frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 10 November 2023
DOI 10.3389/fenvs.2023.1309547

Study on the substitutability of nighttime light data for SDG indicators: a case study of Yunnan Province

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RECEIVED 08 October 2023
ACCEPTED 30 October 2023
PUBLISHED 10 November 2023

CITATION
Quan X, Song X, Miao J, Huang C, Gao F, Li J and Ying L (2023), Study on the substitutability of nighttime light data for SDG indicators: a case study of Yunnan Province.
Front. Environ. Sci. 11:1309547.
doi: 10.3389/fenvs.2023.1309547

Introduction: One crucial method to attain Sustainable Development Goals (SDGs) involves timely adjustment of development policies, promoting the realization of SDGs through a time-series assessment of the degree of accomplishment. In practical applications, data acquisition is a significant constraint in evaluating the SDGs, not only in China but across the globe. Hence, expanding data channels and exploring the feasibility of various data sources for sustainable development assessment are effective strategies to tackle the challenge of data acquisition.

Methods: In light of this issue, this study selected Nighttime Light Data, a remote sensing data source closely linked to human social activities, as an alternative data source. Using Yunnan Province as an example, 16 localized indicators of social, economic, and environmental types were chosen. These indicators were then subjected to a correlation analysis with the Total Nighttime Light Index (TNLI). The relationships between different types of indicators and TNLI were analyzed at both temporal and spatial scales, thus identifying the indicators for which TNLI could serve as a suitable substitute measure.

Results: The study indicates that when the SDG indicators are classified into economic, social and environmental categories, the total value of nighttime light presents a significant correlation and substitutability with economic indicators; significantly correlated with some social indicators, it can reveal the weak links in the development of underdeveloped areas; it is not significantly correlated with environmental indicators, while a trend correlation exists, which can provide some reference values.

Discussion: This study has demonstrated the feasibility of using Nighttime Light Data for sustainable development assessment. It provides a novel evaluation method for countries that, despite a lack of resources for conducting sustainable development assessments, have a greater need for such assessments due to their lower economic development. Furthermore, a multitude of assessment methods can be developed based on Nighttime Light Data.

KEYWORDS

sustainable development, nighttime light, SDG indicator, correlation, COVID-19 pandemic

1 Introduction

At the 70th Session of the United Nations General Assembly held in September 2015, 193 member countries jointly approved the "Transforming Our World: The 2030 Agenda for Sustainable Development", which put forward the sustainable development goals (SDGs), hoping to solve the development problems of human society at social, economic and environmental dimensions with the most comprehensive and integrated approach, and to realize sustainable development by formulating 17 sustainable development goals and 169 specific goals (Ministry of Foreign Affairs of the People's Republic of China, 2021; Guo et al., 2021a; Guo et al., 2021b). In September 2016, China formulated and issued China's National Plan on Implementation of the 2030 Agenda for Sustainable Development, and suggested that the 169 specific goals of SDGs should be evaluated in various respects (The State Council of the People's Republic of China, 2016). Data acquisition is the most fundamental and important part in the evaluation process. China is characterized by vast territory, unbalanced economic and social development and polarized population distribution, so it is relatively difficult to monitor and acquire indicators of some areas in the practical evaluation process. For example, in sparsely populated regions like Tibet and Xinjiang, we do not have enough corresponding workers to gain meticulous statistical results in the data monitoring process. Second, a high cost is required to collect the evaluation data, and most evaluation data are statistical data gained through field research or published by the state, while most prefecture-level statistical data are not published on the internet. Therefore, such data should be collected on site, which requires a high travel cost. Third, the acquisition cycle is long. Sustainable development is a development pattern requiring dynamic evaluation and adjustment, and dynamic regulation should be conducted according to the present international and domestic situations. Timely evaluation is the foundation of dynamic regulation, and the requirement for time attributes is high. However, the current evaluation mode involves a long data acquisition cycle. Fourth, it is inconvenient to make an international comparison. The statistical data of developed countries are relatively complete and published timely, so we can master their sustainable development progress. However, some developing countries cannot publish related statistical data timely or lack statistical items owing to the influence of economic and cultural factors. As a result, data sources are insufficient in horizontal comparison. Therefore, data acquisition is the main bottleneck of SDG evaluation (Song et al., 2018).

In recent years, as global satellite development enters an active phase, satellite-based sensors have realized more and more comprehensive functions, creating increasingly diversified remote sensing products. Characterized by high openness, short acquisition cycle and low cost, remote sensing data are extensively applied in various studies. Thereinto, nighttime light images (NTL) are extensively applied to study human social activities (Li and Li, 2015; Li et al., 2019), such as spatial analysis of population (Lo, 2001; Zhou et al., 2005), urban area analysis (Shu et al., 2011; Yu et al., 2018; Zhao et al., 2020; Yu et al., 2021; Jiang et al., 2022), land use management (Rahman et al., 2021), energy consumption and carbon emissions (Su et al., 2013; Ma and Xiao, 2017; Du et al., 2021; Niu et al., 2021), social and economic development analysis (Li et al., 2016; Yang et al., 2019; Li et al., 2019; Li et al., 2021; Peng et al., 2022; Jiang et al., 2021), air quality analysis (Cao, 2016; Wu et al., 2021), physical fitness analysis (Deng et al., 2022; Liao et al., 2022), and disaster monitoring (Du et al., 2020). These studies are closely associated with the sustainable development and sustainable development goals of the human society. For the specific SDG assessment, Wang et al. integrated NTL, China's Land-Use/Cover Datasets (CLUDs) and statistical data to monitor the Sustainable Development Goals (SDGs).) 11.3.1: "The ratio of land consumption rate to the population growth rate (LCRPGR)" (Wang et al., 2020). Wang et al. used NTL, CLUDs, and digital elevation model data, analyze and verify the spatiotemporal distribution characteristics of China's poverty areas and counties and their SDG 1 evaluation values (Wang et al., 2022). Falchetta et al. used high-resolution population distribution maps (including demographic and migration trends), satellite-measured nighttime light, and settlement information for sub-Saharan Africa. Derive multi-dimensional estimates of electricity access over space and time. Their research show that reveal wide inequalities in the pace and quality of electrification, which cannot be observed in existing statistics. The pace of electrification must more than triple to fulfill SDG 7.1.1 (Falchetta et al., 2020). Therefore, it is highly feasible to choose nighttime light data as the substitutive indicator of sustainable development goals. Remote sensing data will help to increase the SDG evaluation frequency, enhance the timeliness, reduce the data cost, and provide timely and effective supports for the formulation of regional sustainable development strategies. Based on the above, this paper aims to analyze the inner link between nighttime light data and sustainable development indicators by a case study of Yunnan Province, to explore the application range of nighttime light data in SDG evaluation, to provide expansive data for the newly launched SDGSAT-1 (Guo et al., 2023), and to realize multi-evaluation on specific SDGs.

