollution in existing protected areas under natural conditions.

1. Analysis of Dark Sky Protection

1.1 Development of Dark Sky Protection Initiatives

After recognizing the harmful effects of light pollution, astronomers and enthusiasts launched the Dark-Sky Movement, advocating for actions to reduce the adverse impacts of light pollution. Since the late 1980s, DarkSky International, one of the earliest organizations to initiate dark sky protection efforts, has been dedicated to raising public awareness of light pollution and curbing its growth through the development of reasonable outdoor lighting standards (International). In 2001, to encourage the restoration of the nighttime environment, the association launched a certification initiative for dark sky places in collaboration with communities, parks, municipal authorities, and the public. At the first International Starlight Conference in April 2007, the "Starlight Declaration" (La Palma Declaration) was adopted. The Starlight Initiative (Fundación Starlight) was established as the entity responsible for formulating and promoting the declaration[30]. To protect the night sky, the Starlight Foundation was the first to combine science and tourism by establishing the International starlight certification system. It spreads astronomical knowledge through astro-tourism while also fostering local economic development. The Natural Sounds and Night Skies Division of the National Park Service (NPS), as an organizational management entity, also has valuable experience in protecting dark night skies, managing resources, and developing light pollution prevention standards[31]. The NPS has developed comprehensive night sky monitoring reports to systematically monitor the quality of the night sky in U.S. national parks. By monitoring night sky brightness, they can promptly implement effective measures to address potential light pollution. Additionally, the Royal Astronomical Society of Canada has developed initiatives for designating dark sky preserves to limit light pollution caused by urban development[32].

Table 1. Main Institutions of Certifying Dark Sky Sites[33].

Name	Recognition Start Date	Location	IUCN DSAG categories	Recognition number	Participating countries
Royal Astronomical Society of Canada	1999	Canada	1,2a,2c,4a,4b,6b	27	1 (Canada）
DarkSky International	2001	USA	1,2a,2c,3,4a,4b,5,6b	211	24
Ciemne Niebo Polska	2004	Poland	1,6a	5	1 (POLAND）

Fundación Starlight (Starlight Initiative)	2007	Spain	1,2c,2a,3,4,4a,4b,5,6a,6b	60	9
China Biodiversity Conservation and Green Development Foundation	2015	China	1,2a,3,4b,6a	6	1 (China)

With the efforts of relevant astronomy experts and enthusiasts, some night protection activities, including publicity, legislation, and protection organizations (Table 1), have been carried out and their influence has been continuously expanded. In 1958, Flagstaff, Arizona, passed the world's first dark sky legislation (International). In 1988, the International Dark-Sky Association was founded as a non-profit organization in Arizona, USA. In 1988, the National Park Service (NPS) issued a management policy that noted the importance of dark night skies in the national parks to the visitors' experience and cooperated with local governments to limit artificial light in the parks (Service 1988). In 2001, the first World Atlas of Artificial Night Sky Brightness was published[34]. In 2006, Natural Bridges National Monument in Utah, USA, was designated as the first International Dark Sky Park[35]. In 2009, the International Union for Conservation of Nature (IUCN) established the Dark Skies Advisory Group (DASG)[36]. The group, representing the IUCN, provides advice on light pollution and dark sky protection for individuals and other organizations, and has developed a universal category system (DSAG system) for existing certified dark sky places to facilitate unified communication. The DSAG system includes six major categories and corresponding subcategories[36] (Table 2). In 2012, the IUCN adopted a proposal on dark sky protection titled "Dark Skies and Nature Conservation"[37].

Table 2. Types of Dark Sky Locations Developed by DSAG.

Class number	Class name	Class definition	Sub-class numbers
Class 1	Dark Sky Astronomy Site	containing at least one scientific grade research telescope supporting research, and having a surrounding protected area	none
Class 2	Dark Sky Park	protected natural area	2a,2b
Class 3	Dark Sky Heritage Site	protected heritage physical works of mankind	none
Class 4	Dark Sky Outreach Site	a site managed for public night sky viewing	4a,4b

Class 5	Dark Sky Reserve	core protected area and a sustainable development buffer zone of cooperating community, rural and natural area jurisdictions	none
Class 6	Dark Sky Community	a rural municipality, village, town or city	6a,6b

Compared to developed countries, China's awareness of protecting dark night resources began later. However, with the attention and support from the government and international organizations, efforts to protect the night sky are ongoing. To better promote dark night protection projects and public awareness campaigns, the China Biodiversity Conservation and Green Development Foundation (CBCGDF) established the Dark Night Sky Committee (China Night Sky Committee) in 2015. The Ali region in Tibet, China, boasts exceptional dark sky resources and is referred to as the "Third Pole" of top astronomical observatory sites by the international astronomical community. To protect this resource, the Beijing office of the DarkSky International and the China Night Sky Committee have, since 2003, collaborated with local governments to plan a 2,500 km² dark night reserve to prevent light pollution. Additionally, the Nakqu Hangtso Lake Scenic Area in northern Tibet has been strictly planned according to international dark night standards to develop stargazing tourism. Both areas became China's first pilot sites for dark night protection in 2016 and were added to the DarkSky Places Program by the IUCN in 2018 (Table 3), making them China's first internationally recognized dark night protection sites.

Table 3. Distribution of Existing Dark Sky Places in China (as of March 2024).

Name	Recognition Year	DSAG Class	Recognizing Intuition	Location	Protected Area (km²)	Total Area (km²)
Ngari Dark Sky Reserve	2016	1	CBCGDF	Tibet Autonomous Region	2500`	2500
Nagqu Conservation Area for Dark and Starry Sky	2016	4b	CBCGDF	Tibet Autonomous Region	100	100
Yeludang Conservation Area for Dark and Starry Sky	2018	3	CBCGDF	Jiangsu Province	450	450
Taihang Conservation Area for Dark and Starry Sky	2018	2a	CBCGDF	Shanxi Province	7.1	20.4

Geyuan Conservation Area for Dark and Starry Sky	2019	6a	CBCGDF	Jiangxi Province	60	60
Zhaojin Conservation Area for Dark and Starry Sky	2020	4b	CBCGDF	Shaanxi Province	90	90
Xichong International Dark Sky Community	2023	6b	DarkSky	Guangdong Province	0	36
Hehuan Mountain International Dark Sky Park	2019	2c	DarkSky	Taiwan Province	13.45	13.45

The China Night Sky Committee has released the "Dark Night Sky Protection Area Project Standards" in line with international standards to promote the construction, evaluation, and management of dark night areas in China (Foundation 2018). In 2019, CBCGDF hosted the "First China Dark Night Sky Protection Conference." Thanks to the efforts of the China Night Sky Committee, four more locations in China were approved and listed in the DSAG World List in 2020. These locations are Huanghe Wetland Wild Deer Pond, Honggu in Shanxi, Geyuan in Jiangxi, and Zhaojin in Shaanxi (Table 3). Besides these organizations, some cities in China, such as Shenzhen, Chengdu, and Hangzhou, have recognized the importance of dark night protection early on and incorporated dark night areas into their overall lighting plans. For example, Shenzhen established the "Dapeng Starry Sky Park" based on the Shenzhen Astronomical Observatory in Dapeng New District, designating dark night protection areas to develop the night-time economy. The Xichong Dark Night Community in Shenzhen received DarkSky International certification in 2023, becoming China’s first and Asia’s second International Dark Sky Community(Harrison). Meanwhile, regulations related to light pollution are continuously being improved. In 2023, China’s first local legislation for "dark night sky" protection, the "Cold Lake Astronomical Observation Environmental Protection Regulations of Haixi Mongol and Tibetan Autonomous Prefecture," was enacted (Prefecture 2023).

1.2 Distribution of Dark Sky Places

In March 2024, according to the specific dark sky conservation areas listed on the IUCN website updated on February 18th, a statistical analysis was conducted. The IUCN's list of world dark sky places recognizes a total of 323 such areas (Figure 1), with 174 in North America, 8 in South America, 113 in

Europe, 14 in Asia, 2 in Africa, and 12 in Oceania (Figure 2). These dark sky conservation areas are distributed across 32 countries on 6 continents(Figure 3). Developed regions like Europe and America, where dark sky conservation initiatives started earlier, have the most extensive and diverse range of protected areas. North America, with the highest number of dark sky places, accounts for approximately 54% of the total, followed by Europe with approximately 35%. Together, they make up about 90% of the currently certified dark sky conservation areas.

