# Nighttime Light as a Proxy for Socioeconomic and Environmental Change in Urban and Mining Contexts

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**Abstract.** This study applies Nighttime Light (NTL) data in conjunction with socioeconomic and environmental parameters to investigate two contrasting sites in Mongolia: the urban area of Ulaanbaatar and the Energy Resources LLC (ER) open-pit coking coal mine site. The primary objective is to assess the extent to which NTL intensity correlates with key indicators, such as Gross Domestic Product (GDP), population, energy use per capita (EUPC), and carbon dioxide (CO2) emissions.

In Ulaanbaatar, NTL data effectively captures patterns of urban expansion and exhibits strong alignment with economic development and demographic growth. In contrast, the NTL signal at the ER mining site highlights activity zones and infrastructure associated with coal extraction, demonstrating a more variable spatial and temporal pattern that is responsive to market fluctuations and logistical adjustments.

The study further examines innovative interpretations of NTL in both urban and industrial contexts. In urban settings, NTL typically reflects complex, large-scale mixed-use lighting environments. Conversely, in mining areas, NTL is capable of distinctly delineating functional zones, including extraction areas and transportation corridors. Notably, during the COVID-19 pandemic, the relationship between NTL and conventional indicators was disrupted. Despite significant declines in GDP, CO2 emissions, and energy consumption, both NTL intensity and population levels remained relatively stable. This decoupling suggests that NTL may have limitations as a proxy indicator during periods of global or systemic disruption.

Overall, the results highlight the utility of NTL data as both a quantitative metric and a visual diagnostic tool for spatial monitoring and planning in data-scarce contexts such as Mongolia, where official statistics are often limited, delayed, or inconsistent.

**Keywords:** Nighttime light data, Mongolia, Mine area, Correlation analysis.


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# 1. Introduction

In recent years, a growing number of studies have employed nighttime light (NTL) data acquired from satellite-based low-light sensors to assess and analyze anthropogenic activities across the Earth's surface [1]. Owing to their global coverage and high spatial resolution, such satellite observations enable multi-scale analysis ranging from continental trends to sub-kilometer patterns of human activity. NTL data serve as a valuable indirect proxy for understanding the socio-economic and environmental characteristics of a given area, particularly in contexts where ground-based data are scarce or inconsistent. This capability renders NTL especially useful in developing countries such as Mongolia, where access to reliable and timely demographic, economic, and environmental statistics remains limited. Consequently, NTL provides an effective alternative for monitoring human activity and socio-economic dynamics with fewer data constraints.

Mongolia's economy is substantially dependent on its extractive industries, particularly large-scale mining operations such as the Erdenet and Oyu Tolgoi copper-gold mines. As of 2022, the mining sector accounted for approximately 24% of the national Gross Domestic Product (GDP), underscoring its central role in the country's economic development [2]. However, this growth has also brought about increasing concerns regarding the sector's environmental and social impacts, which require further investigation through integrative approaches.

This study explores the relationship between NTL intensity and selected socio-economic and environmental indicators in two contrasting contexts within Mongolia: the urban environment of Ulaanbaatar city and the industrial zone of the Energy Resource LLC open-pit coal mine. By applying both linear and non-linear regression analyses, the study identifies positive correlations between NTL intensity and GDP, population, energy use per capita (EUPC), and carbon dioxide (CO2) emissions. These findings suggest that NTL data can be a valuable tool for capturing spatial and temporal patterns of development and environmental change in resource-constrained settings.

# 2. Methodology

## 2.1. Study Area

As the representative urban area, Ulaanbaatar, the capital city of Mongolia, was selected for this study. Ulaanbaatar is a densely populated region characterized by diverse economic activities. With a population of nearly 1.7 million, the city accounts for approximately half of Mongolia's total population [3]. In addition to its demographic significance, Ulaanbaatar plays a dominant role in the national economy, contributing 63% of Mongolia's GDP in 2022 [3].

For the representative mining site, this study focuses on the mining operations of Energy Resources LLC, located in the Ukhaa Khudag coal deposit in Tsogttsetsii soum, Umnugobi province. Since 2009, ER has been engaged in large-scale coking coal extraction through open-pit mining, operating continuously (24/7), which makes it an ideal candidate for NTL analysis. The mine is equipped with three coal processing plants, each with an annual capacity of 5 million tonnes, resulting in a total processing capacity of 15 million tonnes per year [4].