2 Data sources and research methods

2.1 Overview of research area

Yunnan Province is located in the mountainous plateau of southwest China, and the mountainous area occupies 88.64% of the total area of the whole province (Figure 1). Its west and south parts border on countries like Myanmar, Laos and Vietnam, creating a "borderland, multi-ethnic and underdeveloped" area in such a unique geographical location. To evaluate the sustainable development situation of this area has practical significance for helping Yunnan realize sustainable development. Most existing studies on sustainable development of Yunnan mainly analyze the development advantages and disadvantages of single goals like

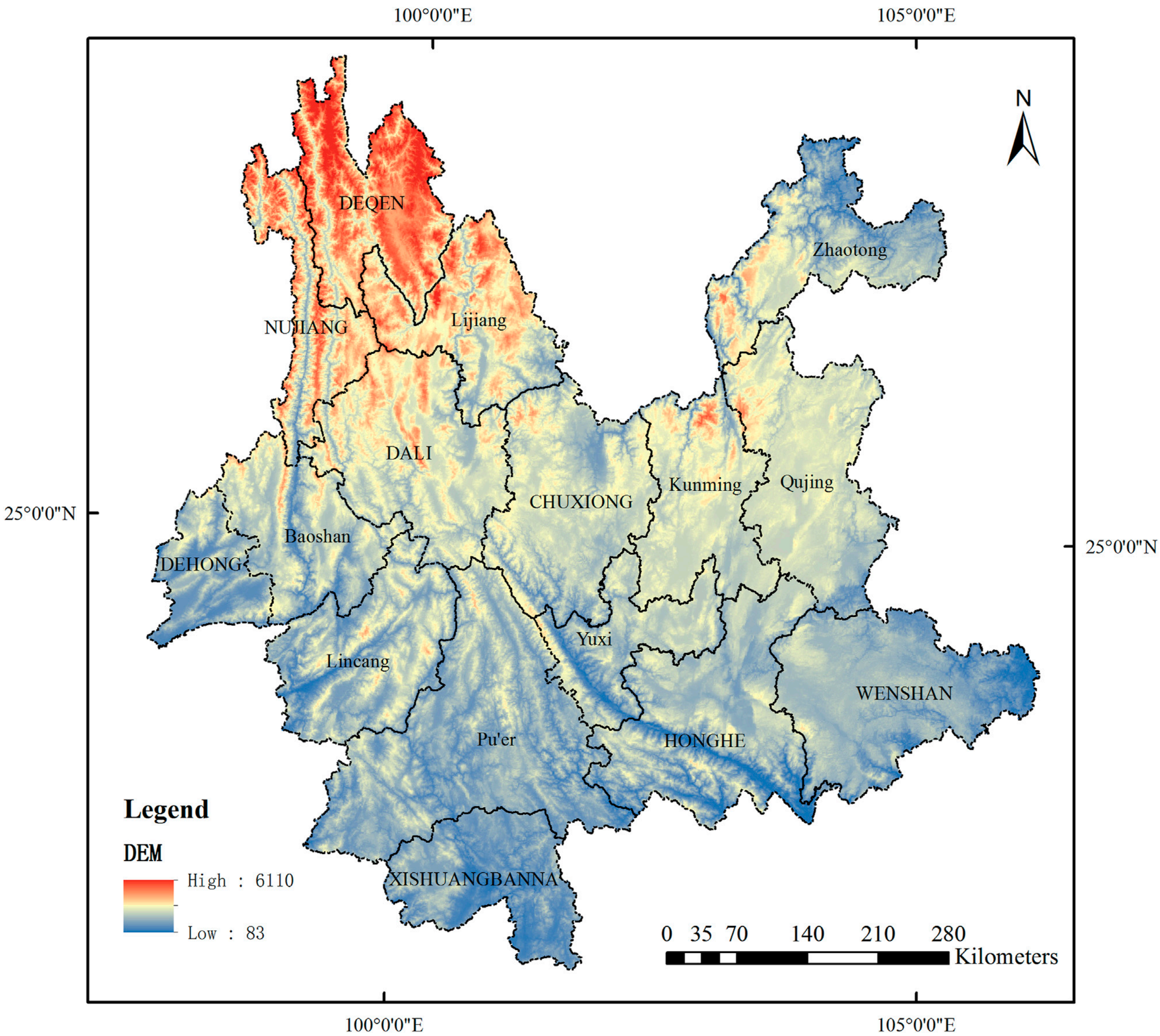

FIGURE 1
Overview of Yunnan Province.

tourism, mineral products and energy, and provide suggestions on the optimization of sustainable development paths. Few studies are conducted to evaluate the overall sustainable development indicators. Meanwhile, to realize the construction goals of making Yunnan Province the demonstration area for national unity and progress, the vanguard of ecological civilization construction, and the radiation center of South Asia and Southeast Asia, Yunan has positively created an innovation demonstration zone for national sustainable development agenda in Lincang City, Yunnan Province (Shen, 2021). However, it is located in the Yunnan-Guizhou Plateau, which is densely covered with mountains, rivers and lakes. As a result, travel inconvenience and external exchange difficulty exist. Besides, its development speed is lower than that of eastern regions. Owing to its complex topography, SDG evaluation has problems like data collection difficulty, basic data missing, field research difficulty, and high cost. By studying the substitutability of nighttime light data for SDG evaluation indicators, we can apply substitutive indicators in complex regions, to expand the SDG evaluation methods, and to make up data deficiencies in the evaluation of some indicators.

2.2 Data sources

2.2.1 Remote sensing data

The Visible Infrared Imaging Radiometer Suite (VIIRS) is the latest generation of earth observation satellite sensors by following the Operational Linescan System (OLS) of the United States Defense Meteorological Satellite Program (DMSP), and it is carried by Suomi National Polar-orbiting Partnership (NPP). Compared with DMSP-OLS, it is greatly improved in the aspect of low-light level imaging, so it can generate nighttime light products of higher quality. NPP-VIIRS nighttime light data were downloaded from the National Center for Environmental Information subordinate to the National Geophysical

TABLE 1 NPP-VIIRS data description.

Data type	Data description	Date time frame	Data acquisition methods
Monthly data without cloud data	The vcm format data exclude those influenced by stray light; vcmsl data include astigmatism correction data, covering more bipolar data, but the quality will decrease	2016–2020	https://payneinstitute.mines.edu/eog/
Annual VNL V1 data	Such data are synthesized on the basis of vcm data, screening out most transient light and dull backgrounds		
Annual VNL V2 data	Improvement is made on the basis of Annual VNL V1, and the annual products are synthesized with the increment of the month. Besides, the abnormal value is corrected with the median of each month (max–min), to filter out most blaze and background values. The loss of light characteristics in some dark areas caused by the problem of threshold range is modified, and pixels polluted by the cloud are removed through standard and scientific processing functions. Moreover, the influence of VIIRS day/nighttime band (DNB) radiation on the atmosphere, landform, vegetation, snow, moon and stray light is corrected		
NB mosaic data	Daily DNB mosaic data and cloud situations: 0–1 no cloud; 2–3 possibility of cloud; 4–5 existence of cloud		

TABLE 2 Monitoring data description.