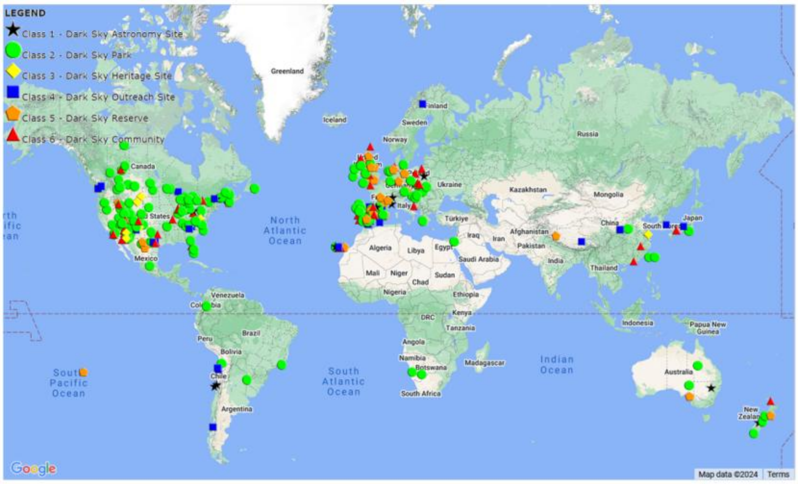


Fig. 1. Map of Dark Sky Places[38].

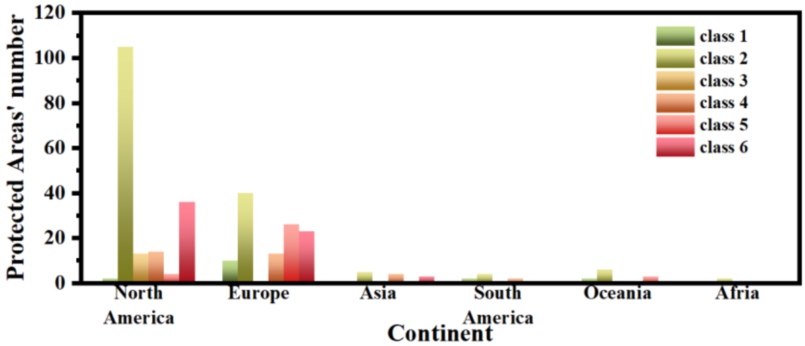


Fig. 2. Number and Types of Existing Dark Sky Places by Continent.

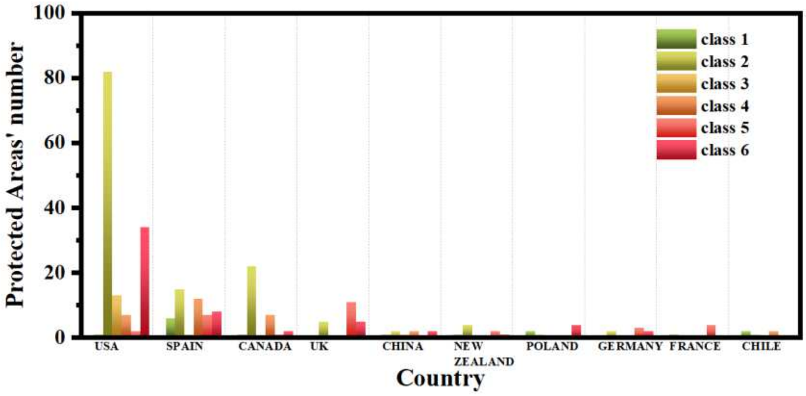


Fig. 3. Top 10 Countries by Number of Dark Sky Places.

We conducted an annual statistical analysis of the 6 classes of dark sky conservation areas listed on the website to obtain a statistical chart of the number of each type of protected area (Figure 4). Class 1 recorded its earliest protected area in 2006. As of 2024, there are 17 certified protected areas, with the largest growth occurring in 2013, when 6 new protected areas were added. Class 2, comprising three subclasses, is one of the most numerous types, showing significant growth from 2014 to 2021 and currently totaling 162 protected areas. Class 3 started recording in 2013 and has the fewest recorded areas, with no new additions in the past four years up to 2024. Class 4, starting from 2004 and including types 4a and 4b, saw accelerated certification from 2012, now totaling 33 protected areas. Class 5 began recording in 2009 and currently has 33 protected areas. Class 6, starting its records in 2001, saw a notable increase in certifications after 2012 and currently includes 63 protected areas.

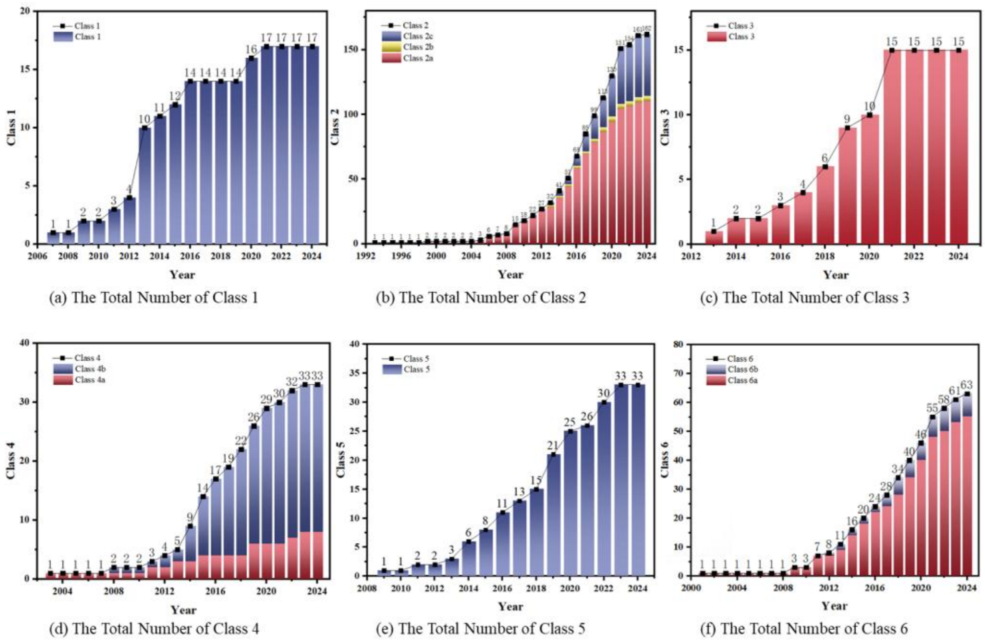


Fig. 4. The Annual Total Number of 6 Classes of Dark Sky Places.

The DarkSky International has the highest number of international dark sky certifications and is the earliest developed institution in this field. Their International Dark Sky Places program is currently certified in 238 dark sky locations across 27 countries by the year 2025. The types of dark sky conservation areas under the International Dark Sky Places program include International Dark Sky Parks (IDSP), International Dark Sky Sanctuaries (IDSS), International Dark Sky Reserves (IDSR), Urban Night Sky Places (UNSP), and International Dark Sky Communities (IDSC). The distribution of 5 types of dark sky locations and their countries is shown in Figure 5. IDSP is the most numerous, accounting for 55.45%.

Following are IDSC (20.85%), IDSR (11.37%), IDSS (8.53%), and UNSP (3.80%). Among countries certified by DarkSky International, the United States leads with 131 certified places, making up 62.09%. Following are the United Kingdom (21 places, 9.96%), New Zealand (8 places, 3.79%), Germany (7 places, 3.32%), and France (5 places, 2.37%).

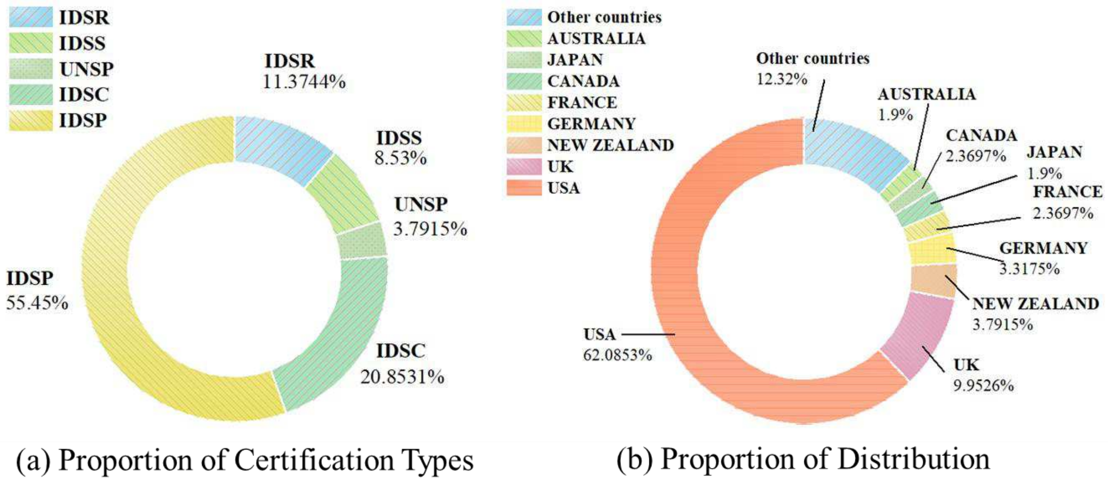


Fig. 5. Analysis of Dark-Sky International Certified Sites.

