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Multi-Scale Dynamic Analysis of the Russian–Ukrainian Conflict from the Perspective of Night-Time Lights

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Abstract: Under the influence of various forces, the conflict between Russia and Ukraine is violent and changeable. The obtaining of battlefield data by conventional means is difficult but necessary in order to ensure security, reliability, and comprehensiveness. The use of remote sensing technology can make up for the deficiencies of conventional methods. By using night-time light data, the total number of night-time lights in the built-up areas of Ukrainian cities within 36 days of the outbreak of the Russian–Ukrainian conflict is compiled in this paper. Furthermore, the dynamic changes in night-time light at the national, regional, and urban scales are analyzed by using the night-time light ratio index and the dynamic degree model combined with the time-series night-time light data. The results show that (1) after the outbreak of the war, more than 60% of the night-time lights in Ukrainian cities were lost. In terms of the night-time light recovery speed, the night-time lights in the pro-Russian areas recovered significantly faster, followed by Russian-controlled areas, and the recovery speed in areas of conflict was the lowest. (2) Decision-making by belligerents affects non-combatant activities and thus corresponds to light at night. The loss of night-time light will be reduced if military operations are reduced and mitigated if humanitarian operations are increased. (3) The changes in night-time light reflect the changes in the conflict situation well. When the conflict between Russia and Ukraine intensifies, the overall change of night-time light shows a downward trend. In this context, night-time light data can be used as an effective source to deduce and predict battlefield situations.

Keywords: night-time lights; NPP VIIRS; Russian–Ukrainian conflict; multiscale analysis; built-up area

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1. Introduction

Since the official outbreak of the Russian–Ukrainian conflict on 24 February 2022, local armed conflicts and riots have had an irreversible impact on the economic development, infrastructure, and population movements in the war zone in the short term. There is a strong link between war and refugees, and wars between nations can cause internal displacement as refugees flee combat zones [1]. On March 11, the United Nations refugee agency stated that 2.5 million people had fled Ukraine due to the ongoing conflict, which represents the fastest increase in refugees over a period of time since World War II. Meanwhile, the U.N. refugee agency predicts that as the war continues, the number of Ukrainian refugees may exceed 4 million.

Given the reality of war, there are significant limitations concerning the acquisition of spatio-temporal information in conflict areas, such as the personal safety of journalists, traffic congestion, and information transparency. Due to the difficulty of conducting a comprehensive field survey in a combat zone, the acquisition of information is completely dependent on official announcements and witness reports, which can result in insufficient

data richness and doubtful authenticity. In contrast to this, the acquisition of ground data through remote sensing satellites stands out for its low cost and high-efficiency characteristics, and remote sensing technology has become an indispensable and important part of many decision-making processes [2,3].

Night-time light data can reflect human activities very well, and in good weather conditions, the dazzling light emitted in human-inhabited areas can be observed from space [4]. It is well known that scale is an important factor in remote sensing image analysis [5]. Due to the differences in scale of geographic information, even from the same type of data, the research results obtained by using single-scale data in a specific area cannot be effectively generalized to other study areas. To address this issue, in this research, the 36-day VIIRS daily data from 24 February 2022, to 31 March 2022 is used as the data for the conflict period, and the monthly VIIRS data in December 2021 is used as the stable pre-war data. In terms of dimensions, three scales are combined, namely at the national level, state level, and city level, in order to analyze the time-series changes in night-time lights.

2. Literature Reveiew

The remote sensing technology of night-time light which is an indirect manifestation of human activities is widely used for the study of population dynamic distribution [6–9], urban scale evolution [10–19], socioeconomic research [20,21], energy consumption estimation [22–24], and various other fields.

Today, there are two main types of night light data used worldwide, namely, the DMSP/OLS Night-time light data and the NPP-VIIRS Night-time light data. Night-time light data has been widely used in studies reflecting human activities and can be used as an ideal data source for obtaining spatio-temporal information in conflict areas. The level of violent conflict and quality of life in Baghdad, Iraq, was studied by using DMSP/OLS data [25]. The DMSP/OLS data has been used to estimate Sri Lanka's GDP and electricity consumption, as affected by the civil war [26]. The impact of war in Russia and the Caucasus, e.g., in countries such as Georgia, has also been studied and monitored with DMSP/OLS data, and it has been verified that the use of DMSP/OLS data can reflect long-term burning of fires and large-scale population movements [27]. The application value of night-time light data, such as DMSP/OLS images in the research of humanitarian crises, for instance, in Syria, has been verified, and the causes of large losses of urban lights can be speculated upon [28].

Compared with DMSP/OLS data, the NPP/VIIRS data has more advantages in terms of spatial resolution, and studies have shown that the observation accuracy of human activities based on NPP/VIIRS data is higher than the former [29,30]. The feasibility of using NPP-VIIRS data in three areas of human activity that have a large impact on society: light pollution, gas flaring, and armed conflict is verified by analyzing the VIIRS data for a long time [31]. Estimates of power shortages and their affected populations with VNP46A2 data during the Ukrainian–Russian conflict have been made [32]. Like other satellites data, NPP-VIIRS has the problem of cloud overcover [33]. The application performance of NPP-VIIRS can be improved by combining it with other multi-source remote sensing data. VIIRS was combined with multi-source data to estimate the total area of fires caused by war in the first month after the outbreak of the conflict between Russia and Ukraine [34].

Differences in spatial and radiative properties between DMSP-OLS and NPP-VIIRS make it difficult to perform time-consistent analyses using both datasets. A cross sensor calibration model of DMSP-OLS and NPP VIIRS noctilucent images has been established [35]. The NPP-VIIRS data was used to simulate DMSP-OLS data to study the urbanization process in Southeast Asia [36]. Simulated DMSP/OLS images with NPP/VIIRS images were also used to assess the dynamics of urban lights in Syria during the civil war [37]. Furthermore, by correcting NPP-VIIRS night-time light using DMSP-OLS, it has been shown that war has darkened Yemen, providing support for international humanitarian aid organizations [38].

In this study, stable night-time light data from the built-up areas of Ukrainian cities are extracted through statistical methods, and data from each city is counted as a sub-area in order to obtain the sum of the night-time light intensity of each city. The night-time light ratio index is obtained by comparing the sum of the night-time light intensity during the war with the sum of the stable night-time lights before the war, so as to reflect the spatial and temporal changes in the relative night-time light intensity affected by the conflict [39]. The NLRI has different meanings at different scales. When the scale is large, NLRI can reflect the trend of human activities in an entire country. As the scale shrinks, the changes to the NLRI are more sensitive, and regional events show continuous directional changes. Such directional changes can be used to reflect the trends of a conflict. This study mainly considers the night-time light changes in areas with a significant human presence, as well as the light emissions from road lamps and traffic flows. It does not focus on rural lighting and vegetation fire but instead conducts a multi-scale analysis of night-time light in areas of major human activity, aiming to explore the value of daily night-time light data in the Russia–Ukraine conflict.

