Characterizing land use with night-time imagery: the war in Eastern Ukraine (2012–2016)

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Abstract

The ongoing military conflict in Eastern Ukraine has resulted in significant land use changes as well as economic shifts particularly in agricultural and industrial activities. The day/night band detectors on-board the Suomi-NPP Visible Infrared Imaging Radiometer Suite provides an opportunity to assess socio-economic impacts of human conflicts based on physical radiometric measurements. In this study, we show a near 50% decrease in night-time light activity in Donetsk and Luhansk (Donbass Region) from 2012 to 2016. Furthermore, by separating night-time light losses between areas inside official city boundaries and those outside, we illustrate the sensitivity to residential land-use types. A 43.5% of night-time light loss inside cities was attributed to residential areas and 17.5% registered outside of cities. Additionally, this separation showed considerable differences for night-time light losses attributed to industrial land-use types with higher losses occurring in regions outside of cities (36.5%) than regions inside cities (24%). The separation of night-time light losses inside and outside cities reveal considerable discrepancies in night-time light losses showing that considerable activity occurs outside of traditionally targeted urban activities. The results demonstrate night-time light losses are sensitive to proximity to civilian-residential populations, and highlight discrepancies between urban cores and their attached peripheries.

1. Introduction

The military conflict in Ukraine has been ongoing since 2013. Most of the fighting has been constrained in the east, particularly in Donetsk and Luhansk, an area of 53.2 thousand sq. km or 8.8% of Ukraine’s total area. Since the start of the war, there have been considerable social and economic impacts with around 1.5 million persons displaced [1] and a nearly 7.5% impact on Ukraine’s Gross Domestic Product (GDP) from 2014 to 2017 [2]. Quantifying the impacts of the conflict’s environmental changes remains difficult however, due to unsafe conditions presented by continued combat operations. Furthermore, government reports may be inaccurate or misrepresented due to incomplete data and restrictions in data access [3]. Global remote sensing of night-time lights has emerged to provide additional contexts in this research.

Economic productivity as well as other various socioeconomic indicators have been linked to night-time lights with brighter areas corresponding to some growth or improvement [4]. In the context of studying armed human conflicts, dramatic decreases in night-time lights have been shown to serve as an indicator for damage to infrastructure as well as reductions in population size and GDP [5]. Remote sensing of night-time lights in conflicts has been based primarily from the older US Air Force Defense Meteorological Satellite Program with more recent studies making use of NASA’s Visible Infrared Imaging Radiometer Suite (VIIRS) or a combination of the two (an in-depth comparison of the two instruments has been provided in the supplementary material). It has been observed that war-torn countries have larger fluctuations in night-time lights, with conflicts leading to sharp reductions in night-time lights and peace agreements eventually stabilizing.
these reductions [6]. Previously, night-time imagery has been extensively used to study conflicts in Syria, Yemen, and Iraq [7–9]. Observed decreases in night-time lights in these conflicts highlight socioeconomic concerns such as areas lacking electricity supply and the potential impacts towards humanitarian efforts. However, remote sensing of night-time lights has not been applied to the physical environmental outcomes of these conflicts including land cover/land use changes (LCLUC) and the characterization of industrial and agricultural activities in regards to declines of political stability in these regions.

Many of the buildings and structures in Eastern Ukraine have endured significant damages as a result of the war. As most buildings emit some form of artificial lighting, this has led to an observable decrease in night-time radiance. Furthermore, unsafe conditions have given rise to flight of local populations resulting in further decreases of night-time lights. These night-time light losses present considerable concerns from both economic and environmental perspectives. To monitor night-time light activity at finer scales, the NASA VIIRS day/night band (DNB) team has developed a Level 3 product coined the NASA Black Marble Product Suite (VNP46). The VNP46AX products (VNP46A1 and VNP46A2) provide daily night-time light monitoring at 500 meter resolution. While both products produce high quality pixel-based estimates of night-time lights, VNP46A1 excludes pixel correction concerning cloud cover and moonlight [10]. The VNP46A2 retrieval algorithm produces measurements of night-time radiance corrected for lunar BRDF (Bidirectional Reflectance Distribution Function) as well as atmospheric and terrain effects. These estimates are accompanied by pixel-level QFs which allows users to remove incomplete or problematic pixels.