2. Study on Nighttime Light Environment Measurements in Dark Sky Reserves

To study the overall light environment distribution characteristics within an ecological area under ideal conditions and the attenuation characteristics of artificial night light from urban interiors to exteriors, Taihang Conservation Area for Dark and Starry Sky located in Jincheng City, Shanxi Province is selected based on the existing dark sky places in China. Field monitoring is conducted to obtain night sky data from the dark sky reserve. On the basis that the reserve is not affected by light pollution, the study aims to analyze the attenuation data of night light from the city center to the pollution-free area, and investigate the characteristics and reasons behind the attenuation phenomemon.

2.1 Study Site Selection

The study focuses on the nighttime light variation characteristics from urban centers to dark sky reserves. Theoretically, the night light intensity in urban centers is the highest due to intense human activity and high building density with various nighttime lighting. As the distance from the city center increases, the density of built environment areas decreases, and the light diminishes, leading to a gradual reduction in night light intensity. To verify this hypothesis and quantify the night light variation from the city center to the dark sky reserve, the study selects a path from the city center to the dark sky reserve and sets up measurement points along this path (Figure 7). The night light environment at each measurement point will be measured, and the collected data is summarized, processed, and analyzed to explore the changes quantitatively.

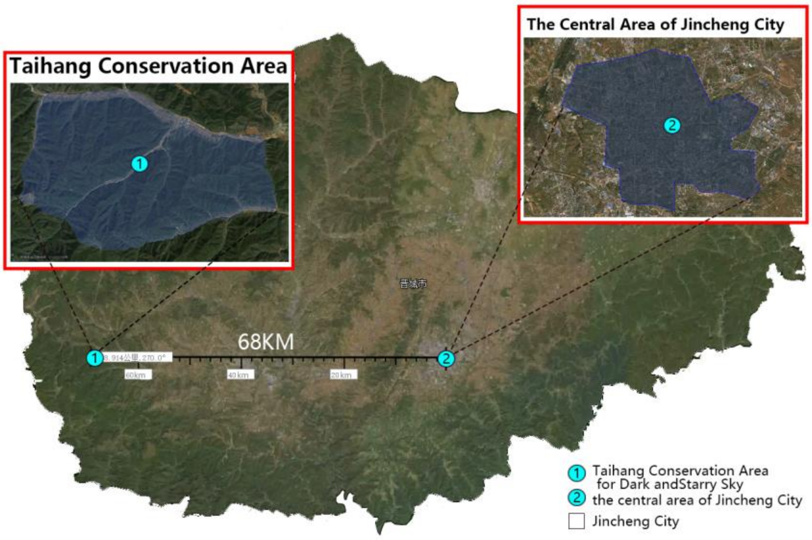


Fig. 6. Distance from the Urban Center of Jincheng City to Taihang Conservation Area

Assessing light pollution in China's nature reserves based on NPP/VIIRS night light remote sensing data, only 52 nature reserves in China, accounting for only 7.32%, were free from artificial light pollution by 2021. As of March 2024, there are 323 dark-sky places worldwide, but only 8 of them in China have received international certification (Table 3). Considering both factors, Taihang Conservation Area for Dark and Starry Sky in Shanxi is selected as the study area. Taihang Honggu is part of the Lishan Nature Reserve in Shanxi, and the night light environment of the reserve was still free from light pollution in 2021. The city center selected for this study is the most bustling commercial area of Jincheng City, specifically the Guomao Building.

2.2 Field Measurement Methods

2.2.1 Arrangement of Measurement Points

Taihang Honggu National Forest Park is a national-level nature reserve located at the junction of 3 mountain ranges including Taihang, Taiyue and Zhongtiao. Due to its terrain primarily composed of mountains, it is impossible to conduct large-scale measurements across the entire reserve. There is a passage road at the bottom of the valley and also a village, Nanyang Village, located at the intersection of two roads. The village has about 200 permanent residents, and the roads lack lighting, so there is minimal artificial light interference within Taihang Conservation Area and the overall night light environment is uniform. Measurement points are evenly distributed along the two accessible roads (Figure 7), with 200 meters between each point, totaling 50 points.

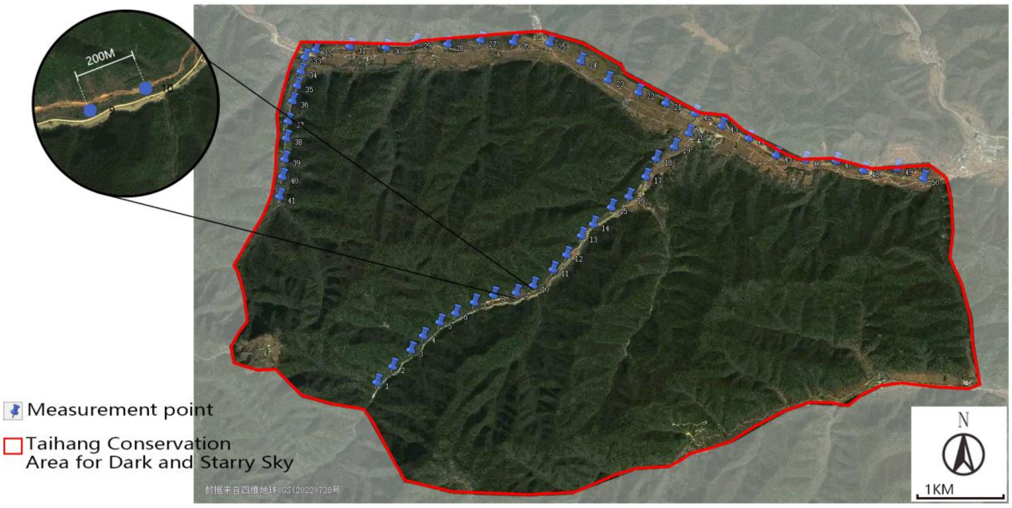


Fig. 7. Measurement Point Map of Taihang Conservation Area for Dark and Starry Sky.

Taihang Conservation Area is located west of the urban center of Jincheng City, Shanxi Province, with a straight line distance of 68 km. Night light environment data is collected along the route from the city center to Taihang. Based on the predicted characteristics of the urban light environment, the measurement points are arranged according to the principle of denser points closer to the city center.

Due to the local topography and current transportation facilities, it is not possible to directly reach the measurement points on the straight line from the city center to Taihang. Therefore, a "Concentric Circle Model" is used for point arrangement. This means that when drawing circles with the city center as the center and set distances as radii, the night light environment at each point on the same circle is considered approximately the same. For example (Figure 8), if point A is 15 km from the city center, a circle with a radius of 15 km will be drawn with the city center as the center, and the light indices of each point on the circle will be considered similar. That is, the night light data measured at point A and B will be the same.

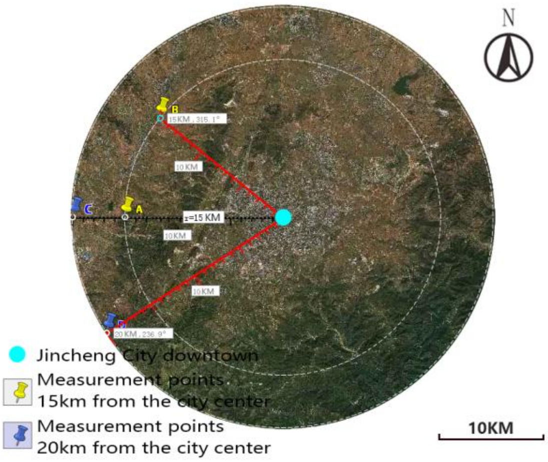


Fig. 8. Measurement Point Replacement Map Using the Concentric Circle Method.