3. Study Area and Data

3.1. Study Area

Ukraine is located in the east of Europe, bordered by Russia to the east; Belarus to the north; Slovakia, Poland, and Hungary to the west; and Moldova and Romania to the south, where the Sea of Azov and the Black Sea are also located. The geographical location of Ukraine is shown in Figure 1. The geographical location of Ukraine is very important, as it lies at a geopolitical intersection between the European Union and the CIS, and especially given its proximity and historical relationship with Russia. Ukraine is extremely rich in natural resources, with its borders encompassing two-fifths of the world's black soil area and more than 70 types of mineral resources [40].



Figure 1. Map of Ukraine's geographic location.

According to the civilian casualty figures updated by the United Nations Office of the High Commissioner for Human Rights on 26 March, since the full-scale outbreak of the

conflict between Russia and Ukraine, there have been 2788 civilian casualties in Ukraine, of which 1081 persons have been killed and 1707 persons have been injured. Under the combined effect of the Russia–Ukraine conflict and sanctions against Russia, the global food supply, microchip manufacturing materials, and energy prices have all been affected to varying degrees.

3.2. Data Sets and Preprocessing

The Suomi National Polar Partnership satellite SNPP/VIIRS global night-time light DNB data is used in this study as the daily data, and the images were obtained from the official website of the National Oceanic and Atmospheric Administration (https://ngdc.noaa.gov/(accessed on 2 April 2022)). The imaging period of the daily night-time light images was selected from the conflict eruption between 24 February to 1 March, a total of 36 days. The monthly night-time light imaging period was selected as December 2021. The night-time light data for 2021, as released by the Payne Institute for Public Policy (https://www.mines.edu/), was used to calculate the built-up area. The night-time light imaging area is 75N/060W, using the coordinate system Select WGS_1984_UTM_Zone_50N. The administrative boundary data were downloaded from the Global Administrative Division Database (https://gadm.org/). The road network data was obtained from the OpenStreetMap (https://www.openstreetmap.org/ (accessed on 27 November 2022)).

Daily NPP VIIRS DNB data has been applied to assess the impact of natural or anthropogenic phenomena on human social activities [41]. In the process of constructing multi-time-series VIIRS images, it is necessary to ensure the continuity of image time and space [42]. Within the time-frame studied in this paper, on some days the NPP VIIRS data was partially missing, such as 19 March and 31 March. According to the idea of averaging, the missing night-time light data on a given day is obtained by interpolating the night-time lights of the nearest two days, the formula for which is as follows:

$$\mathbf{2}\, D_i^t = D_i^{t+1} + D_i^{t-1} \quad (1)$$

In Formula (1), D_i^t, D_i^{t+1} and D_i^{t-1} represent the radiance value of the i-th pixel on days t, $(t+1)$, and $(t-1)$, respectively.

To infer the changing trends of night-time light in a region affected by war, the minimum night-time light value of the research region in the study period should be extracted and compared to the minimum value of night-time light on a day prior to the outbreak of war. If the minimum value during a conflict period is smaller than the minimum value before the conflict period, this means that the area is affected by the conflict and has suffered from the loss of night-time lights.

4. Methods

4.1. Multiscale Analysis Frame of the Night-Time Light Data

The range of urban built-up areas is extracted using statistical methods, and the thresholds of light intensity at night are continuously iterated in order to compare the areas of extracted light with the actual statistical areas under each threshold, until the two areas are the closest, and then the threshold is determined.

Because NPP/VIIRS data are sensitive to night-time light brightness, night-time light not only includes artificial light but also other types of night-time lights, such as forest fires, gas flares, and volcanic eruptions, as well as background noise. There are negative and extremely positive values in the image data, and outliers need to be handled in the image preprocessing stage. In this paper, the built-up area mask is used to remove abnormal lighting outside cities, and thus the night-time light image within the built-up area is de-noised and the data pre-processing is realized using an efficient method. Pixels with negative values are replaced with zero, and pixels with large positive values are replaced with the maximum value of night-time lights in major cities in Ukraine. In the following order, the corrected night-time light images, built-up area masks, and level 1 administrative

boundary data are used to calculate the sum of night-time lights in built-up areas. At various scales, i.e., national scale, region scale, city scale, and road scale, the total level of night-time lights is extracted and a multi-scale dynamic analysis of the situation in the Russia–Ukraine conflict is carried out. The technical method is shown in Figure 2.

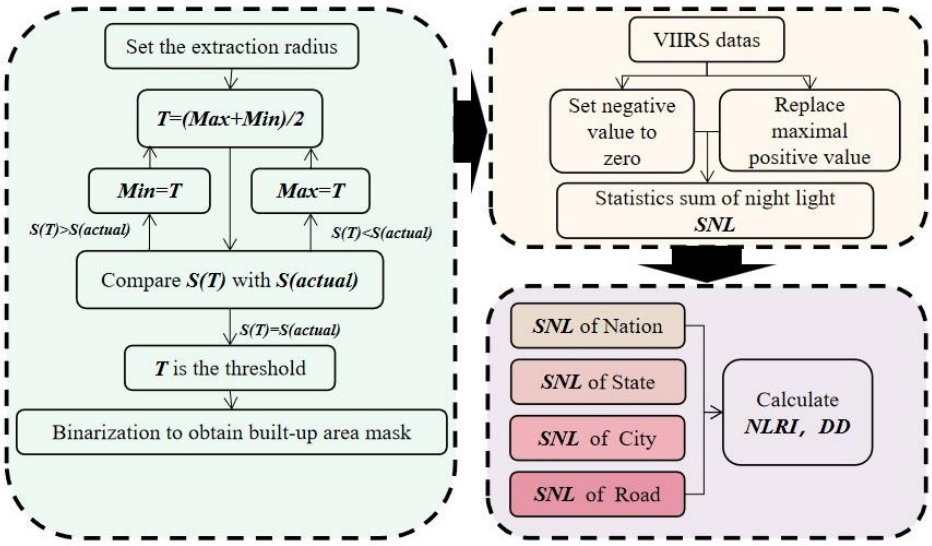


Figure 2. Conceptual diagram of the proposed multi-scale analysis frame.

