Shedding light on the Russia-Ukraine War

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6th October 2025

Abstract

With the Russia–Ukraine war evolving into a prolonged war of attrition, the functioning of the two economies has become central. A small but growing literature uses alternative data to measure economic activity, responding to the limitations of official statistics. In this paper, we use nighttime lights ("NTL") data to track economic changes in both countries.

Ukraine's NTL has fallen by 50% compared to 2022 levels. In contrast, Russia's aggregate NTL showed virtually no change between 2022 and 2025. Within Russia, the Yamal–Nenets Autonomous Okrug, which produces 90% of the country's gas, recorded substantial NTL growth despite reports of declining national gas production. We also identify growth reversals in regions hundreds of kilometres from the Ukrainian border, likely reflecting the effects of standoff weapons. Similar reversals appear along Russia's Western European border but not along other international frontiers, suggesting uneven enforcement of sanctions. Over the war years, Ukraine's economic activity has shifted westward, while Russia's has moved eastward.

Contents

1 Introduction

The war that began in February 2022 had substantial implications for the economies and measurement systems of both countries. Long-running wars, or strategic wars, are wars of attrition. These are shaped to an important extent by the working of the economy. The outcome on the battlefield relies on the ability of the state to foster a well functioning economy and produce or obtain adequate resources including soldiers and their supporting civilian teams, their food and health care, and their materiel.

In a strategic war, the release of economic information has military significance. Hence, there was a decline in the quantity of official statistics. For example, Russian statistics show discrepancies between official reports and independent indicators (Milov, 2022; Becker et al., 2024). Russia's expanded state secrecy law restricts information access, as *"details of Russia's foreign trade, economic policy, and scientific developments may all be classified as secret"* (Bloomberg, 2025; President of the Russian Federation, V. Putin, 2025). Statistics collection in Ukraine also suffers from wartime constraints, often excluding combat zones or occupied territories (IMF, 2025). Many economic indicators ceased to be published after the invasion, including regional production indices, investment statistics, and budget data (SSSU, 2023; SDC, 2024). Population displacement, regional conflict variations, and destruction of statistical infrastructure further complicate economic measurement.

In understanding the war, five questions of economics are of importance:

Aggregate economic impact At an aggregate level, how are the economies of Russia and Ukraine faring, after the war started?

The economy near the front What happens to the economy through physical proximity to the battlefront? Close to the battlefront, we expect a combination of the impact of fighting, evacuations, blackouts, destruction of productive capacity, and the presence of troops and their logistics tail. We expect the zone of destruction to exceed what was seen in previous wars owing to the nature of modern war.

The footprint of standoff weapons Modern war is unique in the extent to which a trench is hard to overcome, but it is not that difficult to hit a factory that is 200 kilometres in the rear. Further away from the battlefront, there would be an adverse impact upon the economy through the new level of presence of stand off weapons. Hence, we expect to see a footprint of standoff weapons deep into the backfield.

Reversal of gains from trade At various elements of the Russian international

border, the natural economic geography had originally evolved in response to the proximity to economic activity across the border (Boschma, 2023). The adverse impact upon the local economy, the distortion away from the natural organisation reflecting proximity to the economy across the border, is likely to vary based on the intensity of new restrictions imposed by the bordering country.

Changing economic geography Over the many years of the ongoing war, the economic geography will have been reshaped through government and private decisions. Understanding this map of shifting economic geography is important from the viewpoint of understanding regional economics, and for resource allocation in long range strikes or air defence.

Ukraine has experienced infrastructure destruction, population displacement, and loss of production capacity. The Russian occupation of industrial zones and the temporary blockade of Black Sea ports restricted exports from Ukraine (Moshensky, 2024; Astrov et al., 2022; Guénette, Kenworthy and Wheeler, 2022).