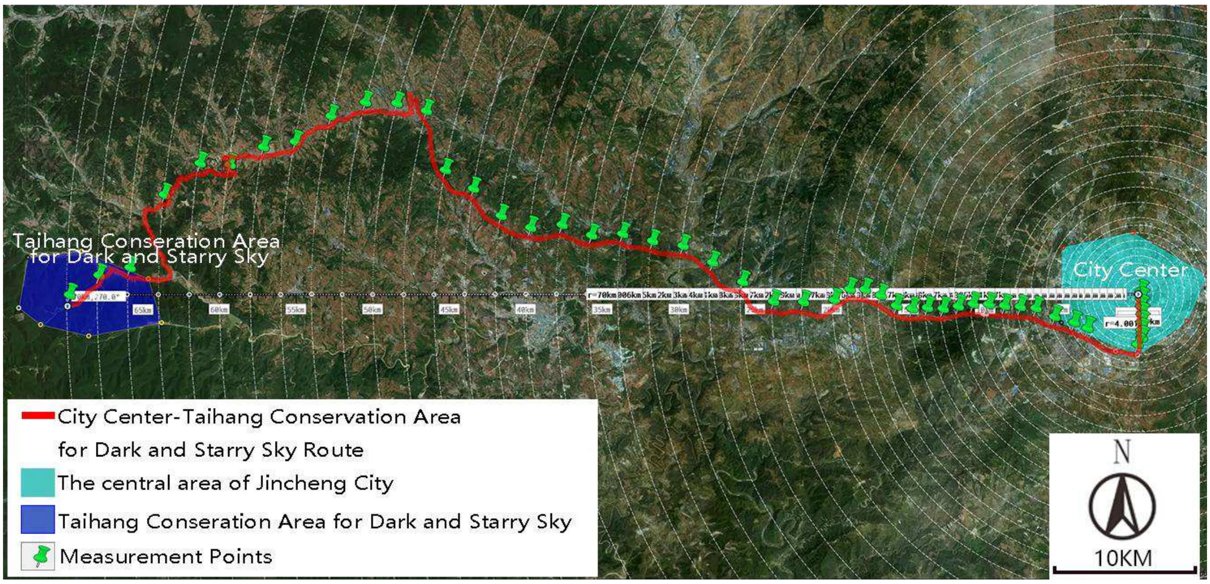


Fig. 9. Distribution of Measurement Points from the Urban Center to Taihang Conservation Area for Dark and Starry Sky.

Based on the "Concentric Circle Model", a route is set from the city center to Taihang using the map, and points will be arranged along this route (Figure 9). Here, the city center is set as point 0, and Taihang as the furthest point, 68 km from the city center. From the city center to the city edge (5 km), 10 points are arranged, spaced 500 meters apart. From the city edge to Taihang, the distance between measurement points gradually increase: 15 points are arranged between 5-20 km, spaced 1 km apart. 25 points between 20-70 km, spaced 2 km apart，totaling 50 points.

2.2.2 Measurement Instruments

To accurately and comprehensively extract dark night protection parameters, multiple instruments are used for multi-parameter measurements of the night light environment in Taihang Conservation Area and along its route. On the one hand, the measurements are based on the evaluation indicators (the visual limiting stellar magnitude) of dark night protection areas of international dark night communities. On the other hand, measurements should be conducted as comprehensively, accurately and systematically as possible where conditions permit. A CL500A illuminance meter is used to measure the illuminance and spectrum of the target area, an Sky Quality Meter to measure the night-sky brightness, an LS100 luminance meter to measure brightness, and a mobile phone to take photos of the surrounding environment at night.

2.2.3 Measurement Method

(1) Measurement Method from City Center to Taihang Conservation Area for Dark and Starry Sky

For most measurement points between the city center and Taihang Conservation Area, which are located on highways where stationary measurements are not possible, the measurement method involves capturing night light environment parameters with instruments extended out of a car window while driving at high speed. The feasibility of this measurement method will be experimentally verified in Section 2.4. Since the spectroradiometer does not measure instantaneously and requires about 30 seconds of exposure time, during which the measured data may not correspond to the target measurement point, therefore only the Sky Quality Meter will be used to measure the night-sky brightness at each measurement point on the route from the city center to the dark sky reserve. Each measurement point is measured four times, and the average value is taken as the night-sky brightness for that point.

(2) Measurement Method within Taihang Conservation Area for Dark and Starry Sky

To comprehensively extract the night light parameters of the dark sky reserve and explore the night light environment distribution characteristics, our "Urban Night Light Pollution Testing Method" is simplified and used as the measurement method[39]. Each measurement point in Taihang Conservation Area has three measurement windows, including an upper window, a horizontal window and a lower window, to measure the overall light environment in all directions. The upper window measures the brightness of the sky, the horizontal window measures artificial night light, and the lower window measures ground-reflected night light. Measurements for each window are taken at eye level, 1.6 meters above the ground, to assess the night light environment distribution characteristics from a human eye perspective. Since the measurement area is a forest park with dense vegetation, efforts are made to minimize the obstruction of the instrument sensors by trees and reduce the impact of vegetation on night light data.

The measurement methods for each window are shown in Figure 10. For horizontal window measurements, the optical sensor is aligned parallel to the face and perpendicular to the ground, measuring the environment in four directions with 90° intervals. The average value of the night light parameters collected from these four angles are taken as the horizontal window night light value for that point.

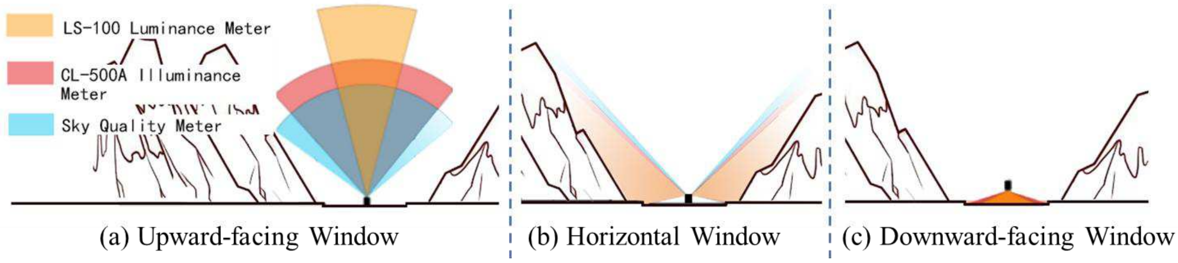


Fig. 10. Schematic Diagram of Measurement Methods for three windows.

2.3 Measurement Environment

Studies have shown that atmospheric conditions significantly impact the night light environment[40]. To minimize the influence of air quality and weather on night light, measurements are conducted on clear, cloudless nights with crescent moons and excellent air quality, as shown in Table 4. The selected dates for measurements are December 17 through December 19, 2022. Since the measurement area is a forest park, the influence of tree foliage and reflections on the light environment at the measurement points must be considered. Therefore, measurements are conducted during winter when the leaves has fallen, and areas with fewer trees are chosen whenever possible. The experiments are carried out during periods of active artificial lighting (18:30-21:30) and less active artificial lighting (21:30-24:00).

Table 4. Dates and Basic Atmospheric and Climatic Conditions of Field Measurements.