4.2. City Mask Extraction

By extracting urban built-up areas from night-time light data, the lack of spatio-temporal characteristics caused by using statistical data alone in urban evolution studies can be solved [43]. In this paper, the method of obtaining a built-up area mask is divided into the following three phases:

(1) Taking the city of Kiev as an example, the center of the city's urban area was first found in Google Earth, and then a circle around the city center that contained the radial built-up area of the city was drawn, thus establishing Kiev's built-up area.

(2) By changing the maximum or minimum value, the night-time light data threshold is constantly constrained, and the area of each night-time light concentration is counted and compared with the statistical areas of urban land. When the areas of the night-time light concentrations are larger than the statistical areas of urban land, it indicates that the threshold is too small. In this case, the threshold is replaced by the original minimum value, so that the estimated area is close to the real area; alternatively, the maximum value is replaced for iteration.

(3) When the threshold is determined, the threshold is used to binarize the stable night-time light data, assigning a value of 1 for the built-up areas and 0 for the non-built-up areas, and thus, a binarized urban mask grid is obtained.

4.3. Night-Time Light Ratio Index

Generally speaking, the intensity of human activity in a certain area can be reflected by using the total night-time light index of the area in question. In this paper, the time-series night-time light data are used to analyze the light dynamics in Ukrainian cities. For the built-up areas of the Ukrainian regions, the total amount of night-time light, SNL, is calculated using the following formula:

$$SNL = \sum_{i=1}^{n} x_i d_i \quad (2)$$

In Formula (2), ***SNL*** represents the total light index of the city at night; n is the total number of pixels in the city region; x_i represents the value of the i-th pixel in the built-up

area and non-built-up area—in the built-up area, $x_i = 1$, and outside the built-up area (that is, in the non-built-up area) $x_i = 0$; and d_i represents the brightness value of the ***i-th*** pixel.

As Li [44] noted, the night-time light ratio index can indicate the night-time light dynamics of a city, and this research also utilizes this index to represent the relative change of night-time light intensity. The transformation formula is:

$$NLRI_i = \frac{s_i}{s_k} \quad (3)$$

In Formula (3), $NLRI_i$ represents the night-time light ratio index on the ***i-th*** day; S_i represents the total urban lighting index on the ***i-th*** day during the war; S_k represents the total urban lighting data from before the war.

4.4. Night-Time Light Dynamics

The dynamic model is used to reflect the changing range and speed of specific ground object information in time units in the study area [45,46], which can effectively display the changing pattern of night-time lights over time. In this paper, the dynamic degree model is used to analyze the night-time light change rate.

$$DD = \frac{d_{ij} - d_{ii}}{d_{ii}} \times \frac{1}{T} \times 100\% \quad (4)$$

In Formula (4), ***DD*** represents the change rate of night-time lights in a specific period, d_{ii} and d_{ij} represent the sum of the intensity of night-time light changes in a certain area at the beginning and end of the research period, respectively, and ***T*** is the length of the time interval.

5. Results

5.1. Dynamic Analysis of Night-Time Light Changes at the National Scale

The urban built-up area mask is extracted using the statistical method. When the threshold is equal to 10.02, the built-up area of Kiev is 393.89 square kilometers, which is close to the statistical area of 394 square kilometers. This threshold is set as the overall threshold in order to extract data for the whole country. The built-up area is shown in Figure 3.

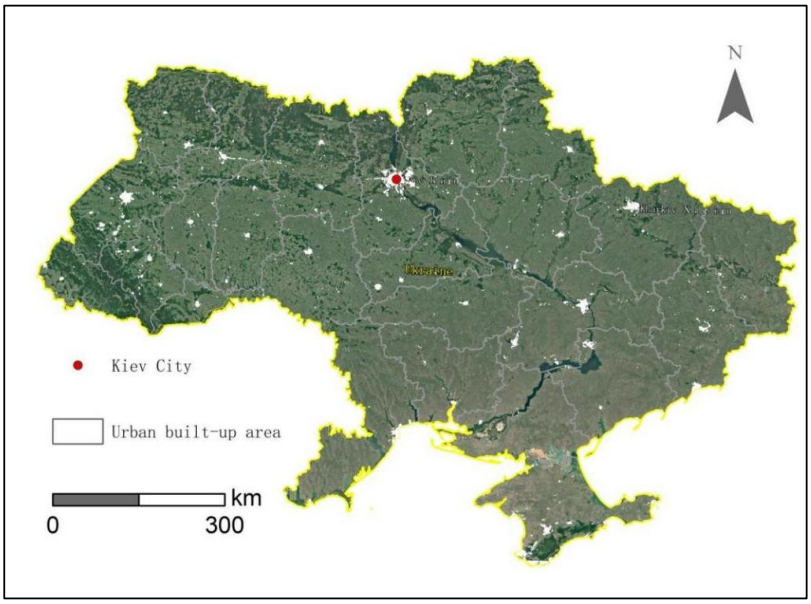


Figure 3. Ukrainian urban built-up areas.

The built-up area data were binarized, where the city value was set to 1 and the non-city value was set to 0. The data were first multiplied with the corrected night-time light data to retain the night-time light intensity of the built-up area, then the unstable night-time light was removed and the city night-time light images were obtained. Following this, the administrative boundary division was then used to analyze the above image and obtain the total amount of night-time light in Ukraine.

More than 60 percent of the country's night-time light was lost after the conflict broke out. We analyzed the dynamic change of night-time light by combining the military clashes and strategies between Russia and Ukraine. By screening the data published by online media, key information affecting the development of the conflict, such as urban control, humanitarian aid, and other key data, can be obtained, as shown in Table 1. Several cities are taken as examples to determine the ways in which different events of the conflict have affected night-time light.

Table 1. Ukrainian cities in military conflict situations. There are three types of cities analyzed here, namely cities in the RC (Russian-controlled area), cities in the UC (Ukrainian-controlled area), and cities in the B (belligerence/conflict area). The plus sign indicates whether a specific event has promoted night-time light restoration, and a minus sign indicates no light restoration prompted by an event.