This is also the case for Russia. Ukraine was increasingly able to engage in strategic war, striking at locations 1000 km. within Russia or more (Polishchuk et al., 2025; Plichta, 2025). Russia faced economic sanctions from Western countries in the form of crude oil price caps, shipping restrictions, export controls, and banking limitations (Milov, 2022; Schmith and Sakhno, 2023; Becker et al., 2024). Military mobilisation, casualties, and emigration reduced Russia's workforce (Kolyandr, 2025). A surge of military production was required to support the war, necessitating shifting resources from the civilian economy (Milov, 2022; Schmith and Sakhno, 2023). The central bank raised rates to support the ruble and fight inflation (Becker et al., 2024), which was one mechanism through which the civilian economy lost ground. Russia responded to the sanctions regime, created evasion networks through shell companies, alternative payment systems, and trade through third countries in order to evade sanctions (Schmith and Sakhno, 2023; Becker et al., 2024; Milov, 2024). Trade with China increased 29.3% to $190.27 billion in 2022, while trade with India grew 121.4% to $30 billion (Becker et al., 2024; Liu, 2023).

Obtaining well measured economic statistics about Russia and Ukraine has become very important. Numerous capabilities from traditional and alt data have been brought to bear on measuring the two economies after the war. Researchers on the Russian economy use vehicle sales and air traffic data (Schmith and Sakhno, 2023), oil price estimates (Becker et al., 2024), and carbon emissions tracking (**meyer˙2023**). For Ukraine, methods include business surveys (Puhachova, 2020) and shadow economy assessment (Polese et al., 2022).

In this paper, we offer novel insights into the five questions listed above using

Nighttime lights ("NTL") data.

NTL data is well established in the literature as a useful measure of economic activity, particularly when the institutional capacity for measurement in the official statistical system is low (J. V. Henderson, Storeygard and Weil, 2012). It has been used for GDP estimation (Sutton, Elvidge and Ghosh, 2007) and development assessment (Bennett and Smith, 2017). In conflict zones, NTL data enables monitoring where ground data collection is infeasible. For example, the existing literature using NTL data on this war finds 50-80% decreases in Ukraine's luminosity after the invasion (Huang et al., 2023; Li et al., 2022; Lin et al., 2024; Wang, Lei and Xu, 2024).

For insights into economic geography, NTL data allows calculation of a country's economic centre of gravity, representing the spatial distribution of economic activity and its movement over time (Grether and Mathys, 2008; Quah, 2011). Cauwels, Pestalozzi and Sornette (2014) used NTL to compute the global economic center of gravity, with results matching Quah (2011), validating this approach.

However, applying NTL data to measure economic activity in Russia and Ukraine presents several methodological challenges. The high latitude of both countries leads to "white nights" and seasonal gaps in satellite observations. Gas flaring in hydrocarbon-rich regions generates extreme radiance values that can distort results. Additionally, vast unpopulated areas contribute background noise, which can accumulate into significant spurious signals. During the war, defensive blackouts further reduce radiance in affected regions, complicating the interpretation of NTL data as an economic indicator.

These challenges call for careful design of the methodology through which the conventional data and algorithms are applied. This paper develops these methods and reports on the state of the Russian and Ukrainian economy going till early 2025. Our key results are as follows:

Aggregate economic impact The aggregate NTL growth for Russia shows that it has been flat from 2022 to 2025. Most Russian gas production takes place in the Yamal-Nenets Autonomous Orkug, and economic activity there has been strong, which runs against conventional views that Russian gas exports have declined sharply. In contrast, the aggregate NTL data for Ukraine shows a sharp decline. For both countries, 2023 was a low after which there has been some recovery.

The economy near the front The oblasts where the war is taking place, and Crimea, have fared surprisingly well.

The footprint of standoff weapons Regions in Russia located hundreds of kilometres from the Ukrainian border experienced a growth reversal: provinces

near the border saw radiance decline by 10–58.8%, while eastern regions recorded gains of 8–18.56%.

Reversal of gains from trade A growth reversal is visible in locations near the border with European countries - which have imposed sanctions more completely - as opposed to the border with other countries.

Changing economic geography The Russian economy has shifted East, away from Europe and the war. There was an eastward shift of the economic center of Russia by 245 kilometres between January 2019 and January 2025. In contrast, the Ukrainian economy has shifted West, away from the war zone.