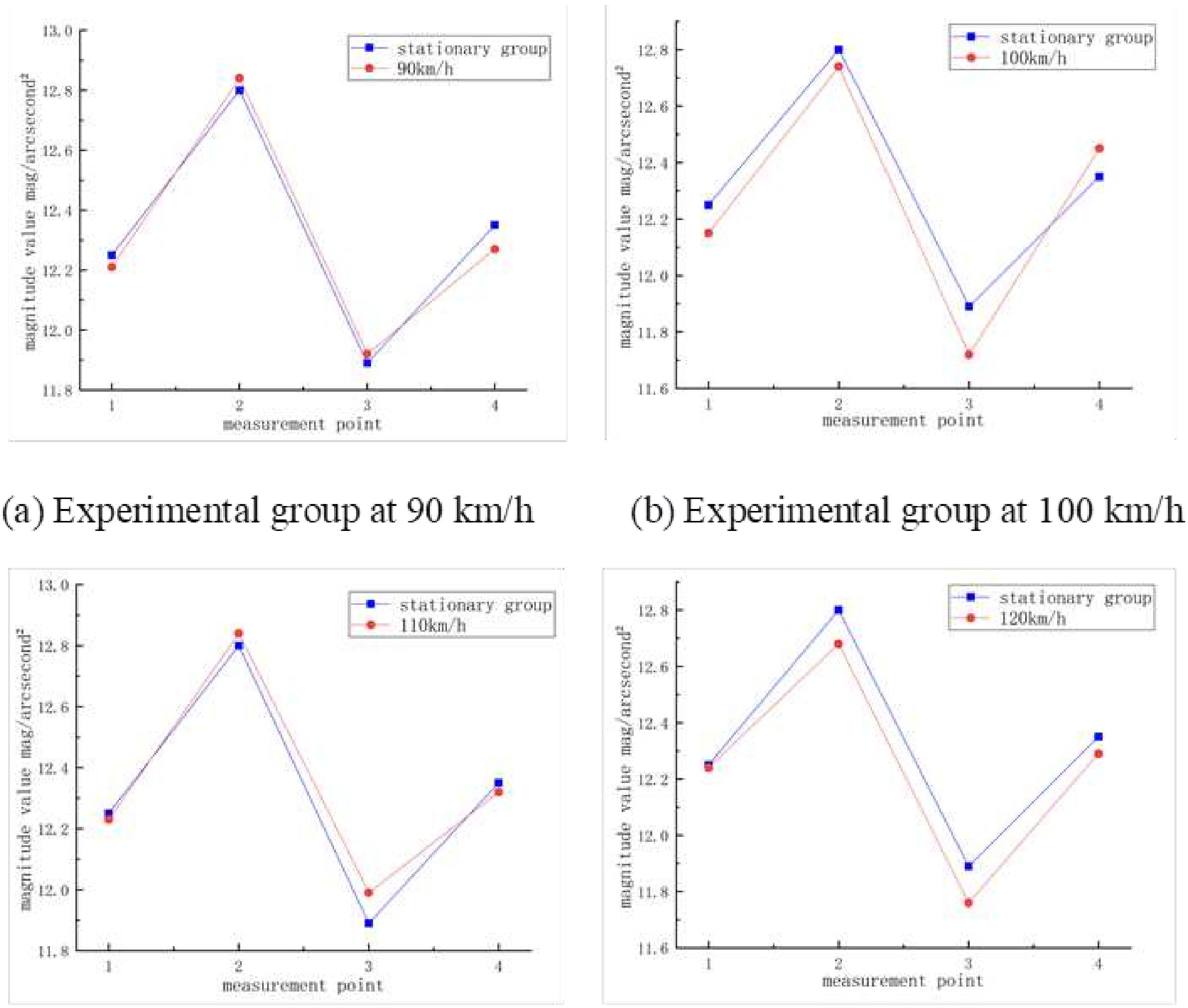
Date	Weather Conditions	Air Quality Index (AQI)	Average Temperature (°C)	Average Humidity (%)	Atmospheric Visibility (Km)	Moon Phase (%)	Sunrise/Sunset Time
2022/12/17 18:30-24:00	Clear	48 (Excellent)	-8	25	17	11 (Waxing Gibbous)	07:31/17:17

2022/12/18 18:30-24:00	Clear	26 (Excellent)	0	21	18	13 (Waxing Gibbous)	07:32/17:18
2022/12/19 18:30-24:00	Clear	34 (Excellent)	-3	28	16	16 (Waxing Gibbous)	07:33/17:19

2.4 Preliminary Experiment

To study the variation of night light from the city center to Taihang Conservation Area for Dark and Starry Sky, measurements must be taken on highways, requiring the use of instruments extended out of car windows at high speeds. An experiment was conducted to understand the relationship between high-speed measurements and stationary measurements.

The experiment is conducted on a closed road section with four measurement points spaced 500 meters apart. Instruments are held stationary on the ground to obtain control group data. Additionally, measurements are taken from a moving vehicle with instruments extended out the window toward the zenith. The vehicle speeds tested are 90 km/h, 100 km/h, 110 km/h and 120 km/h, and the Sky Quality Meter is used to capture night light parameters. 4 sets of experimental data are generated, each with four samples. These are compared with the stationary group data (Figure 11). The results show that measurements taken at high speeds closely match the stationary measurements, indicating that high-speed measurements could be used as experimental data.



(a) Experimental group at 90 km/h (b) Experimental group at 100 km/h

(c) Experimental group at 110 km/h (d) Experimental group at 120 km/h

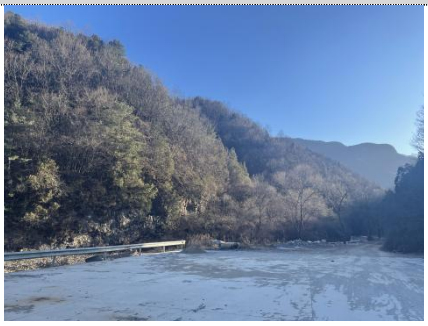
Fig. 11. Comparison of Magnitude Measurements at Different Speeds with Measurements at a Stationary State.

2.5 Field Measurement Analysis within Taihang Conservation Area

2.5.1 Environmental Analysis

The on-site environment of Taihang Conservation Area for Dark and Starry Sky is shown as Table 5. The area is still under development, with Measurement Point 42 located at the park entrance and Point 1 at the end of the road surrounded by developing scenic spots. The area around Point 40 has several abandoned buildings. Overall, the park lacks human infrastructure and is situated between mountains with abundant vegetation, far from urban areas, making it suitable as a dark sky reserve.

Table 5. Surrounding Environment Map of Taihang Conservation Area.

Measurement Point	Field of View Image	Measurement Point	Field of View Image
Measurement Point 1		Measurement Point 2	
Measurement Point 41		Measurement Point 42	

2.5.2 Impact of Human Activities

Nanyang Village is located near Taihang Conservation Area (Figure 12) and has nighttime human activity. To investigate whether village lighting affects the dark sky reserve, measurements are taken at different times based on the villagers' activity patterns. Research shows that 90% of Nanyang's residents turn off their lights and go to bed by 21:30. Therefore, measurements are taken between 18:30-21:30 and 21:30-24:00 to analyze the impact of human activities on the dark sky reserve.

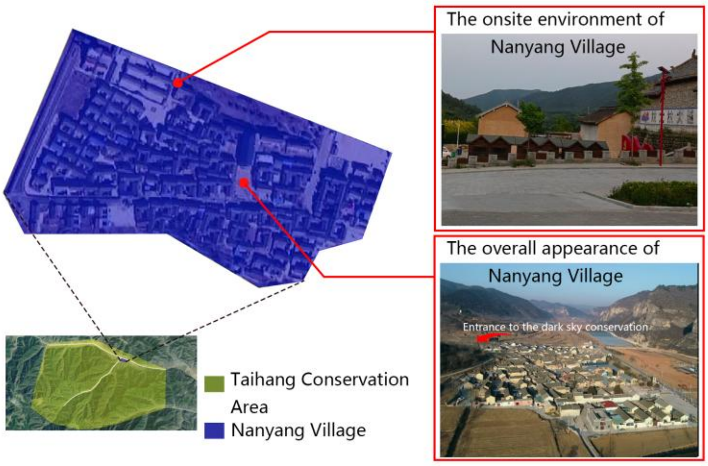
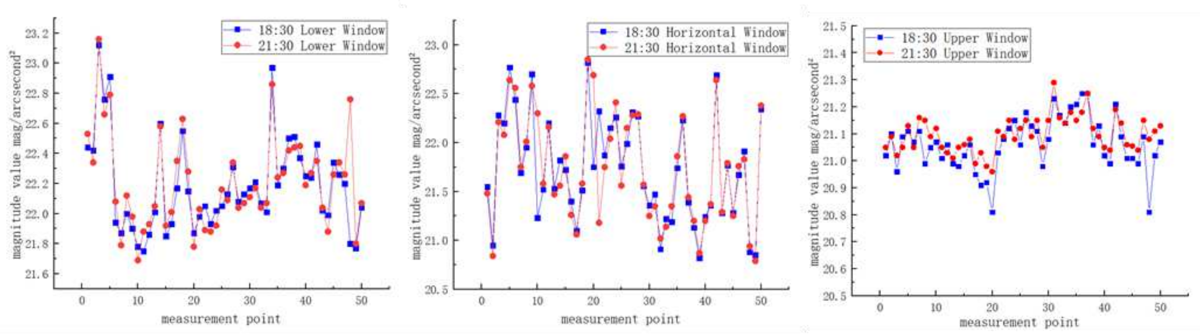


Fig. 12. Location and Surrounding Environment of Nanyang Village in Taihang Conservation Area.