Data source	Data content	Date time frame	Data acquisition methods
China National Environmental Monitoring Centre	Urban air quality; real-time data of automatic monitoring for water quality; national air quality forecast; national surface water fusion data	2016–2020	http://www.cnemc.cn/?eqid=b6aff9dc000ab300000000046439316b
China Online Monitoring and Analysis Platform for Air Quality	AQI; $PM_{2.5}$; PM_{10}; SO_2; NO_2; O_3; CO; temperature; humidity; wind scale; wind direction; satellite cloud picture	2016–2020	https://www.aqistudy.cn/

Data Center (NGDC) of Nation Oceanic Atmospheric Administration (NOAA). Only monthly data of NPP-VIIRS and a small number of annual data were issued, so the previous annual data of NPP-VIIRS were spliced with the monthly data. From 15 October 2019, the nighttime light data of NPP-VIIRS have been migrated from NOAA to the website of Colorado School of Mines/Earth Observation Group (CSM/EOG) (Elvidge et al., 2021), as shown in Table 1.

2.2.2 Statistical/monitoring data

The global indicator framework of various sustainable development goals and specific goals in the *2030 Agenda for Sustainable Development* requires that the sustainable development goals should be assigned according to income, gender, age, race, nation, migration situation, disability situation, geographical location or other characteristics by following the *Basic Principles of Official Statistics*. Moreover, the descriptive information of indicators is given at the indicator level, but no definition is provided for the specific item in specific statistical data. Therefore, some data are detailed according to the descriptive information and Big Earth Data in Support of the Sustainable Development Goals in this study, and the specific data sources are clarified.

The statistical data originate from the Statistical Yearbook of Yunnan Province, Fiscal Revenue and Expenditure of Yunnan Province, China Health Statistical Yearbook, Grain and Oil Price Monitoring Bulletin of Yunnan Province, and Statistical Yearbook of Chinese Urban Construction.

The monitoring data come from China National Environmental Monitoring Centre and China Online Monitoring and Analysis Platform for Air Quality, as shown in Table 2.

2.3 Research method

2.3.1 General thought

First, the nighttime light indexes were extracted after the nighttime light data were processed, and the statistical data and monitoring data were summarized to acquire related data for SDG indicator evaluation. Secondly, the summarized data were divided into social, economic and environmental types according to the classification standards, and their correlation was calculated. Then the correlation and substitutability between different indicators and nighttime light indexes were discussed according to the calculation results. Finally, analysis was made for the influence of the COVID-19 pandemic on sustainable development and the application prospect of nighttime light data in SDG evaluation in the future (Figure 2).

2.3.2 Nighttime light data processing

2.3.2.1 Data preprocessing

The remote sensing data of nighttime light are denoted with the gray scale of digital numbers (DN). Preprocessing is required before analysis is made with nighttime light data. To avoid the impact of projection deformation on image area calculation, area projection (including Albers) was conducted, and later resampling and clipping were carried out (Shi et al., 2014). A large number of service facilities were discovered in large water areas such as the Dian Lake, Fuxian Lake and Erhai when the nighttime light data of Yunnan Province were processed. Owing to the high light intensity and large area, the lake surface might produce light reflection easily, and the satellite can receive the

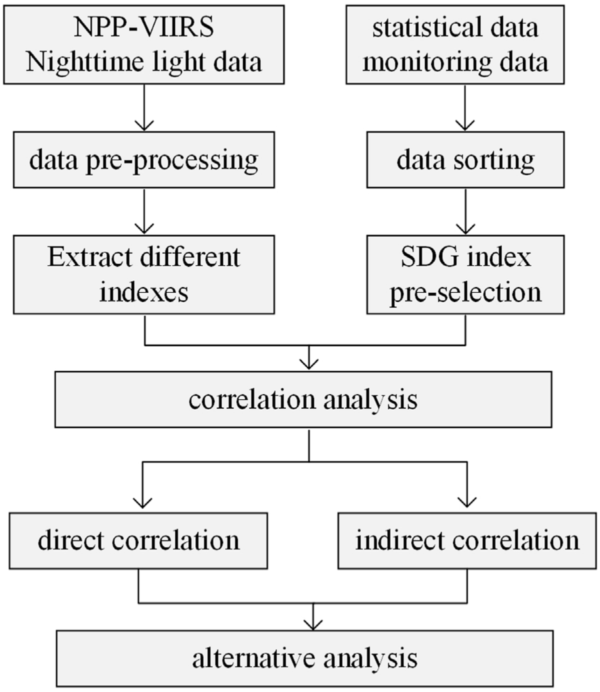

FIGURE 2
Research process.

light reflected from the lake surface. Hence, the lake surface also has a DN value. The maximum light intensity is 2.6. After the expressway or mountainous road is identified, the intensity value reaches about 1. If a uniform threshold is adopted, the lights of most roads will be eliminated, so the changes of passenger and freight development cannot be reflected. Therefore, the DN value should be assigned as 0 after the water area is extracted. In this study, denoising was conducted with noise threshold method according to the comparison results gained via Zheng Tan's denoising methods. Negative values were obtained during denoising in other areas, but this situation was not explained in CSM/EOG data description, so the negative values were assigned as 0. According to related studies, the threshold value of other areas was assigned as 0.41 (Zheng, 2020), and the processing results are shown in Figure 3.

2.3.2.2 Nighttime light indexes

The existing studies have many methods to express the nighttime light indexes, but previous studies indicate that the total nighttime light index (TNLI) is highly correlated to indicators like social economy, population increase and climate changes. Therefore, this indicator was adopted for research and evaluation (Li et al., 2016; Zhu et al., 2017; Andreano et al., 2020; Wang et al., 2021).

$$\boldsymbol{TNLI} = \sum_{DN_{min}}^{DN_{max}} (\boldsymbol{DN_i} \times \boldsymbol{n_i}) \tag{1}$$

Where *TNLI* is the total of *DN* values of lights in the administrative unit; DN_i and n_i are the pixel value and number of pixels at the *i*th gray scale in the administrative unit.

2.3.3 Indicator selection

The nighttime light is one of the effective modes to reflect human social activities at night, and the nighttime light intensity and cover area will effectively display the social activities and movement areas. Social activities depend on the local economic, cultural and urban development degree, and the urban development requires government investment in basic services. In this study, the influence degree of the indicator on the region and the substitutability for the light data were considered according to 248 indicators of 17 goals in the Framework for United Nations Sustainable Development Goals, to obtain 16 localization indicators (LIs) for correlation degree analysis. The 16 localization indicators were further grouped into 34 analyzable variables. For example, GDP was divided into GDP gross and GDP of the primary, secondary and tertiary industries. For the convenience of indicator characteristic analysis, the author discussed the validity of light data in SDG indicator evaluation after referring to the studies of scholars like Zheng Xinzhu and Wu Xutong (Zheng et al., 2021; Wu et al., 2022). In this study, the indicators were divided into economic indicators (basic service expenditures, medical workers, number of beds, crop cultivation area, passenger and freight volume, construction land and public space) and environmental indicators (water consumption, $PM_{2.5}$ and PM_{10}). The specific division is shown in Table 3.