We emphasise reproducible research practices. All data processing and analysis can be replicated using our open Google Colab notebook, which is described in detail in Section 5.

2 Data and Methodology

2.1 Nighttime Lights Data

NTL data is widely recognised as a proxy for economic activity. Brighter areas in NTL imagery indicate higher levels of prosperity, and changes in brightness correlate with economic growth or decline. At a national level, NTL offers a measure of economic activity, free from the difficulties of official economic measurement institutions. The nature of satellite data allows for subnational assessments of regional development, economic geography, and sector-specific trends (Sutton, Elvidge and Ghosh, 2007; Bennett and Smith, 2017; Patnaik and Mendez, 2024). In conflict zones, NTL data is used for assessing damage, tracking displacement, and monitoring socio-economic impacts where ground-based data collection is impossible (Yelistratova et al., 2022; Wang, Lei and Xu, 2024). In the field of European economic geography, nighttime light NTL data has been used to predict GDP in the European Union (Gibson, 2021) and forecast population migration in smaller European countries (Chen, 2020).

NTL data does not respond to short-term fluctuations of economic activity, and it responds with a lag to smoothed economic activity. As an example, the analysis of Indonesia during the Asian Financial Crisis and Rwanda during the genocide, revealed that NTL did not reflect economic distress in the short-run (J. V. Henderson, Storeygard and Weil, 2012).

We use data from the Day/Night Band (DNB) of the **Suomi NPP satellite's VIIRS** instrument. Specifically, we use the stray light corrected version of VIIRS DNB monthly composites of average radiance, which are generated by averaging daily cloud-free observations. This correction addresses artifacts caused by solar

illumination of the instrument during nighttime data collection, and minimises data gaps caused by stray light.

While our data processing pipeline uses the entire available dataset from January 2014 to January 2025 to ensure proper cleaning and correction of quality issues, the results and analysis presented in this paper focus on the period from January 2019 to January 2025 for Russia, Ukraine, and the disputed territories: three years before and after the invasion.

2.2 Administrative Boundaries

Administrative boundary data is sourced from GADM (gadm.org). We use a province-level (ADM1) shape file for Russia (83 provinces) and Ukraine (22 provinces, excluding disputed provinces). This data is used for the spatial aggregation of NTL data and for creating choropleth maps. The following territories are analysed separately as zones of active conflict: Donetsk, Kherson, Luhansk, Zaporizhia, Crimea, and Sevastopol. Additionally, we include boundaries of neighboring countries (Belarus, Estonia, Finland, Lithuania, and Latvia) in Russia's maps to provide geographical context and mitigate visual distortion caused by the map re-projection.

2.3 Data Processing and Cleaning

Processing raw NTL data requires addressing several quality issues inherent in satellite observations (Patnaik, Shah, Tayal et al., 2021). These include missing values due to cloud cover, negative radiance values from calibration errors, outliers caused by gas flares or fires, and background noise. To address these, we employ the `NighttimeLights.jl` package, which automates the correction of major data quality issues (Patnaik, Shah and Thomas, 2022). Key steps include handling missing data by using cloud-free observation counts, removing noise and outliers, correcting for atmospheric attenuation in cloudy months, and interpolating to fill remaining gaps.

2.4 Region-Specific Challenges and Corrections

The use of NTL data to measure economic activity in this region presents some unique challenges:

Solar illumination The high latitude of Russia and Ukraine means that many regions experience extended daylight or strong twilight in summer ("white nights"). This interferes with the measurement of faint NTL and leads to significant data gaps (Figure 1). Our methodology is designed to handle this seasonal data loss.

Background noise To mitigate the impact of background noise being detected as artificial light in areas with little to no economic activity, we filter out all radiance values below a threshold of 4 (Kyba et al., 2017). This issue is particularly important when it comes to the vastness of geographical area that is found when studying Russia or Ukraine, where small amounts of background noise can add up to substantial values.