Analysis of night-sky brightness values collected during these periods (Figure 13) shows high consistency across the three windows, with no significant differences, indicating that human activities does not significantly impact the night light environment of Taihang Conservation Area.



(a) Upper Window (b) Horizontal Window (c) Lower Window

Fig. 13. Distribution of Magnitude Values for Each Window at Different Time Intervals (18:30-21:30 and 21:30-24:00).

Further paired sample T-tests on 300 data points from 50 measurement sites (Tables 6 and 7) indicate that the stellar magnitude values (M=21.06, SD=0.09) during human activities are slightly lower than post-activity values (M=21.07, SD=0.09) but with no significant difference.

Table 6. Paired Sample Statistics of Magnitude Values for Each Observational Window.

Viewing Window	Time Period	Average Apparent Magnitude (mag/arcsec²)	Sample Size	Standard Deviation	Mean Standard Error
Upper Window	18:30-21:30	21.0630	50	0.09784	0.01384
	21:30-24:00	21.0690	50	0.09425	0.01333
Horizontal Window	18:30-21:30	21.7270	50	0.53812	0.07610
	21:30-24:00	21.7348	50	0.55584	0.07861
Lower Window	18:30-21:30	22.1846	50	0.31411	0.04442
	21:30-24:00	22.1452	50	0.41305	0.05841

Table 7. Paired Sample Test of Magnitude Values for Each Observational Window

18:30-21:30& 21:30-24:30	Paired Difference				t	Degrees of Freedom	Significance (Two-tailed)
	Mean Value	Standard Deviation	95% Confidence Interval of Difference				
			Lower Bound	Upper Bound			
Upper Window	-0.00600	0.02828	-0.01404	0.00204	-1.500	49	0.140
Horizontal Window	-0.00780	0.27770	-0.08672	0.07112	-0.199	49	0.843
Lower Window	0.03943	0.34371	-0.05825	0.13711	0.811	49	0.421

The analysis results reveal that there is no significant difference in the measurements for each window during the two time periods, indicating that nighttime human activities in Nanyang Village have not affected Taihang Conservation Area. The main reasons for this are as follows. On one hand, Nanyang Village has a permanent population of only 200 people, resulting in minimal nighttime lighting needs. On the other hand, Nanyang Village is located at the entrance of the canyon, with tall mountains between them, blocking part of the artificial light. These two factors together reduce the village's impact on the dark sky in the Taihang Grand Canyon Reserve, making it an ideal stargazing destination.

2.5.3 Analysis of Night Sky Quality

During actual measurements, only the Sky Quality Meter accurately records the luminance values for each window at the measurement points. Analysis of the 300 stellar magnitude data points shows that all points within Taihang Conservation Area had values greater than 20 mag/arcsecond². The horizontal window data is averaged, representing four horizontal directions at 1.6 meters. Data collected post-human activity (21:30-24:00) is analyzed (Figure 14).

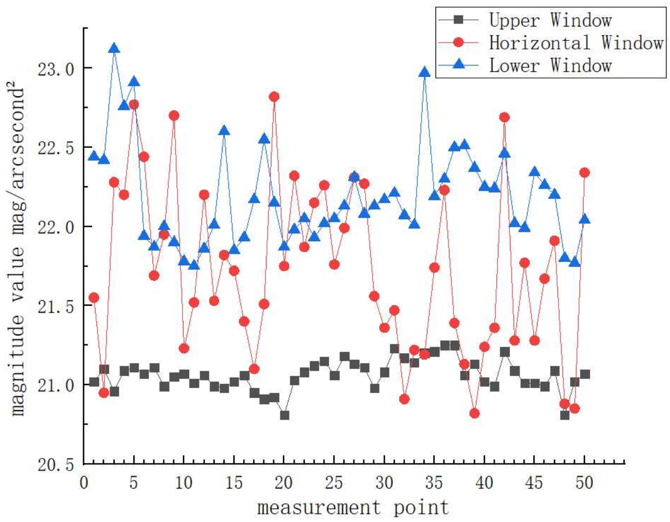


Fig. 14. Magnitude Values at Each Measurement Point of Taihang Conservation Area.

Overall, the upper window measurements are stable and the lowest among the three, with an average value of 21.06 mag/arcsecond². The horizontal window shows the most fluctuation, ranging from 20.82 to 22.82 mag/arcsecond², with an average of 21.73 mag/arcsecond². The lower window also fluctuates, with values between 21.80 and 23.12 mag/arcsecond², averaging 22.18 mag/arcsecond².

The stability and lower values of the upper window data are attributed to the open sky containing light sources like the moon and planets. The horizontal window data varies due to the uneven environment, including obstructions like mountains and trees. The lower window data, directed towards the ground, shows the highest values due to ground reflection and is relatively stable without other obstructions.

A comparison with the Dark-Sky International standards, which require stellar magnitude values between 21.00 and 21.74 mag/arcsecond², shows that the upper window data meet this range, and the horizontal and lower windows exceed it, indicating that the night sky quality of Taihang Conservation Area meets the standards for a dark sky reserve and is not affected by urban night light.

3. Characteristics of Night Light Attenuation from City Center to Taihang Conservation Area for Dark and Starry Sky

The intensity of human activities at night is highest in the city center, which brings the strongest light pollution. As the distance from the city center increases, the intensity of artificial light at night decreases. To explore this characteristic, the study takes the route from the city center of Jincheng to Taihang Conservation Area for Dark and Starry Sky as an example, measuring and recording the magnitude values at each measurement point along the way. Since the upper window magnitude values measured in Taihang Conservation Area for Dark and Starry Sky align most closely with the magnitude values specified by the Dark Sky International for evaluating dark sky reserves, the upper window is used for measurements. Each measurement point is measured 4 times, resulting in a total of 200 data points. These are used later to adjust and test the regression model to quantitatively study the relationship between the upper window magnitude values and the distance from the city center.

The average of the four measurement sets is taken and a graph of the change in magnitude values with distance is plotted (Figure 15). The red dashed line in the figure represents the boundary between the city and the suburbs. As shown in the figure, overall, the magnitude values increase with the distance from the city center. The magnitude value in the city center is 11.24 mag/arcsecond², and it increases continuously with distance. At 5 km from the city center, the magnitude value is 17.82 mag/arcsecond², an increase of 6.58 mag/arcsecond², with a rapid increase. However, beyond 5 km, the magnitude value increases slowly, and at 70 km from the city center, the magnitude value is 20.82 mag/arcsecond², an increase of only 3 mag/arcsecond², showing a slower increase. Compared to the distance of 0-5 km from the city center, the distance from 5-70 km is 13 times greater, but the magnitude change is only 0.46 times that of the 0-5 km range.

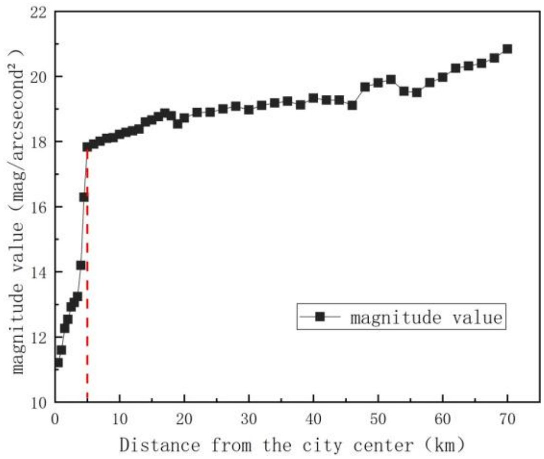


Fig. 15. Magnitude Values at Each Measurement Point from City Center to Taihang Conservation Area for Dark and Starry Sky.

The reason for this is that within the 0-5 km range from the city center, the intensity of human nighttime activities is closely related to night light intensity. Analyzing the satellite map of the city and the distribution of human habitation (Figure 16), it is found that within 5 km from the city center are high-density areas of human activities such as commercial zones, residential areas, and municipal and public service areas. Therefore, the nighttime lighting demand in this range is greater, leading to more light pollution and lower magnitude values. The closer to the city center, the stronger the human nighttime activities, with concentrated lights such as street lighting, commercial lighting, car lighting, and residential lighting that significantly impact the night light environment. As the distance from the city center increases, these activities decrease, causing a significant change in the night light environment and a rapid change in magnitude values within this range, up to the boundary between the city and the suburbs at 5 km from the city center.