State	Type	Outbreak of Conflict	The First Negotiation	The Second Negotiation	Humanitarian Corridor	The Third Negotiation
	Date	**2.24 —**	**0228**	**0303**	**3.5 —**	**3.7**
	Impact	**-**	**+**	**+**	**+**	**+**
Cherkasy	UC	–	–	–	–	–
Chernivtsi	B	IN	IN	IN	IN	IN
Dnipropetrovs'k	B	IN	IN	IN	IN	IN
Donets'k	RC	IN	IN	–	IN	–
Kharkiv	B	IN	IN	IN	IN	IN
Kiev City	B	IN	IN	IN	IN	IN
Zaporizhzhya	RC	IN	IN	IN	IN	–

State	Type	Multinational Intervention	The Fourth Negotiation	Conflict Escalation	The Fifth Negotiation	Russian Troops Withdraw
	Date	**3.14 —**	**3.15**	**3.20 —**	**3.29**	
	Impact	**-**	**+**	**-**	**+**	**+**
Cherkasy	UC	IN	–	–	–	–
Chernivtsi	B	IN	IN	IN	IN	–
Dnipropetrovs'k	B	–	IN	IN	IN	–
Donets'k	RC	–	–	–	–	–
Kharkiv	B	–	IN	IN	IN	–
Kiev City	B	IN	IN	IN	IN	IN
Zaporizhzhya	RC	–	–	–	–	–

Figure 4 shows the time-dependent changes in the Ukrainian national night-time light ratio index. Different columns in the figure represent the five negotiations that took place within the research period of this paper, namely on 28 February, 3 March, 7 March, 15 March, and 29 March. Peace negotiations are closely related to military operations. During the talks, military operations often stagnate. The negotiation results often affect subsequent military operations, which in turn affect human activity. The intensity of night-time light should reflect these changes.

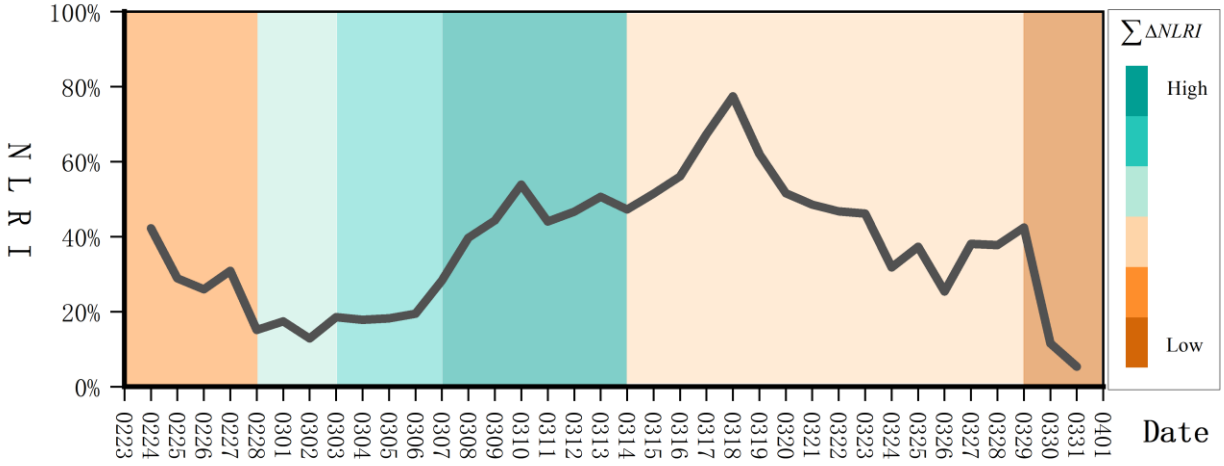


Figure 4. Ukraine's night-time light ratio index from 23 February to 1 April.

After the Russian–Ukrainian conflict broke out on 24 February, the intensity of night-time lights in Ukraine dropped sharply. On 26 February, the Russian side proposed negotiations with the Ukrainian side and halted relevant military operations. On 27 February, the Ukrainian side agreed to the talks. The index image shows a brief rise at this point. The first Russia–Ukraine negotiation did not yield results, but the two sides reached a consensus for further negotiations. Before the second Russia–Ukraine negotiations took place on 3 March, night-time lights did not change significantly.

The second Russia–Ukraine negotiations mainly focused on humanitarian relief and achieved obvious results. The two sides reached a consensus on the formation of a humanitarian corridor for civilians and announced a temporary ceasefire to ensure the evacuation of civilians. It can be seen from Figure 4 that after the second meeting, the night-time lights remained stable and showed an upward trend.

In the third meeting, Russia and Ukraine again reached a consensus on humanitarian issues, but the negotiations were not successful, and Russian military operations continued. During this period, night-time lights showed a "rising-falling-rising" trend.

The fourth negotiation was also unsuccessful, and after four rounds of negotiations, the military operations of Russia and Ukraine slowed down and briefly reached a stalemate, with the conflict situation initially showing signs of easing. At this point, the intensity of the night-time lights was greatly restored; however, with the re-escalation of the situation on 20 March, the Russian side again carried out a large number of military operations, and night-time lights continued to fall.

During the fifth negotiation, the two sides reached considerably more consensus regarding the security of Ukraine. The Russian side agreed to withdraw its troops from Kiev. The phenomenon of night-time light loss that occurred after the fifth negotiation is presumed to have been caused by the large-scale movement of the army and subsequent panic among civilians.

In conclusion, NTRL at the national level can depict how a war situation affects the entire nation. NTRL often increases during Russia and Ukraine's peace negotiations; but, when the war between the two countries worsened, the change was undone.

5.2. Dynamic Analysis of Night-time Light Changes at the Regional Scale

Using the ratio of the total amount of night-time light during the conflict and the total level of night-time light before the conflict, in turn, the daily night-time light ratio index of the Ukrainian regions is attained, with the date as the horizontal axis and the night-time light ratio index as the vertical axis on the presented line graphs; the vertical axis scale is adapted to each region. The night-time light ratio index is shown in Figure 5. When NLRI = 1, it means a return to the pre-war night-time light level.

Overall, almost all of the region's night-time light ratio indexes show a decreasing trend in the early stages of the war, then an increase in the middle period, and then decrease again in the later period. This research divides the period into three segments. The first lasted from 28 February to 18 March, and the average night-time light ratio index of each region is shown in Table 2. After the outbreak of the Russian–Ukrainian conflict, most regions lost more than 50% of their night-time light. Within five days of the outbreak of the conflict, from 24 February to 28 February, the states that responded quickly to the war showed a short "L-shaped" or sinking segment in the line chart, and most of these were in Eastern and Northern Ukraine, where Luhans'k Oblast lost 90% of its night-time light, Kharkiv lost 87% of its night-time light, Chernihiv Oblast lost 88% of its night-time light, and Zaporizhzhya Oblast lost 87% of its night-time light. At this time, these regions were in the conflict zone between Russia and Ukraine. The fighting during this period was very fierce, and the night-time lights reduced rapidly in these areas. On the other hand, the night-time light response speed of the regions located in central Ukraine was relatively slow overall, but due to the rapid advance of the Russian army, the night-time light loss rate of the central cities was still very fast. A transition period of night-time light loss in these areas can be seen, which is shown in the line chart to have a long "L-shaped" opening section. Of these regions, Kiev Oblast lost 74% of its night-time light, Kirovohrad Oblast lost 64% of its night-time light, and Vinnytsya Oblast lost 60% of its night-time light, as they were affected by the different geographical locations of the major cities in each region in regard to the outbreak of the conflict. The change in night-time lights is also varied, and the closer a region is to the combat zone, the more dramatic the reaction. Most of the regions with the "N-shaped" beginning are located on the western side of Ukraine. These regions, such as Volyn and L'viv, are relatively far away from the combat zone and have seen no large-scale advance of the Russian army.