The disturbance of natural environments, early onset of climate change, and discrepancies in land management practices have the potential of creating evermore uncertain socioeconomic circumstances in the already precarious political landscape of Ukraine, Russia, and the rest of the post-Soviet states that find themselves in the complex physical, ecological, and climatic systems of Northern Eurasia. The environmental and socioeconomic changes that are ongoing in this region will have severe impacts on biodiversity, environmental sustainability, and the carbon cycle in ways that can potentially feedback to alter the global Earth system [11]. The armed conflict in Eastern Ukraine presents a unique opportunity of research within the broader theatre of land cover/land use change within Northern Eurasia. The conflict has caused substantial decreases in industrial production leading to economic shifts towards agricultural activities. Despite the increased economic importance of agriculture, areas under militant control have experienced a near 26% crop loss in Donetsk and around 15% loss in Luhansk with the majority of losses attributed to land abandonment [12]. Advancements in night-time imaging will allow us to extend this type of LCLUC research towards specifically urban and industrial regions as well as the broader coupled human-Earth system.

2. Methodology

2.1. Data

The VNP46A2—VIIRS/NPP Gap-Filled Lunar BRDF-Adjusted Nighttime Lights Daily L3 Global 500 m Linear Lat Lon Grid was acquired from the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC), located in the NASA Goddard Space Flight Center in Greenbelt, Maryland (https://ladweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/VNP46A2/). The VNP46A2 product is accompanied by quality flag (QF) layers describing the radiometric quality of retrievals from a pixel-by-pixel basis. These layers were later used to select only valid retrievals of night-time lights. Validated measurements were then masked to include only those pixels contained in Eastern Ukraine, specifically Donetsk and Luhansk oblasts (the primary sub-national administrative unit in Ukraine). Additionally, the subsequent night-time light losses were calculated separately by oblasts. The night-time light composite images were created based on a 4-year period between 2012 and 2016, and changes were calculated based on a ‘baseline’ approach with differences characterized from the beginning of the period and well into the year of measurement; (2012–2013, 2012–2014, 2012–2015 and 2012–2016). This approach was selected to minimize differences in night-time light losses between the progression of the war, and maximize the magnitude of observed losses from the established 2012 baseline period which was free from conflict. Samples were generated to classify and label land-use types targeting only night-time light losses and comparing results by regions inside cities and those outside official boundaries. The overall methodology is shown in supplementary figure 1 along with more in-depth descriptions of the pixel validation process.

2.2. Composite calculation and change detection

Following the quality assessment methodology, measurements of night-time lights were processed to create yearly averaged composite images. Taking the daily validated radiance measurements, yearly averages were calculated from a pixel-by-pixel basis constrained to the temporal axis. For each year in the period, a single composite image was created in order to assess changes from the baseline period (2012). As a result, a total of four ‘difference’ images were created with changes subtracted from 2012–2013,
Figure 1. Map of sample locations within the study area with blue locations indicating regions of night-time light loss outside of cities and black locations indicating night-time light loss inside cities. The demarcation zone in orange highlights the contested region between the government of Ukraine and Pro-Russia forces. The study area is highlighted in red with an inset map of its location to the rest of Ukraine provided in the top left.

2012–2014, 2012–2015 and 2012–2016. From the difference maps, regions involving only night-time light loss were targeted. In our study, night-time light loss is defined as pixels with a 1 standard deviation difference containing negative values. These losses were separated between pixels within official Ukrainian city boundaries and those residing outside the official boundaries. In addition to comparing losses within cities and areas outside cities, night-time light losses within the conflict demarcation zone were separately calculated. The demarcation zone marks the 20 km buffer separating areas controlled by the Ukrainian government and those under the control of Russian-backed separatist groups. Regressions were computed to analyze changes in night-time light activity and have been provided in figure 3.

2.3. Land-use characterization
To examine and characterize the extents of land-use, areas with only night-time light losses were targeted. In order to fully assess the differences between night-time light losses in cities and those outside of cities, samples were generated and recorded by their land-use type. For each targeted region, 200 samples were generated using a simple random approach. The map in figure 1 shows the locations of the sampled points. In total, the generated samples were separated by a set of six classes: (a) Agriculture, (b) Forests, (c) Industrial Regions, (d) Rail/Road Networks (Transportation), (e) Residential Areas, (f) Commercial-Urban Areas. Regions targeting night-time light loss outside of cities did not include commercial-urban land-use types and were omitted from the classification. Furthermore, we distinguish residential land-use types and those between commercial-urban types based on the proximity of non-residential buildings such as businesses, stores, hospitals and other non-residential structures.