## 2.2. Data

This study employs nighttime light (NTL) data spanning the period from 2013 to 2023, obtained from satellite-based observations [5]. Over recent decades, various remote sensing techniques have been developed to detect and analyze the brightness and spatial extent of global NTL networks. A major advancement in this field was the launch of the Suomi National Polar-orbiting Partnership (SNPP) satellite in 2011 by the U.S. National Oceanic and Atmospheric Administration (NOAA). The SNPP, along with its successors NOAA-20 and NOAA-21, carries the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor, which plays a central role in capturing nighttime radiance data.

VIIRS radiance refers to the measured intensity of light emitted from a specific area on the Earth's surface. The primary product derived from this sensor is the VIIRS Visible Night Light (VNL), which provides high-resolution data on the location and brightness of illuminated human settlements, ranging from large metropolitan centers to small towns and dispersed housing clusters.

The quality of the VIIRS-derived NTL data is governed by two main principles. First, rigorous filtering is applied to remove undesirable inputs caused by sunlight, moonlight, stray light, and cloud cover, ensuring only valid nighttime observations are retained. Second, the reliability of the data is enhanced through the inclusion of a high number of observations. By averaging radiance values across multiple scan angles, scan-related distortions are minimized, and seasonal fluctuations are reduced by incorporating data collected over different times of the year. Together, these processes ensure the consistency and accuracy of the VIIRS VNL dataset for analyzing spatial and temporal patterns of human activity.

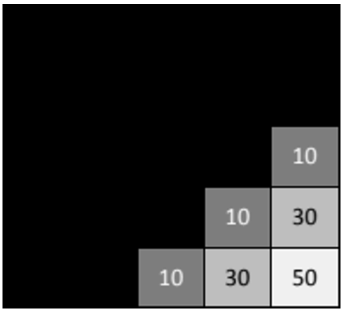


**Fig.1.** Grid map

As shown in Fig.1 each grid cell in the VIIRS dataset comprises 25 square pixels, with each pixel representing the observed radiance intensity at a specific location.

Higher resolution (smaller pixel size) can detect smaller areas of light, giving more detailed information about urbanization patterns. Lower resolution (larger pixel size) smooths out small details. The VIIRS sensor provides significantly higher spatial resolution compared to its predecessors, enabling more precise identification of the spatial distribution of light emissions across various geographic scales. This improved resolution makes VIIRS data particularly suitable for monitoring both urban and industrial areas.

Despite these advantages, several limitations persist. In highly illuminated areas, such as densely populated urban centers or large-scale industrial sites, light emissions can saturate the sensor, potentially resulting in a loss of detail and underestimation of radiance. Additionally, the presence of stray light, especially during periods of high lunar illumination, can degrade the quality of nighttime observations. Although the VIIRS system offers near-global coverage due to its polar orbiting configuration, data gaps may still occur in certain regions and seasons, particularly due to persistent cloud cover or limited observational opportunities at specific longitudes.

### 2.3. Methods

The annual mean radiance values from 2013 to 2023 were extracted and spatially clipped to two target regions: Ulaanbaatar city (UB) and the Energy Resources LLC (ER) coal mining site. ArcMap was utilized for geospatial preprocessing, including the removal of irrelevant areas, application of spatial masks, and refinement of the extracted data. The Otsu thresholding method was employed to delineate illuminated areas, thereby minimizing background noise and enhancing the accuracy of the extracted NTL data. Where necessary, spatial adjustments were performed to ensure alignment with real-world geographic coordinates.

Following these preparatory steps, the processed datasets were imported into MATLAB for further analysis. For each year, pixel-level radiance values were aggregated by summing the intensities within the defined region, resulting in a single representative annual value for both UB and ER. These annual mean radiance values were subsequently used for statistical analysis to explore the relationships between NTL intensity and selected socio-economic and environmental indicators, including Gross Domestic Product (GDP), population, carbon dioxide (CO2) emissions, and energy use per capita (EUPC).