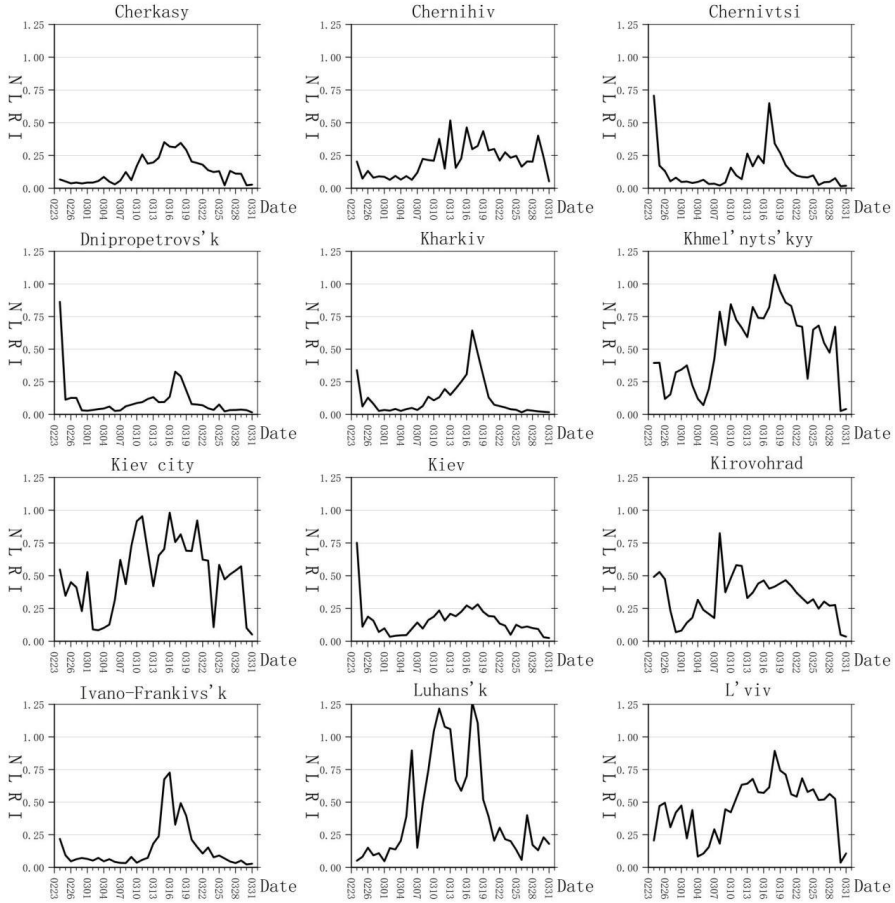


Figure 5. *Cont.*

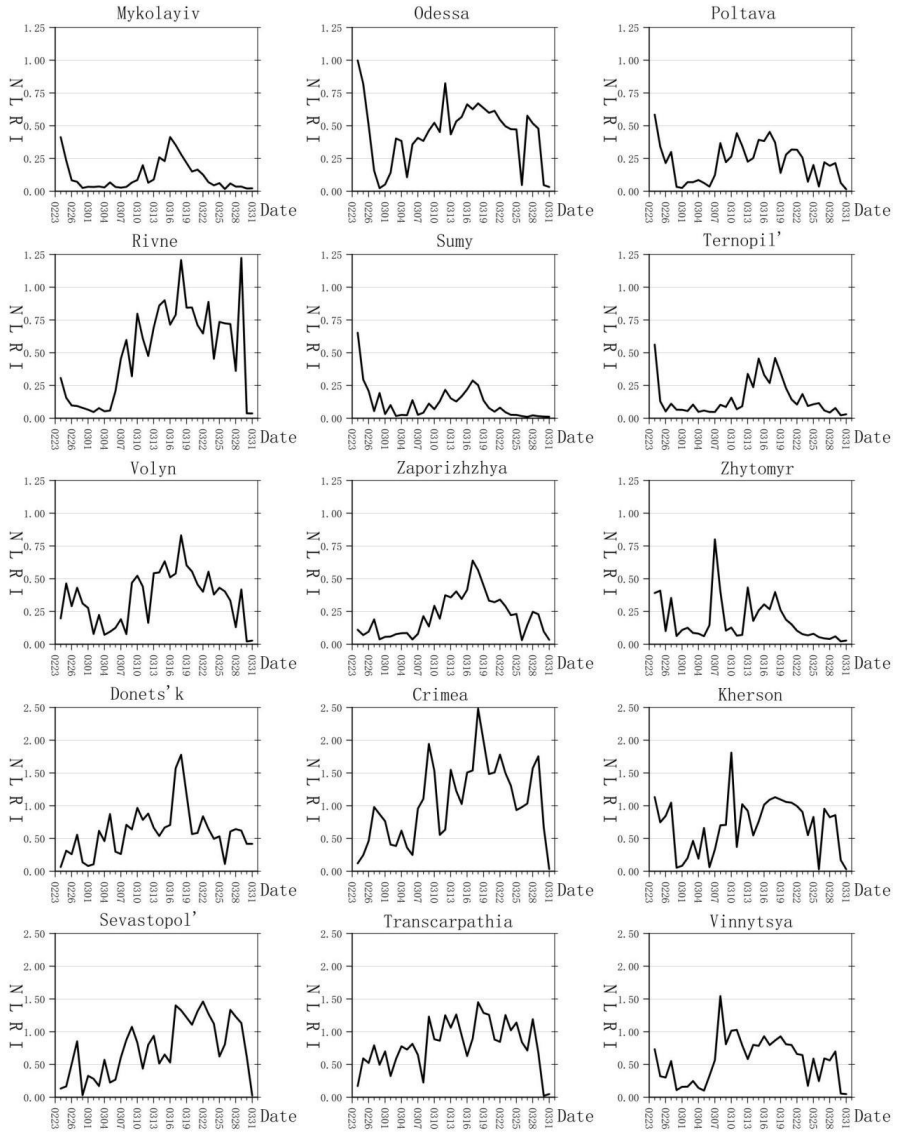


Figure 5. Schemes follow the same formatting.