3. Results

3.1. Night-time light trends
An analysis of the night-time light losses (tables 1–4) show the greatest level of changes occurring in the 2012–2015 period. Subsequent measurements in the 2012–2014 period reveal similar losses with small gains observed into the 2012–2016 period. From comparisons at the oblast level (table 1), Donetsk observed higher losses than Luhansk, reflecting similar patterns with economic and demographic
Table 1. Total area of night-time light loss in Donetsk and Luhansk oblasts represented in absolute area (left) and relative percentage to the total region (right).

| Night-time light loss (oblast) | 2012–2013 | 2012–2014 | 2012–2015 | 2012–2016 |
|-------------------------------|-----------|-----------|-----------|-----------|
|                               | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                       | 1014       | 3.8%      | 1365       | 5.1%      |
| Luhansk                       | 506        | 1.9%      | 758        | 2.8%      |
| Total                         | 1520       | 2.9%      | 2123       | 4.0%      |

|                               | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                       | 1317       | 4.9%      | 1317       | 4.9%      |
| Luhansk                       | 620        | 4.9%      | 620        | 4.9%      |
| Total                         | 1936       | 3.6%      | 1936       | 3.6%      |

Table 2. Total area of night-time light loss in the demarcation zone represented in absolute area (left) and relative percentage to the total demarcation zone (right).

| Night-time light loss (demarcation zone) | 2012–2013 | 2012–2014 | 2012–2015 | 2012–2016 |
|-----------------------------------------|-----------|-----------|-----------|-----------|
|                                         | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                                 | 165       | 5.4%      | 318       | 10.5%     |
| Luhansk                                 | 47        | 2.3%      | 83        | 4.0%      |
| Total                                   | 212       | 4.1%      | 400       | 7.8%      |

|                                         | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                                 | 363       | 12.0%     | 363       | 12.0%     |
| Luhansk                                 | 80        | 3.8%      | 80        | 3.8%      |
| Total                                   | 443       | 8.6%      | 443       | 8.6%      |

Table 3. Total area of night-time light loss within official city boundaries in absolute area (left) and relative percentage to the total area of official boundary regions (right).

| Night-time light loss (cities)          | 2012–2013 | 2012–2014 | 2012–2015 | 2012–2016 |
|-----------------------------------------|-----------|-----------|-----------|-----------|
|                                         | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                                 | 788       | 27.0%     | 1037      | 35.5%     |
| Luhansk                                 | 380       | 17.8%     | 541       | 25.3%     |
| Total                                   | 1167      | 23.1%     | 1578      | 31.2%     |

|                                         | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                                 | 981       | 33.6%     | 981       | 33.6%     |
| Luhansk                                 | 451       | 21.1%     | 451       | 21.1%     |
| Total                                   | 1431      | 28.3%     | 1431      | 28.3%     |

Table 4. Total area of night-time light loss outside of official city boundaries in absolute area (left) and relative percentage to the total area of regions outside of official city boundaries (right).

| Night-time light loss (outside cities)  | 2012–2013 | 2012–2014 | 2012–2015 | 2012–2016 |
|----------------------------------------|-----------|-----------|-----------|-----------|
|                                         | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                                | 226       | 1.0%      | 328       | 1.4%      |
| Luhansk                                | 127       | 0.5%      | 218       | 0.9%      |
| Total                                  | 353       | 0.7%      | 545       | 1.1%      |

|                                         | Abs. (km²) | Rel. (%)  | Abs. (km²) | Rel. (%)  |
| Donetsk                                | 336       | 1.4%      | 336       | 1.4%      |
| Luhansk                                | 169       | 0.7%      | 169       | 0.7%      |
| Total                                  | 505       | 1.0%      | 505       | 1.0%      |

Comparing the regression results (figure 3), we see similar trends to the measurements of targeted losses. For the entire region of study, losses peaked in the 2012–2014 comparison with a near 63% loss. However, comparisons of the 2012–2015 period show the possibility of specific regions with increased night-time light activity despite overall losses comparable to the 2012–2014 case. Such locations could constitute shifts in wartime production with industries related to war efforts observing more activity, particularly unregulated activities such as illegal coal mining. Analyzing the results of the 2012–2016 comparison, the regression reveals general gains from the baseline period (2012) but still exhibits characteristics of certain high measurement locations in 2016, indicating the continuation of production for the locations mentioned before in the 2012–2015 comparison case.
Figure 2. Difference image of total night-time light loss across the entire 2012–2016 study period. Red shades indicate night-time light loss and green areas represent night-time light gain. Degrees of changes are separated by 1 standard deviation from the stable defined region and classed as considerable loss (−3σ), moderate loss (−2σ), small loss (−1σ), small gain (1σ), moderate gain (2σ), and considerable gain (3σ).