Outliers A significant outlier issue in NTL data for Russia stems from extreme radiance values, which are likely indicative of gas flaring and can potentially bias economic analysis. To mitigate the influence of this gas flaring bias, we implement a threshold approach, where radiance values exceeding a threshold of 100 $nW\,cm^{-2}\,sr^{-1}$are filtered out.[1] By setting the cutoff at 100 $nW\,cm^{-2}\,sr^{-1}$, we ensure that nearly all genuine urban and industrial activity is retained, while outliers, primarily from gas flaring or other industrial activities, are excluded from the analysis.

At a conceptual level, it is useful to think that a high temperature factory or gas flare is excluded, but the economic activity associated with the expenditures of its workers is included. This threshold approach complements the statistical outlier removal techniques implemented in `NighttimeLights.jl`, which identify and filter anomalous values through conventional statistical techniques.

3 Results

3.1 Russia

3.1.1 Aggregate radiance of Russia

Figure 2 presents the time series of Russia's aggregate radiance measured each January from 2019 to 2025. This gives a novel perspective on the Russian economy through this period.

There was a peak in January 2022, which may reflect war production and mobilisation prior to the invasion. In comparison, there was a significant decline in aggregate radiance by January 2023, followed by a recovery in 2024, with radiance levels returning to pre-war levels. The data from January 2025 indicates a small decline from the 2024 level. Our main take-away is that the Russian economy in early 2025 was at a value similar to that in early 2022.

[1]This threshold was chosen based on the 99th percentile of NTL radiance observed in Moscow, Russia's most economically vibrant region. For reference, the 99th percentile of radiance in Moscow in 2025 is 97.93 $nW\,cm^{-2}\,sr^{-1}$(Table E.1 in Appendix E).

Figure 1 Time series of average cloud-free observations for Russia and Ukraine

The figure shows the average cloud-free observations for Russia and Ukraine from January 2019 to January 2025. The data reveals a seasonal pattern, with significant gaps in cloud-free observations during the summer months. This is the case in high-latitude regions like Ukraine and Russia, where elongated daylight hours hinder night time imaging and reduce the number of days of observation per month. The highest number of cloud free observations in a month are found in January, which is thus the best month for which measurement can be attempted.

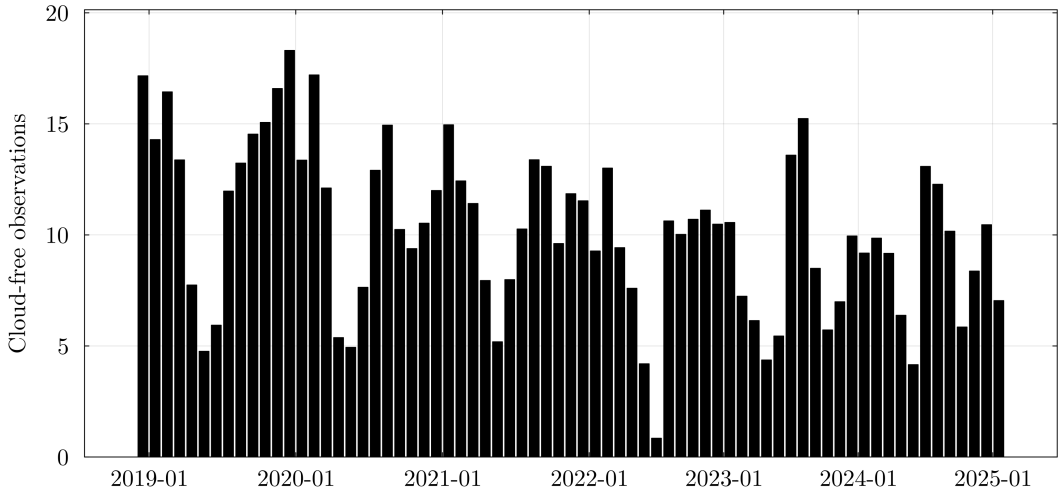
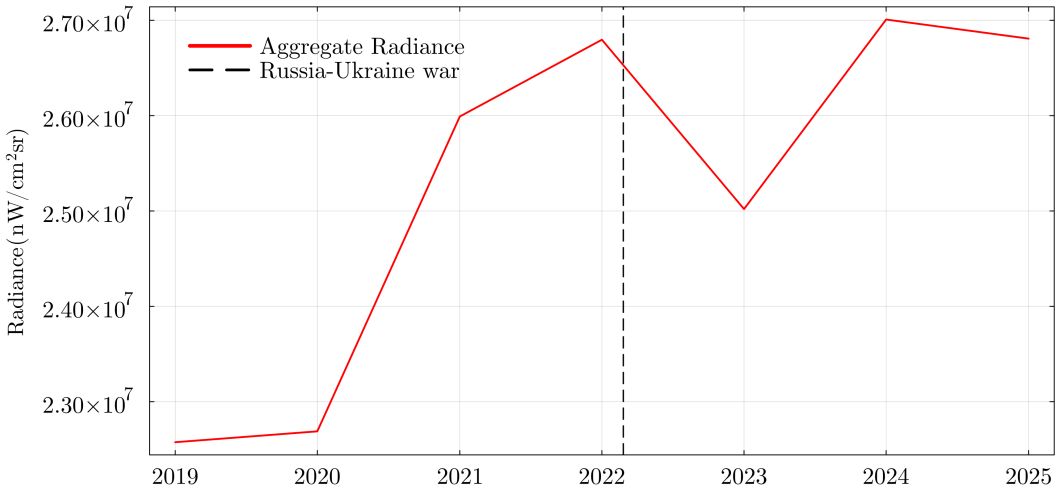