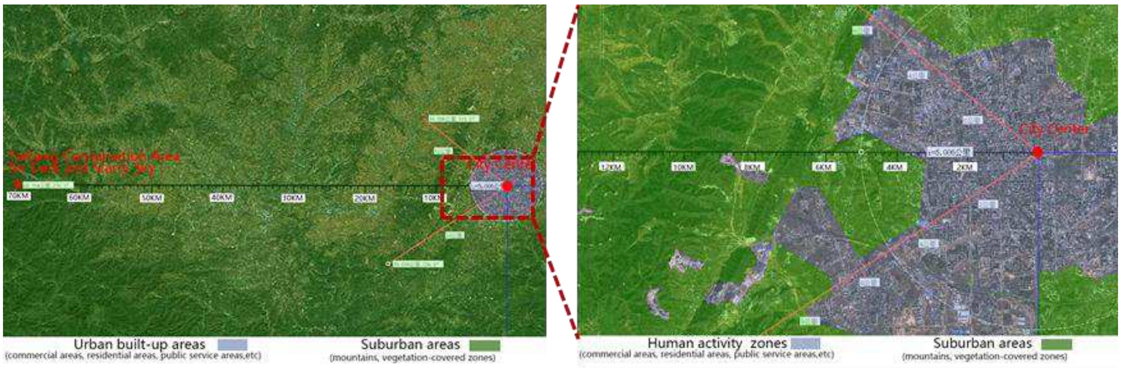


Fig. 16. Functional Distribution from City Center to Taihang Conservation Area.

In the 5-70 km range from the city center, there are scattered industrial zones, residential areas, scenic areas, suburbs, and other low-density human activity zones. Therefore, the night light demand in this range is small, with only necessary road lighting and residential lighting, resulting in minimal impact on the overall light environment from human activities, which is relatively stable and closer to the natural night sky. Therefore, the magnitude values in this range are higher and change slowly. However, this distance is still affected by the nighttime lights of the high-density areas within the city. As the distance from the city center increases, the impact of the city center lights decreases, showing a slow upward trend in magnitude values.

When reaching 68 km, which is Taihang Conservation Area for Dark and Starry Sky, the distance is sufficient to avoid the impact of the city's internal night lights. Additionally, there is only a village with a permanent population of 200 people nearby, with only some residential lighting. Most villagers go to bed at around 21:30, so there is no residential lighting demand after that time. The measurements within Taihang Conservation Area are taken after 21:00 on the day, making the night sky environment in this area primarily influenced by the natural environment and climate, such as moonlight, air quality, and cloud cover. Therefore, the quality of the night sky here is very close to the natural night sky, with magnitude values reaching over 21 mag/arcsecond^2.

3.1 Analysis of the Correlation Between Magnitude Brightness and Distance

Using SPSS, the correlation between the average values of 4 sets of magnitude brightness values and the distance from the city center (Table 8) is analyzed. The Pearson correlation coefficient is 0.731 ($p = 0.000 < 0.01$). Further linear regression analysis (Table 9) with the distance from the city center as the independent variable and magnitude brightness value as the dependent variable shows an R^2 of 0.534. This indicates a significant and strong positive correlation between magnitude brightness and distance from the city center.

Table 8. Pearson Correlation Analysis Statistics of Magnitude Brightness and Distance from City Center.

Research Object	Distance from City Center			Magnitude Brightness Value		
	Pearson Correlation	Significance (Two-tailed)	N	Pearson Correlation	Significance (Two-tailed)	N
Distance from City Center	1		50	0.731**	0.000	50
Magnitude Brightness Value	0.731**	0.000	50	1		50

Table 9. Regression Analysis Results of Magnitude Brightness and Distance from City Center.

Research Object	Distance from City Center			Magnitude Brightness Value		
	Pearson Correlation	Significance (Two-tailed)	N	Pearson Correlation	Significance (Two-tailed)	N
Distance from City Center	1		50	0.731**	0.000	50
Magnitude Brightness Value	0.731**	0.000	50	1		50

3.2 Construction of Distance Correlation Model

The SPSS analysis shows a strong positive correlation between magnitude brightness values and distance from the city center. Therefore, a correlation model can be established to quantify the relationship between magnitude brightness and distance.

(1) Data Validation - Cross-Validation Method

The cross-validation method is used for data validation. This method divides a large dataset into K smaller subsets, with K-1 subsets as the training set and the remaining one as the test set. This process is repeated K times, each time selecting a different subset as the test set. This method, also known as K-fold cross-validation, results in the average of these K validations. In this experiment, 4 sets of data are collected, divided into 4 subsets (Figure 17), each set with similar value distribution characteristics. Each measurement point corresponds to 4 data points, with 3 subsets as the training set and one subset as the test set. The combinations of the training set and test set are shown in Table 10.

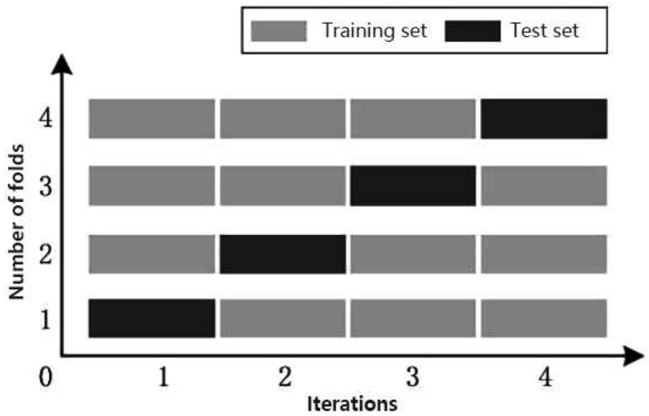


Fig. 17. Data Grouping Diagram of K-fold Cross-Validation Method.

Table 10. Results of Different Training Set and Test Set Combinations

Combination Name	Training Set	Test Set
Combination 1	Group A、Group B、Group C	Group D
Combination 2	Group A、Group C、Group D	Group B
Combination 3	Group A、Group B、Group D	Group C
Combination 4	Group B、Group C、Group D	Group A

(2) Establishment of Mathematical Model - Regression Analysis Method

To obtain a reliable and stable mathematical model, six regression models are used, including linear model, quadratic polynomial model, cubic polynomial model, reciprocal function model, logarithmic model and power function model. The 6 regression models are established for each data group, iterating 4 times. In each iteration, regression models are established for the data in the 4 training sets, then the predicted values were compared with the actual values of the test set. The root mean square error (RMSE) and R^2 mean values of the predicted and actual magnitude brightness values are calculated to evaluate the accuracy of the regression models.

In summary, the logarithmic function model is chosen as the mathematical correlation model for predicting magnitude brightness. The model equation is:

$$M = 1.9204 \cdot \log(D) + 12.6253 \qquad (1)$$

where M is the stellar magnitude value corresponding to different distances from the city center, measured in mag/arcsecond^2. D is the distance from the city center, measured in kilometers.

3.3 Validation of the Regression Model

To verify the logarithmic model obtained from the magnitude brightness and distance from the city center, data from different directions in Jincheng city are collected and compared with the predicted values to check the model's reliability.

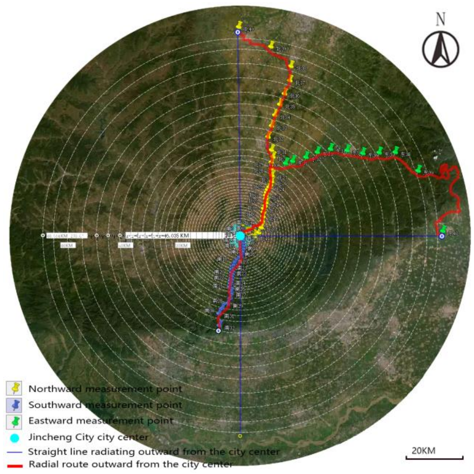


Fig. 18. Arrangement of Measurement Points in the East, South and North Directions from Jincheng City Center.

Using the city center (Guomao Building) as the origin, measurement points are set outward in the east, south and north directions. The concentric circle method mentioned earlier is used to arrange the points. 40 measurement points are set in the east and north directions. In the south direction, measurement points are set until 34 km from the city center, reaching the city boundary. Beyond this point is Qinyang city, and the actual values significantly differ from the model predictions due to human activities in Qinyang city, therefore only 32 points are selected in the south direction. The arrangement of measurement points is shown in Figure 18.