From 1 March to 18 March, almost all the regions showed an upward trend in terms of the total amount of night-time light. The slowing of the battlefield situation, the repeated joint talks between Russia and Ukraine, and the active silence of the Russian side have somewhat stabilized civilian life and thus brought about the restoration of night-time lights. The states with pro-Russian power concentrations are highlighted by the rapid restoration of night-time light to pre-war night-time light levels. For instance, the Donets'k region returned to 87% of its pre-war night-time light levels on 5 March and the Luhans'k region achieved the same on 6 March, when it returned to 89% of its night-time light before the war. These states have seen fewer overt military–civilian conflicts, and civilians have made fewer attempts at fleeing. The loss of night-time lights was therefore quickly remedied. In regard to the Russian-controlled areas, except for Donets'k and Luhans'k, the Crimean Autonomous Region, Sevastopol' Port, and the Kherson Region have all returned to pre-war levels of light. The night-time light levels on the Crimean Peninsula have increased to more than twice the level of night-time lights before the war, which is presumed to be the influence of the military lights caused by the mass accumulation of troops by the Russian army in Crimea.

Table 2. The average luminous ratio of each region in the three time periods (2.24–2.28, 3.1–3.18, 3.19–3.31).

Region	Average Night-Time Light Ratio Index			Region	Average Night-Time Light Ratio Index			Region	Average Night-Time Light Ratio Index		
Cherkasy	0.05	0.17	0.11	Khmel′nyts′kyy	0.28	0.59	0.50	Rivne	0.15	0.53	0.59
Chernihiv	0.12	0.22	0.23	Kiev	0.26	0.16	0.10	Sevastopol′	0.34	0.71	0.99
Chernivtsi	0.23	0.15	0.07	Kiev City	0.40	0.56	0.46	Sumy	0.28	0.12	0.03
Crimea	0.54	1.12	1.19	Kirovohrad	0.36	0.38	0.27	Ternopil′	0.18	0.18	0.09
Dnipropetrovs′k	0.25	0.10	0.04	L′viv	0.48	0.57	0.48	Transcarpathia	0.51	0.89	0.78
Donets′k	0.27	0.72	0.54	Luhans′k	0.10	0.64	0.20	Vinnytsya	0.40	0.67	0.46
Ivano-Frankivs′k	0.10	0.20	0.08	Mykolayiv	0.17	0.13	0.06	Volyn	0.44	0.47	0.32
Kharkiv	0.13	0.17	0.04	Odessa	0.50	0.46	0.39	Zaporizhzhya	0.10	0.26	0.20
Kherson	0.76	0.71	0.65	Poltava	0.29	0.23	0.17	Zhytomyr	0.26	0.22	0.07

The sporadic night-time light ratio in the Zaporizhzhya region showed a relatively stable rise but never returned to its pre-war level. There are many factors affecting this. Strategically, Zaporizhzhya, which connects the Russian-controlled Crimea and Donets'k, is presumably a key target for Russia. The humanitarian corridor from Mariupol to Zaporizhzhya via Berdyans'k restricts the military operations of Russia and Ukraine to a certain extent, making it difficult to carry out large-scale conflicts. Under the bidirectional effect, the change in the night-time light ratio in Zaporizhzhya Oblast is most likely to be reflective of the overall trend of night-time light changes in Ukraine.

During this period, the night-time light growth in other Ukrainian cities can be divided into two types one is a slow growth type, mainly concentrated in the regions within conflict zones. For example, in the Sumy, Kiev, Mykolayiv, and Kharkiv regions, the maximum light intensity at night has only been restored to 30–60% of the pre-war level. One possible reason for this is that the overall conflict situation briefly slowed, but smaller-scale battles still continued. The other is the abrupt growth type, occurring mainly in central and western Ukraine, far from the war zones, such as in the Khmel'nyts'kyy, Transcarpathia, and Vinnytsya regions, where changes to the night-time light ratio index are characterized by a return to pre-war levels and multiple peaks, with the continuous influx of refugees from the war zones, which has led to a continuous increase in night-time lights. From 19 March to 1 April, due to the re-escalation of the situation between Russia and Ukraine, the intensity of night-time light in Ukraine fell once again.

In conclusion, the level of a region's sensitivity to conflict can be indicated by its region scale NTRL. The already-conflicted territory and the one next door are more susceptible to war; in terms of civilian sentiments, the region with a higher proportion of pro-Russian inhabitants is less sensitive to conflict.

5.3. Dynamic Analysis of Night-Time Light Changes at the Urban Scale

Using the five peace negotiation events, the time series of this study was divided into four periods, and urban built-up areas of more than two square kilometers were selected as the objects of this study of night-time light dynamics. A total of 176 small and larger cities were chosen. Taking the night-time light intensity after the first peace negotiation as the starting benchmark, the change in night-time light is visualized using a stacked graph, as shown in Figure 6. The orange segment represents the amount of night-time light lost in this period compared to the previous period, the yellow segment is the amount of night-time light in this period, the yellow segment plus the orange segment represents the night-time light in the previous period, and the orange segment is the level of reduction of night-time light. When night-time light recovers, the cyan segment represents the level of night-time light increased in this period compared to the previous period, the yellow segment depicts the night-time light of the previous period, the cyan segment plus the yellow segment represents the night-time light in the current period, and the ratio between the cyan segment and the yellow segment is the increasing rate of night-time lights. In the base map, at the time of writing, the colored area is controlled by Russia and the striped area is the conflict zone between Russia and Ukraine.