Figure 2 Time series of aggregate NTL of Russia (measured in January)

This figure shows Russia's aggregate NTL radiance measured each January from 2019 to 2025. This shows that the Russian economy in early 2025 was at similar values to those seen at the pre-invasion peak.



3.1.2 Subnational aggregate radiance of Russia

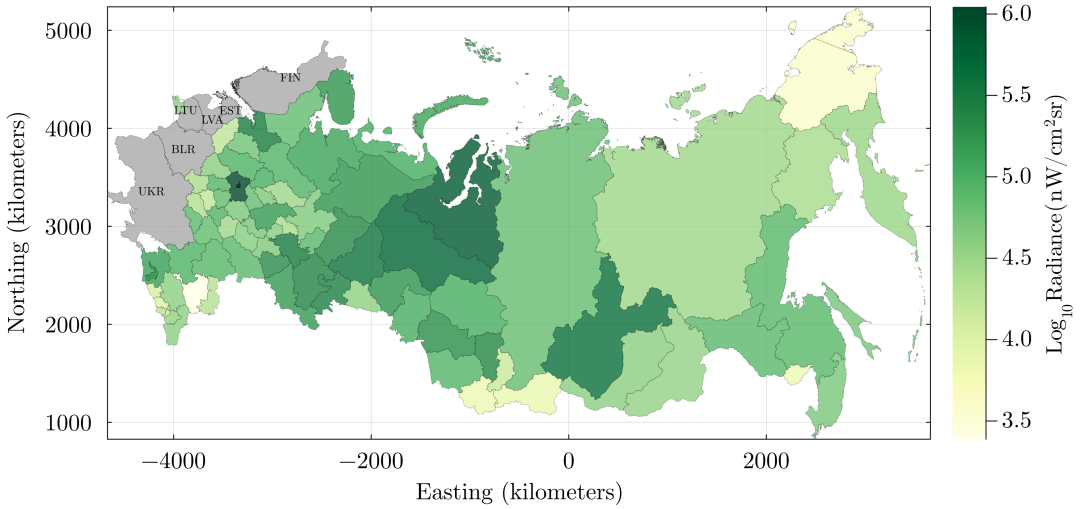
Figures 3 and 4 present the subnational distribution of NTL in January 2019 (pre-war baseline) and January 2025 (three years after the invasion), respectively.

The pre-war economic geography of Russia (Figure 3) shows the spatial concentration of activity characteristic of the Russian economy, with Moscow as the dominant economic center, followed by St. Petersburg and other urban centers in the European part of Russia. This western orientation of economic activity reflects Russia's trade and investment patterns, with economic integration into Europe (Korhonen and Simola, 2022).