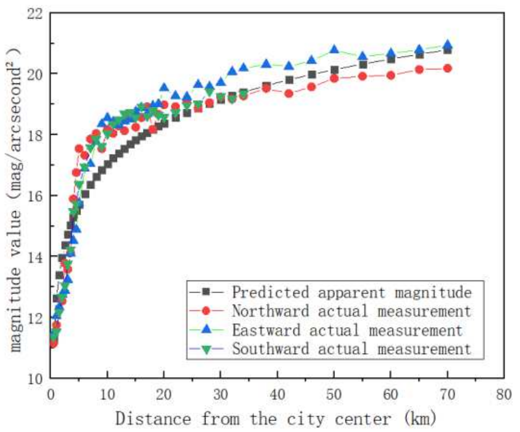


Fig. 19. Difference between Actual and Predicted Magnitude Brightness Values in the East, North and South Directions.

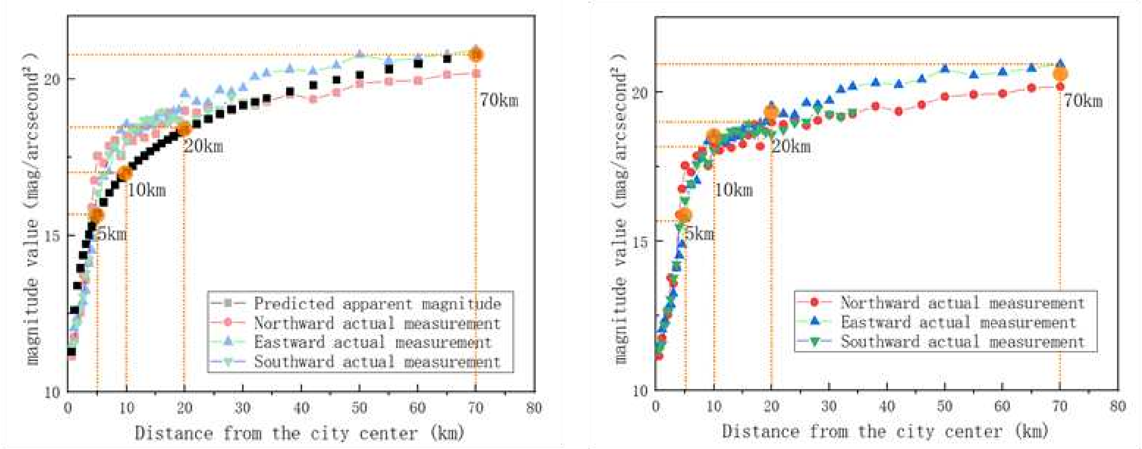
Table 11. Error Analysis of Model Predictions and Actual Measurements in the East, South and North Directions.

Classification	North direction	South direction	East direction
Root Mean Square Error (RMSE)	0.799	0.809	0.854
Mean Relative Error	3.729%	4.023%	4.295%

Model validation is conducted by comparing the predicted and actual measurement values, as shown in Figure 19. The overall trend of the predicted and actual values is consistent, with small dispersion between the points. To quantitatively evaluate the prediction accuracy, the root mean square error (RMSE) and mean relative error (MRE) between the predicted and actual values in the 3 directions are calculated, as shown in Table 11. In the north direction, the RMSE is 0.799, indicating a difference of 0.799 mag/arcsecond^2 between the predicted and actual values. The MRE is 3.729%, indicating a relative error of 3.729%. In the south direction, the RMSE is 0.809, with an MRE of 4.023%. In the east direction, the RMSE is 0.854, with an MRE of 4.295%. Therefore, the logarithmic model of magnitude brightness and distance from the city center is considered reliable.

4. Discussion

Nighttime light pollution is usually considered an issue that arises within urban areas. However, the analysis of night light data from Jincheng city center to Taihang Conservation Area for Dark and Starry Sky shows that the area affected by urban light pollution extends far beyond the city limits, especially regarding the background night sky. Further analysis of the night light attenuation characteristics reveals that as the distance from the city center (a high light pollution area) increases, the degree of light pollution decreases continuously. Considering the scale of urban construction in Jincheng, within the high-density night activity area 0-5 km from the city center, nighttime lighting intensity is high, and human activities significantly impact the overall light environment. In the 5-70 km low-density night activity area, nighttime lighting intensity is low, and the overall light environment impact is minor, but still influenced by city center lighting. At 68 km from the city center, in Taihang Conservation Area for Dark and Starry Sky the distance is sufficient to be unaffected by urban light pollution. And with mountain barriers blocking surrounding village lights, this area's night sky approaches a natural state, with magnitude values reaching 21 mag/arcsecond^2.



(a) Predicted Night Light Attenuation Values (b) Measured Night Light Attenuation Values

Fig. 20. Analysis of Night Light Attenuation.

Additionally, the analysis of the night light measurements and model predictions in different directions (excluding the east) reveals that in the 0-5 km range, the increase in night sky brightness accounts for the largest proportion (Figure 20), averaging about 45% of the total range (Table 12). Notably, the northern 0-5 km range accounts for over 70% of the increase. In the 5-10 km range, the increase in night sky brightness averages about 16.93%, and in the 10-20 km range, the average increase is about 11.08%. The night light attenuation process analysis indicates that within the 0-5 km range from the city center, the night sky is most affected by night light, with the highest magnitude value increase. The 5-10 km range is moderately affected, and the 10-20 km range is less affected. The influence diminishes with increasing distance from the city center due to decreasing population density and light density.

Table 12. Growth Proportion of Magnitude Values at Different Distances from City Center

Distance Range (km)	Predicted Growth Proportion	Measured Growth Proportion (North)	Measured Growth Proportion (South)	Average Growth Proportion of First Three Items
0-5km	46.48%	70.76%	45.24%	54.16%
5-10km	14.21%	6.98%	29.60%	16.93%
10-20km	14.02%	8.97%	10.26%	11.08%
20-40km	13.96%	5.04%	7.87%	8.29%
40-70km	11.26%	8.19%	6.98%	8.81%

This analysis indicates that the quality of the night sky in the dark sky reserve is influenced by urban light pollution, with the closer distances experiencing greater negative impacts.

Based on the field survey of Taihang Conservation Area for Dark and Starry Sky and the surrounding cities, several effective measures can be proposed to mitigate the excessive interference of nighttime lighting on the natural night sky. First, in terms of dark sky reserve site selection, the analysis concludes that nighttime lighting within 5 km of the city center has the strongest interference with the night sky. This interference significantly decreases with distance increasing. Therefore, it is advisable to choose areas far from the city center for establishing dark sky reserves. Dark sky reserves should not be built within 40 km of the city center. For example, in Jincheng, Taihang Conservation Area for Dark and Starry Sky, 68 km to the west of the city center has night sky magnitude values reaching 21 mag/arcsecond^2, meeting the Dark Sky International's standards for dark sky reserves and representing an unpolluted natural night sky. For ecologically fragile areas and regions with high dark night requirements (such as observatories), larger dark sky reserves can be established with core areas protected at different levels. Additionally, management around the reserves needs to be strengthened, especially in areas where tourism and related developments are undertaken after defining the dark sky reserves. Increasing population at the boundaries of the reserves can encroach on the reserve boundaries, and unreasonable use of lighting at the boundaries can disrupt the internal light environment of the reserves[41]. For cities near dark sky reserves, using appropriate lighting fixtures and controlling lighting periods can effectively reduce nighttime light interference[42].

This study focuses on the night light attenuation characteristics from the city center to the dark sky reserve, model establishment and attenuation verification in different directions, which fills the gap in field observations for dark sky reserves in China. However, there are still some limitations. This study is based on a single dark sky reserve, determining the sensitive distance for night light interference, but this sensitive distance may vary due to factors such as elevation and population size in different cities[43]. The proposed measures for dark night protection need further optimization and quantification of their effectiveness in practice.

Acknowledgments

The authors would like to thank editors and the anonymous reviewers for their valuable and constructive comments to improve our manuscript.

Declaration of Conflicting interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research was funded by The National Natural Science Foundation of China, grant number 52178067.

Data availability

All relevant data supporting the findings of this study are available at https://github.com/ShengHongyi/Values-of-Taihang-Conversation-Area

Author contributions

Ming Liu.,Methodology, Supervision, Funding acquisition,Software,Writing - review & editing;Hongyi Sheng.,Conceptualization, Data curation, Formal analysis, Software, Writing - original draft;Wenjing Wang.,Validation, Software, Writing - review & editing;Chenglong Wu.,Validation, Software, Writing - review & editing;Ruicong Li.,Investigation , Validation, Writing - review & editing;Qingyuan Liu.,Validation, Writing - review & editing.

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