2.3.4 Correlation analysis

Wang, Chen, and Zhen et al. employed linear regression analysis to examine the relationship between NTL and various socio-economic factors, including the economy, population, transportation, energy consumption, environment, and other relevant indicators (Wang et al., 2020; Zheng et al., 2020; Chen et al., 2022). Linear regression offers robust modeling and interpretability, making it the preferred choice for exploring the connection between nighttime lighting and diverse sustainable development metrics. This study investigates the correlation between TNLI and LI from 2016 to 2020.

$$\boldsymbol{LI} = \boldsymbol{aTNLI} + \boldsymbol{b} \tag{2}$$

where a is the slope, and b is the intercept.

3 Results and analysis

3.1 Correlation between TNLI and various indicators of the whole province

In this study, correlation analysis was made with provincial TNLI and localization indicators, and the results are shown in the 34 specific indicators (Table 4). Four indicators including education expenditure, quantity of employment in the primary industry, quantity of employment in the tertiary industry and urban development land have a significant correlation with TNLI at the level of 0.01, indicating that the 4 indicators are highly related to TNLI; 13 indicators including expenditures for medical care and public health, total energy consumption, energy consumption of the tertiary industry, and total output value have a significant correlation with TNLI at the level of 0.05, indicating that the 13 indicators are highly related to TNLI; 17 indicators including

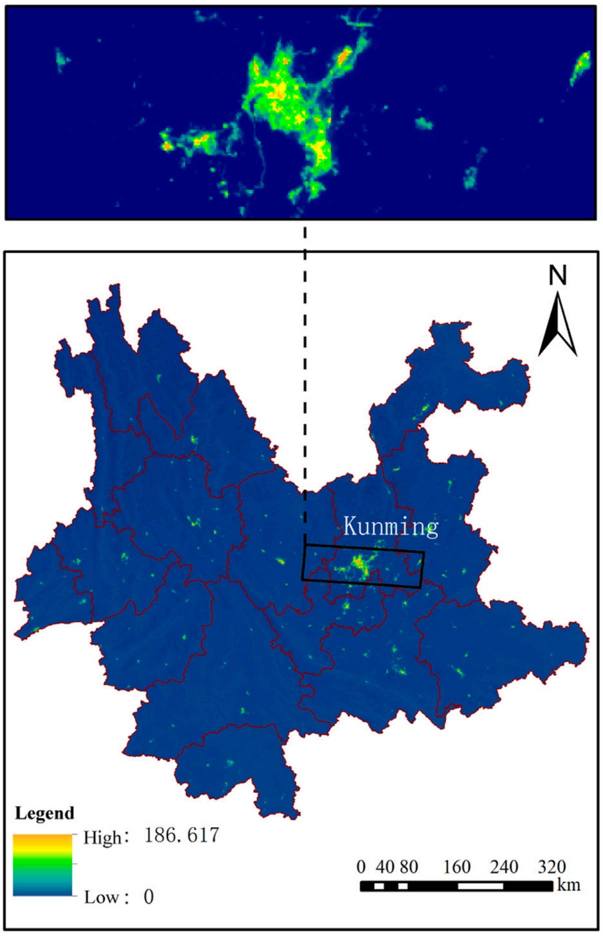

FIGURE 3
Nighttime light in Yunnan Province in 2020.

energy consumption of the primary industry, energy consumption of the secondary industry and total tourism income do not have a significant correlation with TNLI, so the correlation between the 17 indicators and TNLI is relatively low, and TNLI cannot be used to substitute these indicators.

A contrastive analysis was made after the 34 indicators were classified according to economy, society and environment, and the following results were gained. TNLI showed a high correlation with 10 indicators in 19 subdivided indicators of economic class; TNLI presented a high correlation with 6 indicators in 9 subdivided indicators of social class; TNLI had a high correlation with 1 indicator in 6 subdivided indicators of environmental class. Therefore, TNLI can be used to substitute some related indicators in evaluation, while TNLI has a low correlation with environmental indicators, so the evaluation precision is relatively low.

The total nighttime light index and economic indicators have a significant correlation mainly because the nighttime light can reflect the expansion and activities of a city, and regional economy is the main framework to support urban expansion and nighttime activities. Meanwhile, with the urban expansion and increase of nighttime activities, economic growth can be promoted, and a virtuous circle will be formed. Thereinto, basic service expenditures (education, medical care and public health, social insurance, and employment expenditure) and nighttime light indexes show an obvious correlation, and the basic service expenditures can reflect the developmental level of a city. When the government funds increase obviously in medical care and public health, social insurance, and employment expenditures, it means that the population of the city rises, the economy grows, and the city develops rapidly. As for the nighttime light, the city changes are reflected in the brightness degree and brightness scope. The increase of basic service expenditures indicates urban development, which is reflected as the increase of TNLI. But it is worth thinking about that TNLI has a significant positive correlation with the average wage indexes of state-owned firms and other firms, while it has a negative correlation with the average wage indexes of urban collective firms. Though the significance is low, the trend is obvious. Hence, the social and economic development has produced a certain influence on the development of urban collective firms in Yunnan Province.

The total nighttime light index presents a significant correlation with some social indicators. Thereinto, TNLI has a significant correlation with the quantity of employment; it presents a positive correlation with the population of the secondary industry and tertiary industry, but shows a negative correlation with the population of the primary industry. With the development of the secondary industry, more and more factories are established, the employment demand increases, and the quantity of employment rises. Many large factories have obvious nighttime light brightness, so the quantity of employment in the secondary industry has a significant correlation with the value of TNLI. Yunnan Province is a large tourism province, and its service industry develops rapidly. TNLI and the quantity of employment in the tertiary industry increased year by year from 2016 to 2019, showing a high growth rate. Though the total quantity of employment increased during the COVID-19 pandemic in 2020 when compared with that in the previous year, the growth rate was low. TNLI has a significant correlation with urban construction land, but has no significant correlation with the cultivation area. However, the negative correlation trend is consistent with the urban expansion trend. With the urban expansion, the nighttime light area increases, the total brightness rises, and the agricultural cultivation area decreases. The possible reason of not presenting a significant correlation is as follows. Some plowlands are ecological projects transformed in the activities of returning farmland to forests and returning farmland to grassland, rather than building land. Therefore, the amplitude of light growth is inconsistent with the reduction of agricultural land, which results in a low correlation.