3.2. Land-use characteristics

Night-time lights across the study region followed a cluster pattern, centering mostly around large urban areas as well as their periphery industrial zones. Most pixels, especially in large open agricultural areas, exhibited a relatively flat and unchanging stable pattern. Night-time light clusters remained quite high closer to urban areas while areas outside of these areas saw diminishing activity. Areas corresponding to these losses were correlated with industrial plants outside of city centers as well as in transportation access points, particularly railways connected to large scale industries. For municipalities alongside the Sea of Azov such as Mariupol, night-time lights were consistently decreasing, potentially corresponding to losses in the local tourism economy.

Comparing the generated samples (tables 5 and 6), we see mixed land-use characteristics between cities and regions outside of cities. Inside cities, most losses were attributed to residential areas, with considerable regions also attributed to industrial and urban land types. In regions outside official city boundaries, industrial regions dominated with considerable regions also attributed to agricultural and residential land types. We see in both instances, high regions of residential and industrial land-use. The magnitude of residential night-time light loss suggests that the conflict has affected the general populace more so than any other interest group such as those tied to agriculture and industries. However, when comparing the land-use impacts of night-time light losses outside of cities, we see an even stronger response in industries. Samples outside of cities reveal larger relative differences, but from previous results (tables 3 and 4), we see smaller areal extents of losses in regions outside of cities, further emphasizing the domination of industries well outside of official city boundaries. A close examination of the two regions reveals that many industries lie directly outside of these official boundaries and in some cases exhibit higher night-time light measurements than urban cores (figure 4).

From the sampled land-use results, industries exhibited the most dominant regions of night-time light loss. However, by identifying the physical locations of these samples, the proximity of other land-use types to industries reveal important land-use relationships, particularly those between industries and transportation networks (figure 5). Supplies for industrial activities are typically connected by transportation networks, particularly railways and could include such activities as transporting minerals and
Figure 3. Regression results of night-time light composite comparisons from the baseline 2012 period up to 2016 ((a) 2012–2013, (b) 2012–2014, (c) 2012–2015, (d) 2012–2016)). Blue lines indicate a 1–1 correspondence, red lines indicate regression.
Table 5. Land-use characteristics within official city boundaries.

| Land type       | Loss total |
|-----------------|------------|
| Agriculture     | 4.5%       |
| Forest          | 3%         |
| Industry        | 24%        |
| Residential     | 43.5%      |
| Rail/road       | 8%         |
| Urban (commercial) | 17%      |

Table 6. Land-use characteristics outside of official city boundaries.

| Land type       | Loss total |
|-----------------|------------|
| Agriculture     | 33%        |
| Forest          | 4.5%       |
| Industry        | 36.5%      |
| Residential     | 17.5%      |
| Rail/road       | 8%         |

ores from mines to processing or refinement facilities. In the absence of transportation activity such as disruption due to fighting, lack of supplies could see industries decreasing production. Similarly, the reverse could be exhibited where industries affected by the conflict have scaled back production and as a result, the transportation networks become less utilized. Comparing the results previously (tables 3 and 4), we see similar rates of rail/road (transportation) utilization suggesting that there is no dominating factor in night-time light loss between transportation networks and industries, and that there is stable losses for networks going into cities and for networks leaving cities. Similar relationships are reflected in forest and agricultural land-use types, with proximity to processing centers reflecting night-time light losses in regions otherwise typically located away from artificial lights.

4. Discussion

Between 2012 and 2016, night-time lights in Eastern Ukraine were generally decreasing, with losses especially accelerating in the comparisons from 2014 and 2015, but stabilizing into 2016. These trends show correspondence with major events in the progress of the military conflict in Eastern Ukraine with the start of the conflict beginning in 2014, fighting escalating in 2015, and reflecting the eventual ceasefire period of 2016 following the signing of the Minsk-II protocol. In particular, these trends were more seriously reflected within the Demarcation Zone separating Ukrainian forces and pro-Russia forces, where fighting is the most severe. The results from table 2 show a near two-time increase of night-time light loss within the demarcation zone increasing from 4.1% from 2012–2013 to 7.8%, 9.5%, and 8.6% in the time-periods of 2012–2014, 2012–2015, and 2012–2016 respectively. By comparison, night-time light loss within cities (which experienced the largest percentage of loss) peaked only by 35% when comparing losses from 2012–2013 to those in the 2012–2015 period.