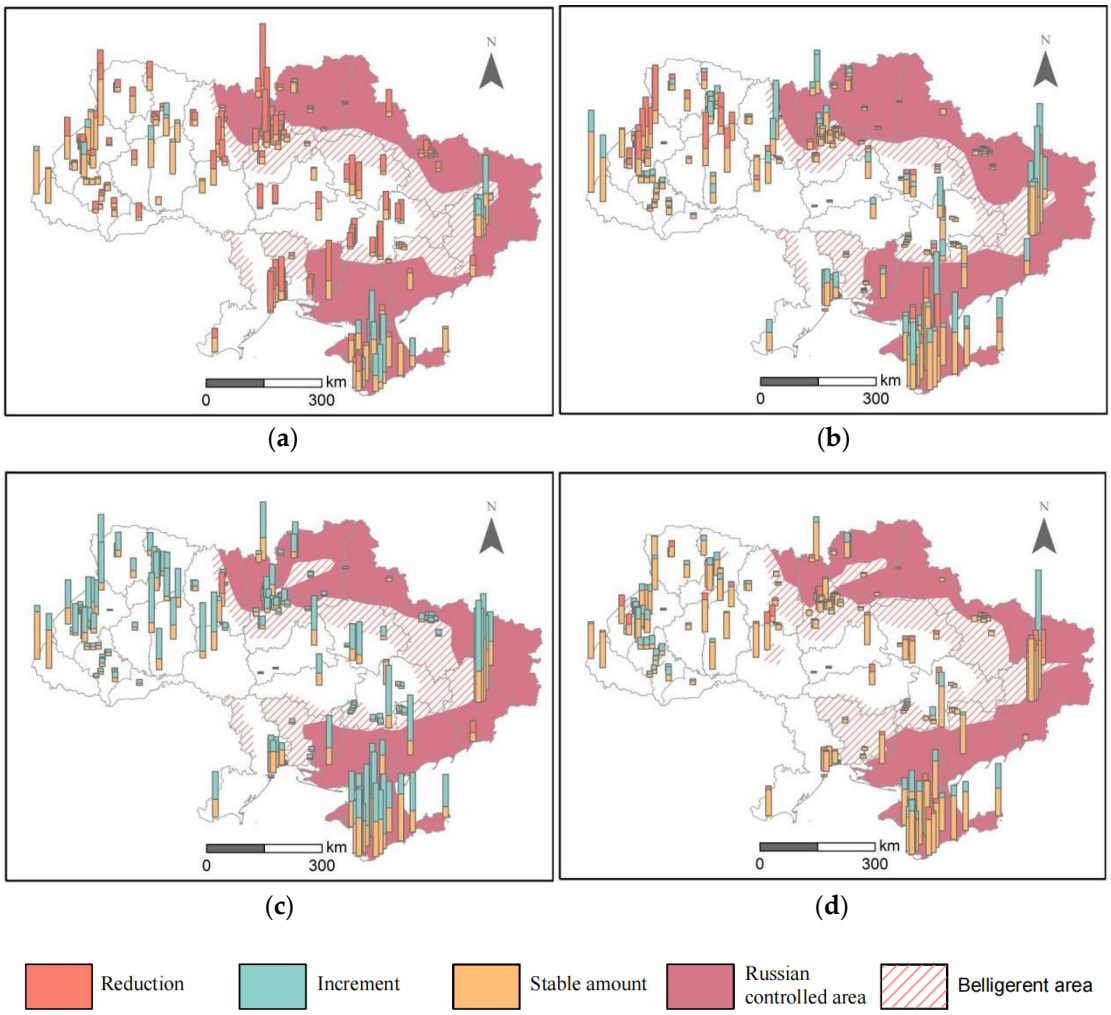


Figure 6. Dynamics of night-time light in Ukraine during the five negotiation events: (**a**) dynamics of night-time lighting during the first and second negotiations; (**b**) dynamics of night-time lighting during the second and third negotiation; (**c**) dynamics of night-time lighting during the third and fourth negotiations; and (**d**) dynamics of night-time lighting during the fourth and fifth negotiations.

In Figure 6a, when compared with the first period, it can be seen that the night-time light intensity of the southeastern region, such as the Crimean Peninsula and Donets'k, increased rapidly, with a growth rate of over one. Secondly, with the spread of the war to the interior, there was a large area of abrupt night-time light loss in cities in central Ukraine, and the loss of night-time light is generally greater than 60%. The Russian side advanced faster in the early stage of the conflict, and prior to the second peace negotiation, it controlled many cities in Donets'k, Luhans'k, and Crimea, where night-time light recovered quickly. As the Russian army entered the Kiev Oblast and surrounded the city of Kiev, the night-time light around the city of Kiev was greatly reduced. The rapid spread of war has led to the loss of night-time light in cities in central and western Ukraine.

In Figure 6b, due to the consensus reached by Russia and Ukraine on humanitarian issues, humanitarian passages to Mariupol and Vornovaha were opened and night-time lights along Zaporizhzhya and Donets'k correspondingly appeared. The results of the negotiations were not successful and Russian military operations continued, but the speed of their advancement was significantly slowed. The light levels of the central cities did not change much in terms of night-time light intensity, while the western Ukrainian cities experienced a significant night-time light intensity decline, such as in L'viv, during this period. The light loss exceeded 70%. Foreign players entered the war using the western side of Ukraine as an entrance.

Panic caused by civilians also affected the loss of night-time lights. In Figure 6c, most of the cities depicted show an increasing night-time light trend. While Russia and Ukraine have reached a certain degree of consensus on humanitarian issues, Russia has repeatedly announced that it has entered a state of silence and has stopped negotiating on military operations, thus making the overall war situation worse. There has been some recovery, and some public activities have resumed.

In Figure 6d, the direction of night-time light loss has been reversed, the speed of night-time light loss in the war zone has decreased, and the stable night-time light in the original Russian-controlled area has been lost. There may be two reasons. First, the long-term Russian offensive led to the military becoming fatigued, and the Ukrainian side tried to launch a counter-offensive in some areas, which caused a reverse loss of night-time light. Second, the Russian war strategy has been adjusted, and the large-scale army transfer has caused panic among the people. Based on this, one might also simply say that there may have been a slight change in the subsequent development of the situation in Russia and Ukraine. Analysis of the temporal and spatial changes of night-time light based on the dynamic degree can intuitively reflect the changes of night-time light, which is confirmed in this paper.

In summary, the NTRL change at the urban scale possesses directivity. In the control zone, the night-time light loss was less severe than it was in the combat zone. Humanitarian aid can stabilize the local combat situation, causing a modest increase in night-time light output.

5.4. Dynamic Analysis of Night-Time Light Changes at the Road Scale

Twelve regions affected by the earliest phases of the conflict were selected as examples in this study, including Chernihiv, Dnipropetrovs'k, Donets'k, Kharkiv, Kherson, Kiev City, Kiev, Luhans'k, Odesa, Sumy, and Volyn. Ukrainian road network data were obtained from OpenStreetMap to calculate the density of the road network by region. Specifically, Kiev has the highest road network density, with the majority of road types being highways. The road types seen in Dnipropetrovs'k and Chernihiv are the second most common, also known as trunk roads. Table 3 shows the dynamic changes in road lighting in 12 regions by using the five negotiations between Russia and Ukraine as time points.