The total nighttime light index has a relatively low correlation with environmental indicators, but the trend is obvious. As for different indicators, the correlation between TNLI and water consumption of the primary and secondary industries is insignificant and no such trend exists. However, it is highly correlated with domestic water consumption. As for the reason, the statistics of domestic water consumption covers service water consumption and common domestic water consumption of the tertiary industry. Besides, the activity degree of service industry is closely associated with the water consumption, so TNLI presents a significant correlation with the domestic water consumption. The value of $PM_{2.5}$ or PM_{10} has a negative correlation with TNLI (Chen et al., 2022). This is consistent with Zhang's results of predicting

TABLE 3 Localization indicators after screening.

Dimension	Goal	Specific goal	Indicator	Localization indicator	Corresponding name
Economy	1	1.a	1.a.2	Proportion of expenditures for basic services (medical care and public health, education, and social insurance) in the total government expenditure	Fiscal expenditure
	7	7.3		Energy consumptions of different industries	Division of energy consumption according to three industries
	8	8.1	8.1.1	Annual growth rate of GDP *per capita*	GDP *per capita*
	8	8.5		Annual incomes of different occupations	Labor remuneration for personnel employed in urban firms of different sectors at the end of the year
	8	8.9		Annual income from tourism	Tourism development situations
	8	8.9		Income from day trip to the border	Exchange revenue from day trip to the border
	9	9.2		Output value above designated size	Output value of industries above designated size
	17	17.11		Total border trade volume	Total export-import volume of various cities and prefectures
Society	2	2.1		Cultivation area for agricultural products	Cultivation area for main agricultural products
	3	3.c	3.c.1	Number of health workers	Number of personnel engaging in healthcare institutions; number of beds *per capita* among 10,000 people
				Number of beds *per capita* among 10,000 people	
	8	8.5		Quantity of employment	Division of year-end employment according to three industries
	9	9.1	9.1.2	Freight and passenger volume	Freight and passenger volume of main years
	11	11.3		Sustainable city construction	Construction land area
	11	11.7	11.7.1	Area of open public space in urban construction district	Public space area
Environment	6	6.4		Water consumption	Water consumptions of different industries
	11	11.6	11.6.2	Annual mean of fine particulate matter in the city ($PM_{2.5}$, PM_{10})	Monthly urban particulate matter values

$PM_{2.5}$ via VIIRS nighttime light data in Beijing-Tianjin-Hebei region (Zhang et al., 2020). Meanwhile, Xu et al. also constructed a correlation model with $PM_{2.5}$ by utilizing the DN value of DMSP/OLS nighttime light data in Shanghai, and the results show that the nighttime light index has a significant correlation with $PM_{2.5}$ (Xu et al., 2015). Zhang and Zhao conducted verification through establishing a model of nighttime light index and $PM_{2.5}$ in time series, while they selected different areas. However, the overall results are consistent with our research results in Yunnan. Therefore, it is considered that the spaces are connected, so $PM_{2.5}$ has a correlation with nighttime light index in spatial scale, which can be verified by the fact that the correlation is high in different cities in this study. At the same time, the correlation analysis and prediction model of nighttime light index and $PM_{2.5}$ is established in time series, so they are correlated in time series.

3.2 Correlation between TNLI and SDG indicators of different cities

Cities at different development levels have significant differences in light intensity and scope. To further analyze the applicability of lights in cities at different development stages, and further measure the correlation between TNLI and various indicators, correlation analysis was made for the localization indicators and TNLI of various cities and prefectures in this study. Besides, the former five indicators having a significant correlation were screened and sorted (Table 5).

As shown in Table 5, when correlation analysis is made for TNLI and indicators of various cities and prefectures, it is discovered that the most correlated 5 indicators among the 20 segmentation variables are associated with economy. Besides, GDP and TNLI of the tertiary industry present a high significant correlation. In 16 cities and prefectures, 6 ones present a significant correlation between TNLI and GDP of the secondary industry; 5 ones present a significant correlation between TNLI and total output value; 5 ones show a significant correlation between TNLI and GDP *per capita*; 4 ones display a significant correlation between TNLI and GDP of the tertiary industry; 4 ones present a significant correlation between TNLI and import volume. The results of the 5 indicators are almost consistent with the correlation analysis results of provincial indicators.

Table 5 and Table 6 indicate that the applicable indicators have both similarities and obvious differences. As for the similarities, GDP and TNLI have a significant correlation in various cities and prefectures, but different cities show different types of significantly correlated GDP industries. Thereinto, in Kunming, Qujing,

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TABLE 4 Correlation between TNLI and provincial indicators.

Localization indicators	TNLI		Localization indicators	TNLI	
	Pearson correlation	Significance		Pearson correlation	Significance
Education expenditure	.985**	.002	Average wage index of urban collective firms	−.682	.205
Expenditures for medical care and public health	.938*	.018	Average wage index of other firms	917*	.028
Expenditures for social insurance and employment	.947*	.014	Number of health workers	.956*	.011
Total energy consumption	.904*	.035	Average number of beds per 10,000 people	.933*	.021
Energy consumption of the primary industry	.812	.095	Highway freight volume	.557	.329
Energy consumption of the secondary industry	.871	.055	Highway passenger volume	−.831	.081
Energy consumption of the tertiary industry	.904*	.035	Urban construction land	.964**	0.008
Total output value	.896*	.040	Urban public space	.824	0.086
GDP of the primary industry	.836	.078	Quantity of employment in the primary industry	−.983**	.003
GDP of the secondary industry	.940*	.018	Quantity of employment in the secondary industry	.943*	.016
GDP of the tertiary industry	.876	.051	Quantity of employment in the tertiary industry	.971**	.006
GDP *per capita*	.887*	.045	Total water consumption	.308	.614
Total tourism income	.655	.231	Agricultural water consumption	.659	.227
Foreign exchange earnings from tourism	−.124	.843	Industrial water consumption	−.506	.385
Growth rate of industrial added value above designated size	−.186	.764	Domestic water consumption	.879*	.050
Export volume	.707	.182	$PM_{2.5}$	−.762	.135
Import volume	.928*	.023	PM_{10}	−.830	.082

Note: ** Significant correlation at the level of 0.01 (two-tailed); * significant correlation at the level of 0.05 (two-tailed).

TABLE 5 The former five indicators of each city and prefecture and their correlation degree.