The separation of night-time light loss between regions inside official city boundaries and those outside cities highlights discrepancies of night-time light behaviors. Previous studies [13, 14] have applied night-time imagery in assessing broad scale spatio-temporal changes in cities. However, these studies make no distinctions in whether night-time lights occur officially within a municipality’s official population centers, often targeting only the ‘clusters’ of night-time lights, whether or not they make distinctions as to whether areas are urban or non-urban. Conversely, some studies [15, 16] may omit such areas outside of urban centers, clipping results only to administrative boundaries. The results we present in this study establish that much of the night-time lights outside of official city boundaries belong to heavy industries who often emit night-time light radiance comparable to dense urban cores. Without addressing these discrepancies involving industries whose geographic placement is often right outside of their urban cores, such analysis has the potential of introducing both errors of commission and omission, falsely attributing such pixels as belonging to population centers or removing key areas contributing to economic outcomes. Our results show the influence of such large scale industries found outside of official city boundaries and highlight their sensitivity in the observation of human activities.

The usage of artificial lighting within the context of night-time lights reflects the unique capabilities to quantify socio-economic concerns using physical radiometric measurements through satellite remote sensing. While many studies focus on analyzing purely human concerns such as population growth, hazard/disaster response, and quite recently the effects of the COVID-19 pandemic [17–19], these activities also serve as important indicators for the physical environment. In our study, we establish the impacts of land-use through analyzing changes in night-time lights, specifically targeting areas with losses. Losses in commercial-urban and residential areas signify impacts to human populations, but from an environmental perspective reflects the degree of land abandonment with spillover effects to agricultural regions especially in farm areas outside of urban cores. This carries considerable environmental concerns, particularly in forest reclamation and stresses to vegetation and soil [20]. Increased forest growth provides increased carbon sequestration leading to positive effects to the environmental system [21], however also increasing the likelihood of wildfires [22]. Additionally, growth of new vegetation in previous croplands have found to increase...
the propagule pressure of weeds, pests, and pathogens [23]. As crop productions further decline, the remaining fields within governmental control are likely to experience additional stress which will result in soil depletion [24]. Furthermore, night-time light losses in industrial areas corresponding to abandoned mines and chemical processing facilities have the potential of introducing catastrophic environmental disasters. Coal-beds containing iron sulfide (FeS$_2$) can react to form sulfuric acid (H$_2$SO$_4$) when exposed to oxygen [25]. The acidification of ground water threatens water supplies and can lead to severe contamination. Observations of night-time light losses provide a unique and novel approach to studying these environmental effects and can serve as indicators for the strength and efficacy of environmental policies.

The separation of our results between Donetsk and Luhansk oblasts reveals interesting patterns. Across each measure of study, losses in Donetsk far exceeded those of Luhansk. Comparisons at the oblast, city, and outside-city levels (tables 1, 3 and 4) reveal differences ranging around 50% of that between Luhansk and Donetsk, with the greatest difference measured at 43% (city level comparing 2012–2015) and the lowest difference measured at 67% (outside cities comparing 2012–2014) highlighting overall less night-time light activity in Luhansk. Figure 6 shows the differences in economic factors between the two oblasts with a side-by-side illustration with the corresponding night-time light loss. Measurements within the demarcation zone however revealed starkly contrasted results with differences between Luhansk and Donetsk ranging between 22% and 29% (table 2). Given such low values, these results indicate that losses in the demarcation zone within Donetsk were much greater than those in Luhansk, and suggests that fighting was more severe in Donetsk than in Luhansk. Discrepancies in such low measurements for Luhansk could be reflected by lower population and Gross Regional Product (GRP—often used to describe GDP of specific regions) when compared...
Figure 6. Comparisons of Gross Regional Product (left) and night-time light loss (right) highlighting differences in Donetsk and Luhansk. Decreases in economic activity correspond to increases in night-time light loss, mirroring an inverse relationship between these two factors. Gross Regional product is often applied as GDP for specific regions. Economic data was obtained from Statistical Bulletin ‘Gross Regional Product in 2017,’ produced by SSSU.

5. Conclusion

The night-time light losses within Eastern Ukraine indicate significant changes in land use affected by the on-going military conflict. The impacts to general populations in this conflict reflects shifts in economic and industrial activities that have experienced cascading effects to the land cover/land use change outcomes of this region. Our study illustrates the improved capability of the VIIRS platform in investigating these phenomena and presents a methodology of studying human conflicts and their impacts to the environment. As one of few wholly human indications of environmental changes, the study of night-time lights allows a uniquely anthropogenic approach in studying land-use outcomes. As the military conflict in Eastern Ukraine escalates, satellite remote sensing will allow us to continue to study both humanitarian and environmental outcomes of the war. The evidence provided here establishes the high impacts of land cover and land use change from the military conflict in Eastern Ukraine and presents additional contexts to the complex landscape of the overall Northern Eurasian physical and political environment.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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