Regression analyses, both linear and non-linear, were conducted to quantify these relationships. Residual plots were examined to evaluate the appropriateness of each regression model and to inform refinements in the analytical approach. Fitted values for each parameter were then generated based on the final models. Model performance was assessed using standard validation metrics, including the correlation coefficient ($R^2$), p-values, and Root Mean Square Error (RMSE), providing a comprehensive evaluation of model fit and predictive accuracy. Finally, scatter plots comparing estimated and observed values were produced to facilitate visual inspection of model consistency and reliability.

## 3. Results and Discussion

This study examines NTL data in relation to two contrasting land-use types: a mining area and an urban area. These regions exhibit distinct social, economic, and environmental characteristics, which are expected to produce divergent patterns in NTL intensity and associated socio-economic indicators. Due to these fundamental differences, it is anticipated that NTL trends would reflect the unique dynamics of each area. However, the analysis reveals that the divergence between the two regions is less pronounced than initially assumed. Both the ER mining site and UB city demonstrate a consistent increase in NTL intensity over the 2013-2023 period, as exemplified by the national scale NTL in 2023 as shown below in Fig.2.

In the case of the ER mining site, the upward trend in NTL intensity may reflect increased mining operations, heightened demand for coal, or rising market prices for coking coal. In contrast, the growth in NTL intensity in Ulaanbaatar is more likely attributed to urbanization processes and economic development, which typically correspond with increased human activity, infrastructure expansion, and population growth. These findings suggest that, despite their differing functions and contexts, both urban and industrial regions can exhibit parallel patterns in NTL dynamics, driven by sector-specific but equally influential socio-economic forces.

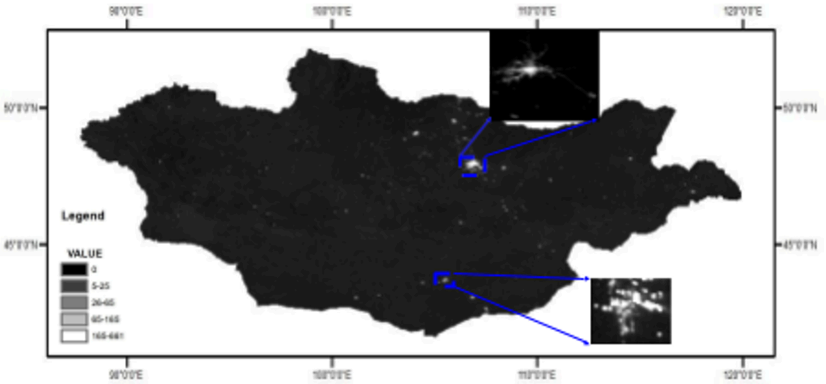


**Fig. 2.** NTL over Mongolia averaged for the period 2023

### 3.1. Ulaanbaatar

Otsu's method [6] was employed to determine an optimal threshold for binarizing the NTL imagery. This technique identifies a threshold that minimizes intra-class variance and maximizes inter-class variance, effectively separating the pixel intensity values into two distinct classes: typically referred to as "light" and "dark." In this context, pixels with intensity values below the threshold are categorized as the dark class, while those above are assigned to the light class, representing illuminated areas. This binarization process facilitates the delineation of regions exhibiting significant nighttime light emissions.

Following binarization, the total area of the NTL-illuminated region in Ulaanbaatar was estimated. First, the total extent of the grid map was divided by the number of pixels to compute the area represented by a single pixel (Fig. 3). This pixel area was then multiplied by the total number of pixels classified as '1' (i.e., above the threshold) in the binarized image, yielding an estimate of the total illuminated area. This approach provides a standardized and replicable method for quantifying the spatial extent of NTL across different regions and time periods.

**Fig. 3.** NTL featuring Ulaanbaatar before and after binarization

As urban areas continue to expand, the extraction of spatiotemporal patterns from NTL data provides valuable insights into urban growth and human activity dynamics. Figure 4 illustrates the spatial distribution of NTL in Ulaanbaatar city at biennial intervals from 2013 to 2023.