City and prefecture	GDP of the secondary industry		Total output value		GDP per capita		GDP of the tertiary industry		Import volume	
	Pearson Correlation	Significance	Pearson Correlation	Significance	Pearson Correlation	Significance	Pearson Correlation	Significance	Pearson Correlation	Significance
Kunming	0.929	0.022	0.901	0.037	0.93	0.022	0.873	0.53	0.864	0.095
Qujing	0.988	0.002	0.984	0.003	0.977	0.004	0.979	0.004	0.579	0.307
Yuxi	0.807	0.098	0.698	0.19	0.669	0.217	0.659	0.226	0.495	0.397
Baoshan	0.882	0.048	0.848	0.069	0.814	0.093	0.834	0.079	0.876	0.051
Zhaotong	0.822	0.088	0.76	0.136	0.807	0.099	0.7	0.188	−0.971	0.029
Lijiang	0.828	0.083	0.734	0.158	0.711	0.178	0.707	0.182	−0.521	0.368
Pu’er	0.951	0.013	0.58	0.305	0.524	0.365	0.504	0.387	−0.226	0.714
Lincang	0.582	0.303	0.944	0.016	0.932	0.021	0.908	0.033	−0.204	0.742
Chuxiong	0.788	0.113	0.742	0.15	0.635	0.25	0.744	0.149	0.097	0.877
Honghe	0.912	0.031	0.798	0.105	0.786	0.115	0.734	0.158	0.951	0.013
Wenshan	0.821	0.088	0.8	0.104	0.805	0.1	0.787	0.114	−0.808	0.098
Xishuang banna	0.996	0	0.987	0.002	0.953	0.012	0.968	0.007	0.877	0.051
Dali	0.856	0.064	0.805	0.1	0.773	0.125	0.755	0.14	−0.94	0.017
Dehong	0.833	0.08	0.757	0.139	0.747	0.147	0.742	0.151	0.65	0.236
Nujiang	0.871	0.055	0.888	0.044	0.886	0.045	0.914	0.03	0.699	0.189
Diqing	0.824	0.087	0.742	0.151	0.675	0.211	0.679	0.207	−0.979	0.021

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TABLE 6 Indicators related to the visibility of cities and prefectures.

City and prefecture	Significantly correlated indicators	City and prefecture	Significantly correlated indicators
Kunming	GDP *per capita*, GDP of the secondary industry, GDP, and total tourism income	Chuxiong	Total tourism income, industrial water consumption, and crop cultivation area*
Qujing	GDP (primary industry, secondary industry, tertiary industry, and *per capita*), total water consumption, domestic water consumption, export volume, and $PM_{2.5}$*	Honghe	GDP of the secondary industry, industrial water consumption, import volume, $PM_{2.5}$*, PM_{10}*, and crop cultivation area
Xishuangbanna	GDP (primary industry, secondary industry, tertiary industry, and *per capita*), and domestic water consumption	Wenshan	Agricultural water consumption, domestic water consumption, total water consumption, and PM_{10}*
Baoshan	GDP of the secondary industry, and PM_{10}*	Yuxi	-
Zhaotong	Import volume*	Dali	Import volume*, and oil plant cultivation area
Lijiang	$PM_{2.5}$*	Dehong	Total water consumption, and oil plant and crop cultivation area
Pu'er	GDP of the secondary industry	Nujiang	GDP (tertiary industry and *per capita*), total water consumption, total cultivation area*, and crop cultivation area
Lincang	GDP (primary industry, tertiary industry, and *per capita*), and export volume	Diqing	Import volume*, and oil plant and sugarcane cultivation area

Note: Items with * are indicators of negative correlation.

Xishuangbanna, Baoshan, Pu'er and Honghe, TNLI has a significant correlation with GDP of the secondary industry. Kunming, Baoshan, Honghe and Qujing are major industrial cities of Yunnan Province where industrial GDP occupies a high proportion. The growth rate can match the variation trend of the total nighttime light index. Therefore, TNLI can demonstrate the city development structure to some extent. Meanwhile, among the 12 cities and prefectures, the TNLI value of 6 ones is significantly correlated with the import-export volume; the export volume presents a positive correlation with TNLI of nighttime light, and the import volume presents a negative correlation with nighttime light indexes. This clearly shows the variation trend of the social development of Yunnan Province and even China in international trade. With the progress of the urban economy, society, science and technology, China begins to focus on export from import gradually.

3.3 Changing situations of TNLI and indicators during the COVID-19 pandemic

The COVID-19 pandemic greatly affected human social activities in 2020, and even changed people's production mode and lifestyle. Therefore, an impact was also produced on the correlation between nighttime light and SDG indicators. The applicability of light remote sensing data can be verified through analysis on the relation between remote sensing data of lights and SDG indicators during the pandemic period. The annual TNLI values from 2016 to 2020 were obtained after the nighttime light images were processed. Results show that the annual total nighttime light index grew from 2016 to 2020, and the nighttime light intensity increased obviously from 2016 to 2019, with the average annual growth above 5.8%. From 2019 to 2020, the growth rate of TNLI obviously dropped to only 2.79%. As for the reason, COVID-19 broke out around the world in the end of 2019, and mass infection appeared. Most of Chinese areas were locked down, to stop the pandemic transmission. Yunnan Province has a long boundary line and complex landform, and many people illegally cross the national border, making pandemic prevention and control the most complicated and difficult here. A large number of border cities closed their borders due to the impact of the pandemic, and suspended the import and export trades. In the first half year of 2020, Yunnan Province took lockdown measures due to the pandemic influence, resulting in the decrease of brightness. In the second half year, the pandemic was controlled, and the economic society began to move orderly, so the economic growth rebounded. Therefore, TNLI started to rise, but the growth rate was low. This situation was consistent with the indicators like GDP of Yunnan Province, and a small growth rate was presented.

According to the analysis on the light weakening areas (Figure 4) in 2020 and 2019, Kunming City is the mega-city of Yunnan Province, central city of Yunnan City Cluster, and important central city of Western China. After the pandemic broke out, the light intensity in densely populated areas weakened obviously, and aggregated weakening was presented in a large area. Moreover, the road lights linked to surrounding cities also showed a trend of extensive weakening. In tourism cities with famous sceneries including Lijiang, Xishuangbanna and Yuxi, the nighttime light weakening areas mainly gathered in hotel clusters of scenic spots, such as regions around Fuxian Lake of Yuxi City, Jinghong of Xishuangbanna, and regions around the seabeach scenic spot of Dali. However, in underdeveloped and sparsely populated cities of border regions including Pu'er, Lincang, Baoshan and Dehong, light weakening mainly happened to road lights, borders and villages. Owing to the impact of the pandemic, the import and export business was strictly controlled in these areas, resulting in poor logistics. However, in Table 4, the highway passenger volume and freight volume show a low correlation coefficient with TNLI. To deeply analyze the relation between passenger and freight volume and TNLI, the road total nighttime light index (RTNLI) was extracted, and the correlation with passenger and freight volume