In Figure 7, during the period from February 28 to March 3, the nighttime road lights in most states increased, with the largest increase of 185% seen in Donets'k, as compared to February 28, and the largest decreases in Kiev City, Kiev, Sumy and Chernihiv. After the first negotiation, the conflict between Russia and Ukraine eased to some extent. Donets'k, as the first prefecture controlled by Russia in the conflict, has a higher number of pro-Russia citizens than elsewhere in the country and, as the main channel connecting Russia and Ukraine for both civilians and the military, road lights were quickly restored. Between March 3 and March 7, the night-time lights on roads in all regions except Kiev City showed a downward trend; however, between March 7 and 15, the night-time lights on roads in all states except Kiev City showed an upward trend. Kiev was heavily affected by the early outbreak of the conflict on 24 February and lost a significant number of night-time lights, so it was easy to recover those in later stages. During the second half of March, as the war dragged on, the night-time lights on the roads declined. Between 15 March and 29 March, there was little change in Donets'k and Luhans'k, and the night-time lights on roads in other states showed a downward trend, except in the city of Kiev.

Table 3. The night-time road light dynamics of each region in the five times negotiation periods (28.02., 03.03., 03.07., 03.15. and 03.29.).

Region	Density of Road Network (km/km^2)	The Total of Road Lights at Night (nW/cm^2/sr)					Road Night-Time Light Dynamics (%)			
		2.28	3.3	3.7	3.15	3.29	2.28–3.3	3.3–3.7	3.7–3.15	3.15–3.29
Chernihiv	0.105	47,242	31,410	20,109	38,625	27,851	−33.51%	−35.98%	92.08%	−27.89%
Dnipropetrovs'k	0.110	26,337	32,984	21,979	31,017	14,347	25.24%	−33.37%	41.12%	−53.74%
Donets'k	0.099	24,064	68,628	41,640	44,522	46,742	185.19%	−39.32%	6.92%	4.99%
Kharkiv	0.084	24,226	26,644	18,410	25,941	11,820	9.98%	−30.90%	40.91%	−54.44%
Kherson	0.058	10,703	14,014	10,985	16,622	11,615	30.93%	−21.61%	51.31%	−30.13%
Kiev City	0.559	15,016	12,711	21,671	12,809	28,899	−15.35%	70.49%	−40.89%	78.69%
Kiev	0.100	41,577	28,148	24,758	37,665	34,302	−32.30%	−12.04%	52.13%	−8.93%
Luhans'k	0.073	20,656	31,233	25,029	31,625	31,346	51.20%	−19.86%	26.36%	−0.88%
Odessa	0.094	23,144	40,629	31,860	46,573	31,550	75.55%	−21.58%	46.18%	−32.26%
Sumy	0.096	32,106	18,703	16,827	22,837	9245	−41.75%	−10.03%	35.71%	−59.52%
Volyn	0.094	17,099	20,682	12,947	26,851	16,801	20.95%	−37.40%	107.40%	−37.43%
Zaporizhzhya	0.078	14,477	19,163	14,620	21,866	16,973	32.37%	−23.71%	49.56%	−22.37%

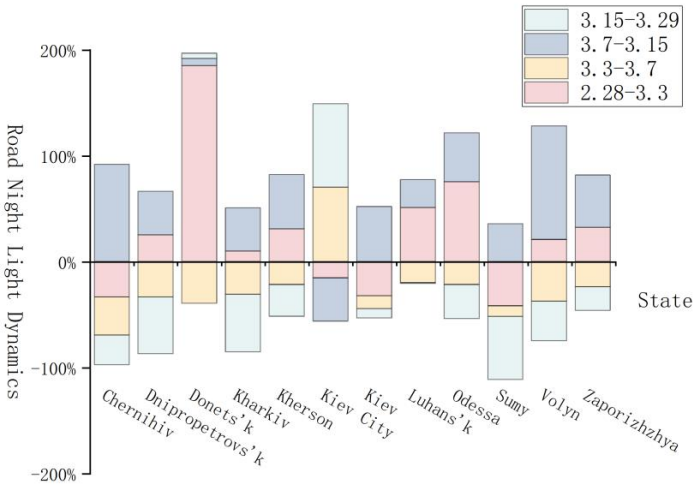


Figure 7. The night-time road light dynamics of twelve regions.

In conclusion, region and road lights at night are strongly associated. The production of night-time light from the roadways encircling the city increases as the region's night-time light increases.

6. Discussion and Conclusions

After the outbreak of the conflict between Russia and Ukraine, the night-time light in the whole country decreased sharply, and most provinces lost more than 60% of their night-time lights due to the war. As a good representation of human activities, the night light data reflects socio-economic development, population migration, and energy consumption. Possible reasons for the reduction of night lights in the war zone of the Russia-Ukraine conflict are as follows: (1) city light and power systems were damaged during the conflict; (2) the exodus of people caused a loss of urban population and thus a reduction of night-time light; and (3) the government's curfew policy affected the emission of light at night. The possible reasons for the large increase in night-time light intensity in some areas after the outbreak of the conflict are as follows: (1) civilian life in the regions with a larger number of pro-Russian individuals had an easier return to normal after being controlled by the Russian side; (2) military lighting caused by the deployment of troops and abnormal ignition points caused by the conflict; and (3) the refugee corridor for humanitarian aid inhibits surrounding military combat to a certain extent, which may lead to enhanced local night-time light.

In this paper, the night-time light ratio index and dynamics on different scales are calculated from the 36-day corrected Ukrainian NPP VIIRS data, and the quantitative

analysis of the night-time light damage caused by the conflict outbreak is carried out over the time and space of the conflict. The following three conclusions are drawn:

(1) The unique perspective of night-time light data can clearly and intuitively monitor the impact of war on residents' social activities and can reflect various types of information, including the spread of conflict and refugee migration.

(2) Combined with time sequence analysis of the restoration and the loss of night-time light, dynamic laws can often echo the changes in actual conflict situations. Using night-time light data to analyze and predict the trends of the conflict can enable researchers to view the battlefield situation at a macro level.

(3) The observation of the battlefield situation from the perspective of night-time light can reduce or eliminate the casualty risks faced by collectors of field survey and ground survey data and compensates for the lack of statistics obtained through credible, reliable, and efficient means.

In this paper, the use of daily night-time light data to examine the conflict situation has a lag of at least one day, and it is impossible to monitor conflict changes caused by emergencies in real-time. In addition, due to the limitations of the resolution of night-time light data, it is difficult to identify areas with relatively small economies such as villages and towns. The total level of night-time light in the built-up areas is extremely small and, as the correlation with the evolution of the conflict situation is insufficient, it should be combined with other high-resolution remote sensing data. The application of remote sensing earth observation in emergencies not only breaks the restrictions of national boundaries and geographical conditions but also breaks the time boundary between the past and the present. The combination of remote sensing and emergency investigation has many advantages, such as breaking through the limitation of visual space-time and frequency spectrum, revealing the law of multi-scale, and maintaining the objectivity of news. A function model between the light intensity attenuation index and the severity of a war or the degree of economic contraction from the perspective of night-time light intensity response to the regional economy may be established through further research.

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