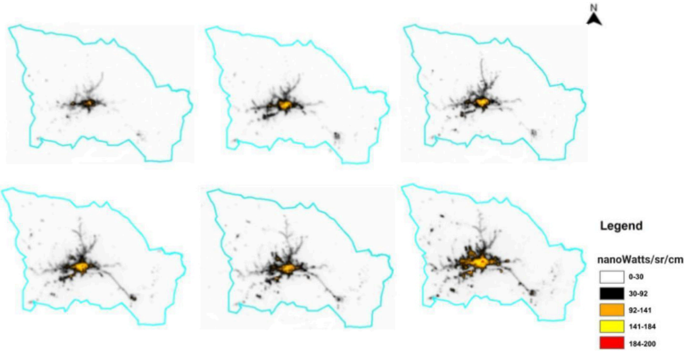


**Fig. 4.** NTL images of Ulaanbaatar city for 2013, 2015, 2017, 2019, 2021, and 2023

Ulaanbaatar is undergoing rapid urbanization, accompanied by a significant population influx, creating an upward pattern of socio-economic and environmental indicators, such as NTL intensity, GDP, CO2 emissions, and EUPC [3,10,11]. An upward trend in NTL intensity reflects the spatial expansion of urban areas and heightened economic activity. However, socio-economic growth is also closely tied to environmental consequences. For instance, increased GDP and electricity consumption associated with urban and economic development contributes to higher CO2 emissions, thereby intensifying the city's carbon footprint and exacerbating climate change impacts.

GDP data for Ulaanbaatar were obtained directly from the National Statistical Office of Mongolia [3], representing Ulaanbaatar's contribution of approximately 63% to national GDP. Linear regression analysis between NTL intensity and Ulaanbaatar GDP yielded a strong positive correlation: $R^2 = 0.82$, $p = 0.0042$. Though smaller compared to others GDP is still disrupted by COVID-19. The observed 82% variance explained by NTL aligns with global studies [12], validating its use for real- time GDP estimation in data-scarce regions like Mongolia.

Given these interdependencies, it is essential to systematically monitor these indicators and investigate their interrelationships. To assess the connections between NTL and socio-economic as well as environmental parameters, statistical techniques including correlation analysis and regression modeling were employed. These methods facilitate a comprehensive understanding of how urban development influences, and is influenced by, both socio-economic dynamics and environmental pressures

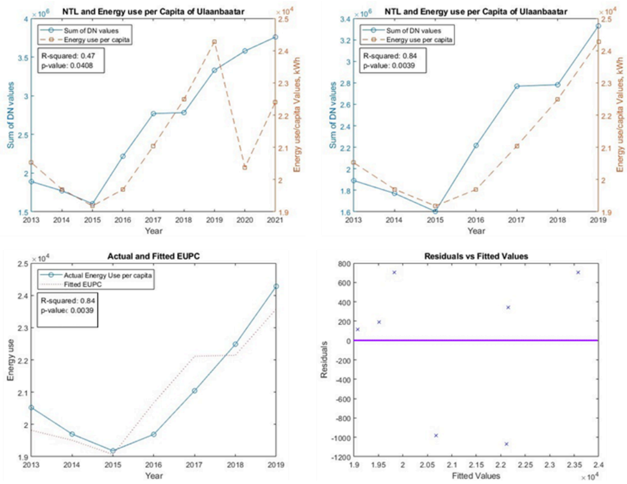


**Fig. 5.** Relationships between NTL and EUPC in Ulaanbaatar

EUPC exhibited a consistent upward trend throughout the study period, with the exception of a noticeable decline in 2020 (Fig. 5a). This drop aligns with the global economic downturn caused by the COVID-19 pandemic, during which global GDP contracted by approximately 3% due to widespread lockdown measures [7]. The deviation observed in 2020 is attributable to external disruptions rather than underlying economic or demographic trends. As such, the relationship between EUPC and other variables during this period is considered anomalous and may distort the validity of correlation analyses. Consequently, data from 2020 and 2021 were excluded from the second plot to maintain the robustness and interpretability of the regression results (Fig. 5b). As a result, the R-squared value increased from 0.47 to 0.84, while the p-value decreased from 0.0408 to 0.0039. These improvements indicate a stronger correlation and greater statistical significance, thereby supporting the validity of using NTL data as a proxy for estimating energy use at the urban scale. Furthermore, the residuals plot (Fig. 5d) reveals that the residuals are randomly distributed around zero, with no discernible pattern or trend. This suggests the absence of autocorrelation and heteroscedasticity, confirming that the model assumptions are met and that the regression results are robust.