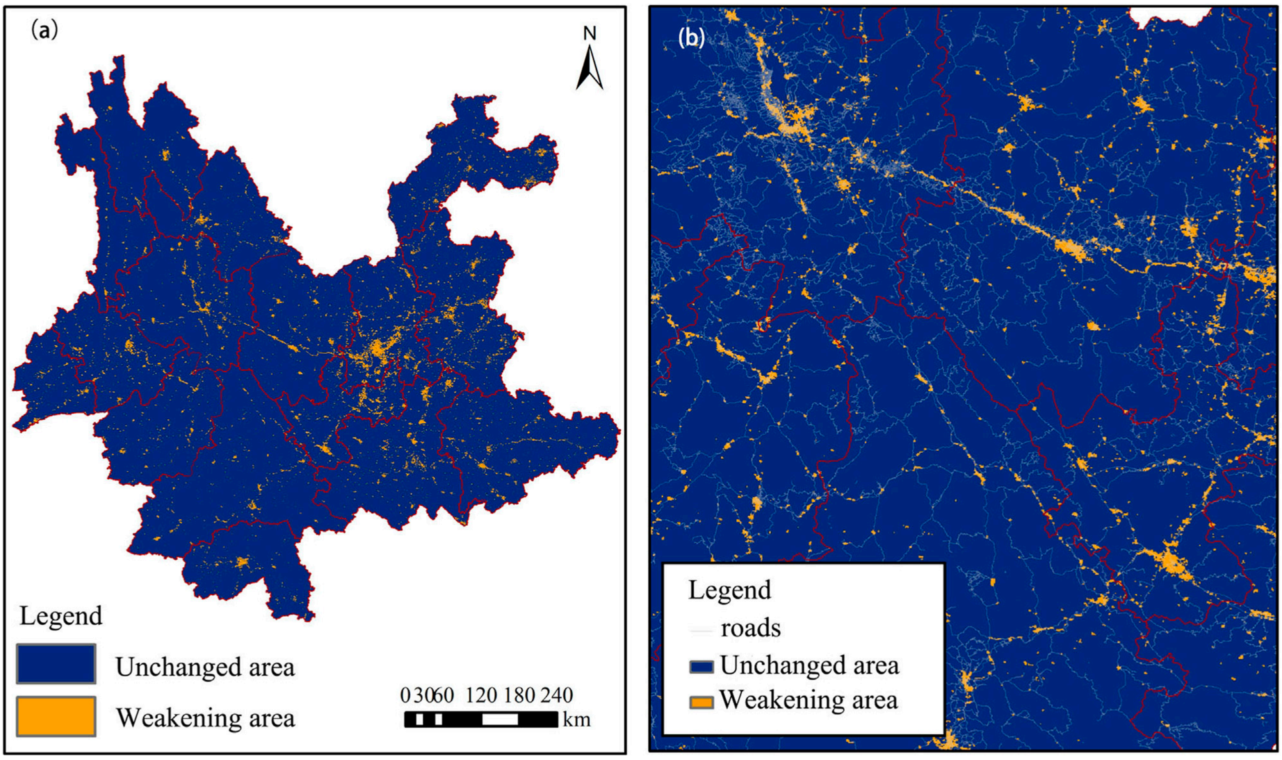

FIGURE 4
Nighttime light weakening area in Yunnan Province from 2019 to 2020 **(A)** and nighttime light weakening area overlaps with road network **(B)**.

TABLE 7 Correlation between RTNLI and road indicators.

		Total passenger volume	Total freight volume	Passenger volume (highway)	Freight volume (highway)	Passenger volume (highway + railway)	Freight volume (highway + railway)
RTNLI	Pearson correlation	−0.561	0.791	−0.682	0.756	−0.58	0.792
	Significance	0.325	0.111	0.205	0.139	0.305	0.11

was calculated. After road network extraction, correlation analysis was made for RTNLI and various indicators like passenger volume and freight volume, and the results are shown in Table 7. The passenger volume has a negative correlation with RTNLI, and the freight volume shows a positive correlation with RTNLI. Besides, RTNLI has a low correlation with the freight volume, as many urban road networks overlap building lights in the process of road network extraction. The urban road network brightness is influenced by building lights and roads, so unusually high values of nighttime light intensity appear. As a result, RTNLI has a low correlation with indicators like passenger volume and freight volume, and the road network should be further extracted and analyzed.

As early as 2020, some researchers had used NTL data to analyze the regional and global and human reactions to COVID-19. Elvidge et al. the degree of change in NTL light and darkness in residential administrative units of the Chinese population before and after the epidemic, demonstrating the feasibility of using nighttime lighting as a proxy to monitor the fluctuations in economic activity levels (Elvidge et al., 2020). Wang et al. examined the impact of the COVID-19 pandemic in Toronto, Canada, on residential areas, public facilities, and commercial areas to gain an initial understanding of how the pandemic affected human (Wang et al., 2022). Beyer et al. analyzed economic changes in India during the pandemic using nighttime light data and daily electricity consumption data (Beyer et al., 2020). The combination of our research in Yunnan Province with other regions and reveals profound connections between nighttime lighting data and disease outbreaks. While these connections may not be directly caused by an outbreak, they provide crucial information changes in socio-economic and human activities, aiding our understanding and response to such outbreaks. **Economic Activity**: Nighttime lighting data can effectively reflect the level of activity. During an outbreak, governments may impose lockdowns or restrictions, leading to business closures, labor shortages, and supply chain disruptions. These changes manifest in nighttime lighting data as businesses close or reduce their

TABLE 8 Nighttime light sensors of different types.

	DMSP/OLS	NPP-VIIRS	International space station	LJ1-01	SDGSAT-1
Availability	1992–2013	2011-	2003	2017-	2021
Country	The US	The US	The US, Russia, etc.	China	China
Spatial resolution	2.7 km	742 m	5–200 m	130 m	40 m (Visible bands)

operating hours, leading to diminished lighting. Human Behavior: Nighttime lighting data can also capture changes in human behavior. During an outbreak, individuals may self-isolation, stay at home, reduce social interactions, and limit nighttime outings, in a decrease in nighttime lighting. Moreover, curfews and indoor occupancy restrictions can further influence nighttime lighting Consequently, nighttime lighting data can serve as a valuable monitoring tool in large-scale health emergencies, aiding decision-making and resource allocation.

4 Discussion

4.1 Nature of correlations and substitutability degree between nighttime light index and SDG indicators

Nighttime light imagery captures the temporal patterns, spatial extent, and intensity of human activities by utilizing visible and near-infrared wavelengths. Sustainable development entails the harmonious progression of human economy, society, terrestrial resources, and environment. Sustainable development indicators can measure the progress of human advancement towards sustainability and the potential of future sustainable development. Therefore, the inherent correlation between nighttime light indexes and SDG indicators lies in the interconnection between human economic and social activities and the global resources and environment (Henderson et al., 2018). By establishing links between nighttime light indexes and indicators of human social activities as well as the interrelations between human activities and resource-environment indicators, a certain scope of the relationship between nighttime light and the three dimensions of SDG indicators—economic, social, and environmental—can be delineated. Simultaneously, synergies and trade-offs exist among SDG indicators, which are intricate (Miao et al., 2022). Through these relationships, seemingly unrelated indicators can be further associated with nighttime light indexes.

4.2 Result differences caused by nighttime light sensors of different types

With the development of human society, the progress of remote sensing technology and the increase of human demand for development region, situation and development density, the Nightsat satellite system has become increasingly mature (Elvidge et al., 2007). Nighttime light data widely used at present also include Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) data from the United States Department of Defense in 1992, photographs from the International Space Station (ISS-P) NTL data jointly issued by countries like the US and Russia in 2000, luojia1-01 (LJ1-01) NTL data operated by Wuhan University, China in 2018, and SDGSAT-1 NTL data newly released in 2021. The different technological levels of these sensors have led to performance differences (Jiang et al., 2018), as shown in Table 8.