The consistent patterns observed between 2013 and 2019 were significantly disrupted beginning in 2020, primarily due to the effects of COVID-19 lockdowns. These restrictions led to a sharp decline in economic activity and energy consumption, as evidenced by the steep drop in CO2 emissions [10]. Similar downward trends were also observed in other socio-economic and environmental variables. This phenomenon is consistent with global findings reported by Le Quéré et al. [8] and Doll et al. [7], who documented temporary reductions in CO2 emissions during the pandemic, attributed to decreased industrial production, reduced transportation, and lower overall electricity consumption.

In contrast, the pre-pandemic data (2013–2019) exhibit a clearer and more consistent upward trend in CO2 emissions [10], which corresponds with ongoing urban and economic development. Excluding the pandemic-affected years (2020-2022) from the analysis resulted in a substantial improvement in model performance, with the R-squared value increasing from 0.29 to 0.86. This enhanced fit is further supported by the similarity between the observed and fitted values, reinforcing the potential of NTL data as a reliable proxy for estimating urban CO2 emissions in non-disrupted periods.

### 3.2 Energy Resources mining site

The NTL data in assessment methodologies presents valuable opportunities for enhancing safety measures, promoting sustainable development, and analyzing socio-economic dynamics within the mining sector. Energy Resources LLC began its operations in 2009, investing approximately USD 1.4 billion in the Ukhaa Khudag project and contributing 1.2 trillion Mongolian tugriks in taxes. Within the first two to three years of operation, ER developed extensive infrastructure, including a coal processing plant, an 18-megawatt power plant, a water distribution system, residential housing, and educational facilities. These developments are likely to contribute directly or indirectly to the observed increase in NTL intensity at the site.

Analysis of spatial NTL patterns over time reveals distinct phases of mining activity (Fig. 6). The central administrative and vehicle service areas, which are represented by a persistent yellow cluster, exhibited stable light intensity throughout the study period, indicating continuous operational activity. In 2013, high NTL intensity was observed at the initial extraction site located immediately west of the main office. However, this intensity gradually declined by 2016, corresponding with a drop in global coal prices. Beginning in 2016, the NTL signal began shifting southwest, marking the transition to a second extraction site. Over subsequent years, light emissions expanded across this new site, reflecting resumed or increased mining activity.

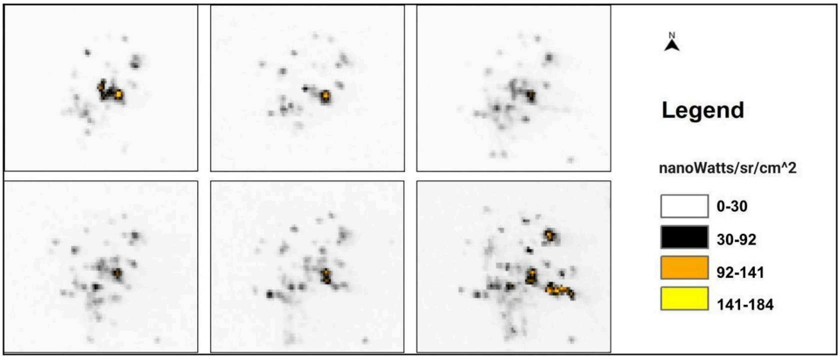


**Fig. 6.** NTL images over ER mining site for 2013, 2015, 2017, 2019, 2021, 2023

By 2023, a pronounced expansion of high-intensity NTL emissions was observed southeast of the main administrative complex, corresponding to the enlargement of logistics infrastructure. This rise in NTL radiance coincides with the operational commencement of the Gashuun Sukhait railway in 2021, a critical development that substantially enhanced coal export throughput. The spatial redistribution of luminosity thus mirrors the dynamic progression of ER's mining infrastructure and operational priorities, underscoring the efficacy of NTL remote sensing as a tool for tracking industrial expansion in geographically remote or data-limited environments.

The integration of NTL data into mining sector assessments presents a valuable opportunity to enhance safety protocols, sustainable conservation strategies, and socio-economic monitoring. ER commenced mining operations in 2009, followed by a USD 1.4 billion investment in the Ukhaa Khudag project, which contributed MNT 1.2 trillion in tax revenue. Within two to three years of initial operations, ER established a coal processing facility, an 18-megawatt power plant, a water distribution network, residential complexes, and an educational institution, i.e., infrastructural developments likely to have directly or indirectly elevated NTL emissions in the region.