This study did not consider the influence degree of different nighttime light sensors on the correlation between substitutive indicators. However, scholars have proven that the model accuracy can be increased with a higher resolution ratio and long observation time series. Guo meticulously compared and analyzed the abilities of many different sensors to investigate the spatial variability. Results indicate that SDGsat-1 NTL images are superior to VIIRS-DNB and LJ1-01 images in spectrum and spatial resolution, and better than ISS-P, LJ1-01 and VIIRS-DNB images in the ability of differentiating various land-use types with RGB wave band and gray intensity (Guo et al., 2023). Zhang also made a correlation analysis on LJ1-01 and NPP-VIIRS NTL data and $PM_{2.5}$, and the results show that LJ-1 data have revealed extra details and increased the precision of predicting $PM_{2.5}$ (Zhang et al., 2020).

4.3 Global applicability of substitutive indicators

Through analyzing the correlation between nighttime light index and SDG indicators, this study tries to make up the defect of traditional survey data in update frequency, which is a common problem all over the world. Moreover, it expects to strengthen dynamic monitoring and regulation on the sustainable development level of cities. The feasibility of this idea in Yunnan Province has been verified in this study, but no study is conducted in a global scale. However, scholars of other countries made a correlation analysis on the single indicator. Corona evaluated the political and economic activity indicators of Mexico (IAEM) with nighttime light data, and realized improvement (Corona et al., 2023). Galimberti assessed the usefulness of satellite-based nighttime light data for predicting the annual GDP growth of 167 countries around the world from 1993 to 2014, and the results indicate that nighttime light data and GDP have a significant correlation (Galimberti, 2020). Hasi Bagan made a correlation analysis on the construction areas and nighttime light data of 50 cities around the world, and the results show that the nighttime light data are corresponding to the building zone density (Bagan et al., 2019). Meanwhile, many scholars have verified the relation between nighttime light data and $PM_{2.5}$ and PM_{10} (Ji et al., 2018). The above studies can support the substitutability analysis of nighttime light data for some missing SDG indicators around the world, while the results in different countries vary greatly.

5 Limits

In this study, some indicators have a low correlation with TNLI, which is inconsistent with the expected results. Factors causing such results might include the following. First, various indicators are not uniformly distributed: economic indicators occupy nearly 56% of the 34 indicators, social indicators take up 26%, and environmental indicators account for 18%. Therefore, owing to the lack of subdivided indicators, the correlation between nighttime light data and various types cannot be completely reflected. Second, different types of indicators vary in the intrinsic correlation: economic indicators present the highest intrinsic correlation, while environmental indicators show the lowest intrinsic correlation. Third, only the total nighttime light index was used to represent the nighttime light index in this study. The studies of some scholars show that the total nighttime light index is the most sensitive to human social activities, but different types of indicators might have different correlations with different nighttime light indexes. Fourth, the time series was short in this study, and an analysis was made for the correlation between nighttime light intensity and SDG indicators from 2015 to 2020 only, while some indicators require a long time series to observe their correlation with nighttime light intensity. Finally, COVID-19 has produced a long and persistent impact on social development. However, only the first year of COVID-19 was analyzed in this study, and no continuous study or analysis was carried out. Therefore, it cannot fully reflect the advantage of using nighttime light data to analyze social changes after COVID-19. Meanwhile, it is also the most regrettable that only nighttime light data were adopted to study the substitutability for SDG indicators in this paper, while other data sources were not excavated. Hence, severe deficiency still exists in substitutability, and few assistances can be provided for dynamic contrast on sustainable development between countries.

Based on the above factors which cannot be considered or realized temporarily, the author of this paper will try to focus on the following points, and make in-depth analysis. In research data, a longer time series will be chosen with the development of COVID-19, to obtain uniformly distributed classification indicators. In the aspect of research methods, a correlation analysis will be made with different indicators like average light intensity, composite light index and light-area ratio, to find out the most appropriate indicators. Moreover, different correlation equations will be applied in the future, and multiple correlations will be added when the relation between data is considered, to discover more complicated relations between nighttime light indexes and SDG indicators. Moreover, other multi-source data will be integrated, to explore faster evaluation methods with strong applicability in the future.

6 Conclusion

Through considering the influence of SDG evaluation indicators on the region and the substitutability for light data, 16 localization indicators were obtained and further divided into 34 subdivided indicators. After an analysis was made for the correlation between total nighttime light index and these subdivided indicators of Yunnan Province from 2016 to 2020, the following results have been gained. 1. Among the 34 subdivided indicators, TNLI has a significant correlation with 20 indicators, so it is highly feasible to evaluate the substitutability of nighttime light data for SDG indicators. Thereinto, 1. a.2 (proportion of the basic service expenditure in the total government expenditure), 8.1.1 (annual growth rate of GDP *per capita*) and 3. c.1 (number of health workers and number of beds *per capita* among 10,000 people) have a relatively high correlation with the total nighttime light index, so the total nighttime light index can be applied for substitution evaluation. 2. The 34 indicators were divided into economic, social and environmental classes, and the following conclusions have been obtained: TNLI has a significant correlation with 10 economic indicators among the 19 ones, a significant correlation with 6 social indicators among the 9 ones, and a significant correlation with 1 environmental indicator among the 6 ones. Therefore, substitution evaluation of nighttime light is more applicable to economic and social indicators, while the performance in environmental indicators is not good. 3. The nighttime light data have different correlations with various industries. Generally speaking, the total nighttime light index shows a relatively high correlation with the secondary and tertiary industries. In addition, the leading industries of different cities can be judged according to the correlation between nighttime light data and GDP and total energy consumption of different industries. 4. During the COVID-19 pandemic, the total nighttime light index and GDP of Yunnan Province in the year presented a decreasing growth rate but a slight increase in the total quantity. TNLI has a relatively high correlation with indicators affected by the pandemic, such as quantity of employment and wage index. These indexes can reflect the influence degree of the pandemic on the local society to some extent and the bad consequences caused to sustainable development by such influence. Therefore, the total nighttime light index can be choosen to analyze the influence of the pandemic on sustainable development.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XQ: Conceptualization, Methodology, Resources, Software, Writing–original draft. XS: Formal Analysis, Writing–review and editing. JM: Data curation, Investigation, Visualization, Writing–review and editing. CH: Funding acquisition, Project administration, Validation, Writing–review and editing. FG: Supervision, Validation, Writing–review and editing. JL:

Validation, Writing–review and editing. LY: Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work is supported by the Open Research Program of the International Research Center of Big Data for Sustainable Development Goals, Grant No. CBAS2023ORP04.

Acknowledgments

The authors would like to thank the editor and reviewers for their valuable comments.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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