Spatiotemporal analysis of NTL intensity reveals distinct operational patterns. The administrative headquarters and vehicle service areas (represented by the central yellow cluster) exhibited consistent luminosity, indicative of stable operational activity. In 2013, high-intensity lighting was concentrated at the primary extraction site, immediately west of the main office; however, luminosity at this location diminished progressively until 2016, coinciding with a decline in global coal prices. Post-2016, a spatial shift in light emissions occurred, with activity relocating southwestward toward a secondary extraction site before expanding across the area. By 2023, a pronounced increase in NTL intensity was observed southeast of the main complex, attributable to expanded logistics operations. This surge in luminosity along transport corridors aligns with the 2021 inauguration of the Gashuun Sukhait railway, a critical infrastructure project that facilitated a marked increase in coal export capacity.

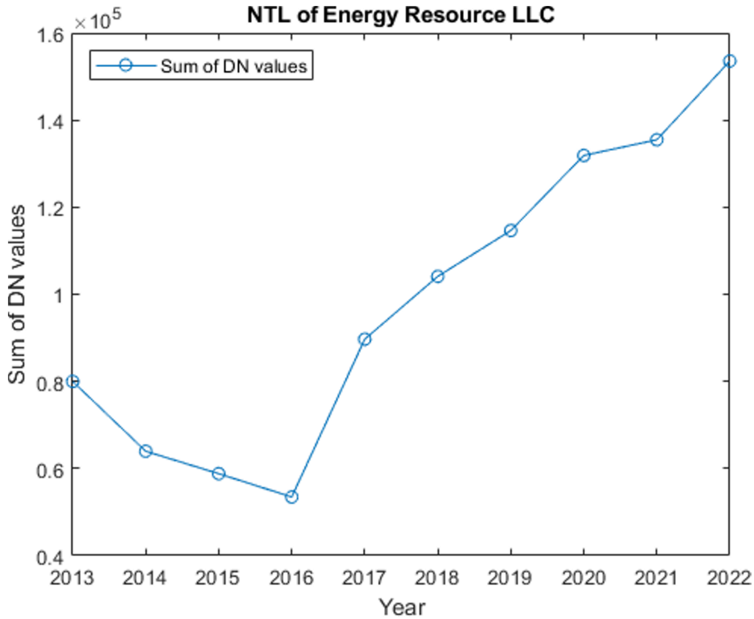


**Fig. 7.** NTL of ER for 2013-2022

In Fig. 7 the NTL data demonstrate an overall increasing trend between 2013 and 2023; however, a distinct three-year decline is observable from 2013 to 2016. This pattern is similarly reflected in both CO2 emissions [11] and annual tax contributions, albeit with minor deviations. The period of decline corresponds closely with the global downturn in coal prices, which began in 2012 and persisted until 2016. Conversely, the subsequent recovery in NTL intensity, CO2 emissions [11], and tax revenues after 2016 aligns with the rebound in global coal prices, suggesting a strong linkage between these variables and external market conditions.

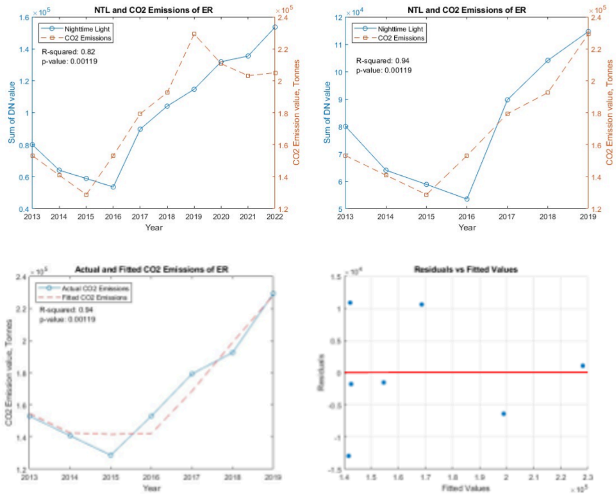


**Fig. 8.** The relationship between NTL intensity and CO2 emission in ER from 2013 to 2019 (2022)

The initial regression plot demonstrates a robust positive correlation between nighttime light (NTL) intensity and CO2 emissions within the mining region as shown in Fig.8, supported by a moderately strong correlation coefficient. However, a notable anomaly occurs in 2020, marked by a sharp decline in both NTL and CO2 emissions [11], a trend which is consistent with Ulaanbaatar's emissions data during the same period. This deviation is likely attributable to the COVID-19 pandemic and subsequent lockdown measures, which disrupted industrial activity. Consequently, post-pandemic years were excluded from the analysis to enhance the reliability of the observed relationship between the two variables.

Residual diagnostics reveal a random distribution around zero, with no evidence of systematic bias or heteroscedasticity, confirming the model's validity. These findings suggest that NTL data could serve as a more efficient and cost-effective proxy for estimating localized CO2 emissions compared to conventional measurement techniques.

## 4. Discussion

This study presents a comprehensive analysis of the NTL dynamics in Mongolian urban and mining regions, examining their socio-economic and environmental implications through correlations with datasets from Ulaanbaatar and ER, alongside other socio-economic variables. A consistent trend observed across nearly all datasets is a pronounced decline in 2020, coinciding with the COVID-19 lockdown measures. This exogenous shock introduced significant disruptions to data continuity, thereby compromising model robustness. To mitigate these distortions and enhance analytical clarity, post-pandemic observations were excluded from subsequent analyses.

In Ulaanbaatar, a strong positive correlation exists between NTL intensity and GDP, reinforcing the utility of NTL data as a proxy for economic activity. Notably, GDP exhibited greater resilience to lockdown-induced disruptions compared to other variables. In contrast, EUPC and CO2 emissions experienced marked volatility during this period, rendering NTL-based estimations unreliable. Such anomalies underscore the limitations of NTL-derived models in the face of unforeseen systemic shocks. Census data, however, remained the least affected variable, demonstrating its stability as a reference dataset. These findings align with established literature, which associates higher CO2 emissions per capita in economically developed urban centers with elevated energy demand, industrial activity, and transportation density [9].

Within the ER mining concession, all measured variables, including NTL intensity, CO2 emissions, and fiscal contributions, exhibited synchronous fluctuations with global coal price trends, particularly the prolonged downturn from 2012 to 2016. The observed rise in CO2 emissions concurrent with increasing NTL intensity reflects the environmental trade-offs inherent in mining expansion and operational scaling. Comparative analysis of urban and mining sites reveals divergent analytical opportunities: while larger urban areas enable complex, multi-variable assessments due to their socio-economic heterogeneity, mining sites benefit from the high spatial resolution of VIIRS data. This permits precise geolocation of light emissions, facilitating targeted identification of high-intensity zones (e.g., active extraction areas or logistics hubs) and their associated environmental impacts.

## 5. Conclusion

This study demonstrates the utility of NTL data as a robust proxy for monitoring socio-economic and environmental dynamics in contrasting settings: the urban landscape of Ulaanbaatar and the industrial mining operations of Energy Resources LLC (ER). The findings reveal that NTL intensity correlates strongly with key indicators such as GDP, energy use per capita (EUPC), and CO2 emissions, validating its applicability in data-scarce regions like Mongolia.

In Ulaanbaatar, NTL trends effectively captured urban expansion and economic growth, with high-resolution VIIRS data delineating spatial patterns of development. The strong positive relationship between NTL and GDP underscores its potential as a real-time indicator of economic activity, though the COVID-19 pandemic highlighted limitations during systemic disruptions. Notably, while GDP remained resilient to lockdowns, EUPC and CO2 emissions exhibited pronounced volatility, emphasizing the context-dependent reliability of NTL-derived models.

At the ER mining site, NTL dynamics mirrored operational shifts and market fluctuations, particularly the 2012-2016 coal price downturn and subsequent recovery.

The spatial redistribution of light emissions aligned with infrastructure developments, such as the Gashuun Sukhait railway, illustrating NTL's capacity to track industrial activity and logistical expansions in remote areas. The consistent linkage between NTL, CO2 emissions, and tax contributions further underscores the environmental trade-offs of mining-led growth.

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