By January 2025 there were changes in the spatial distribution of activity, while the pattern of economic concentration persisted (Figure 4). Moscow and St. Petersburg remained economic centers, but there were reductions in radiance in western border regions near Ukraine, Belarus, and the Baltic states. Conversely, eastern regions, with connections to Asian markets or with resource extraction industries, showed stable or increased radiance. These changes likely reflect Russia's reorientation of trade and investment patterns in response to Western sanctions, with increased economic integration with Asian partners, particularly China, and the imprint

Figure 3 Subnational aggregate radiance (log scale) — Jan 2019

The figure provides a baseline view of Russia's traditional pre-war economic geography. The map shows the spatial concentration of economic activity in Russia, with the highest intensity NTL in Moscow. Belarus, Estonia, Finland, Lithuania, Latvia and Ukraine are also shown in the map for context.
The European part of Russia shows higher economic activity levels compared to the areas of Siberia and the Far East, except for urban and industrial centers.



of standoff weapons used by the Ukraine Armed Forces. These results augment and attenuate the understanding of the regional economics as seen in Yakovlev, Malyutina and Bagamaeva (2024) and Arapova (2023).

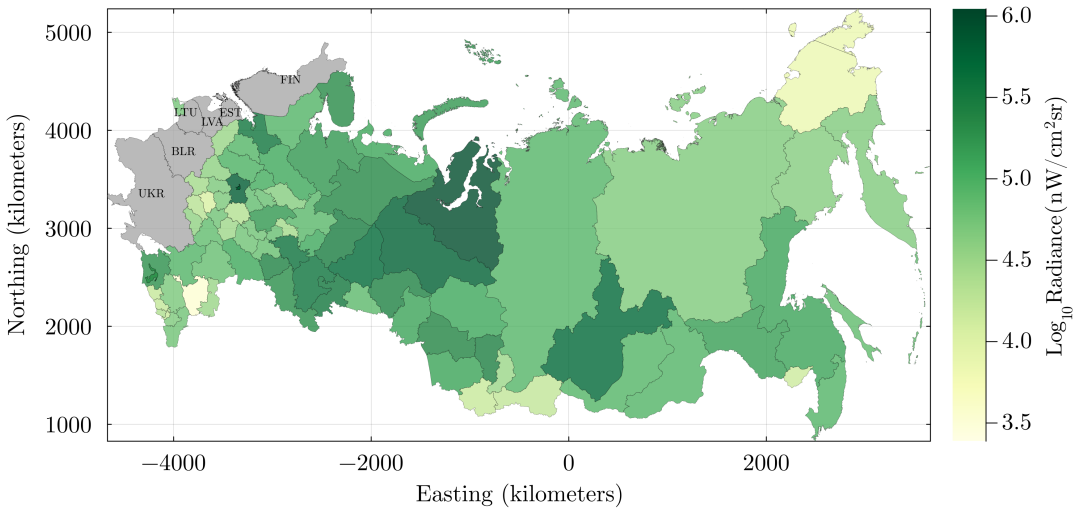
3.1.3 Subnational trends in Russia

Figure 5 depicts the subnational NTL growth during the pre-war period, from January 2019 to January 2022. Figure 6 shows the subnational NTL growth during the post-war period, from January 2022 to January 2025. Figure 7 provides an overview of the subnational NTL growth across the study period, from 2019 to 2025. Figure 8 highlights the difference in subnational NTL growth between the post-war (Jan 2022-Jan 2025) and pre-war (Jan 2019-Jan 2022) periods, showing the shifts in economic activity patterns.

The subnational analysis reveals regional variations in Russia's economic response to the war and sanctions. In the pre-war period (Figure 5), economic growth was balanced across Russian regions, with both western and eastern areas showing

Figure 4 Subnational aggregate radiance (log scale) — Jan 2025

The figure shows Russia's economic geography in January 2025, three years after the invasion of Ukraine. While Moscow and St. Petersburg remain economic centers, the map reveals key changes: western border regions show decreased activity, while eastern regions have increased radiance.



positive trends. Border regions with Ukraine and the Baltic states displayed growth (typically 4-46%), as did resource-rich areas in Siberia and the Far East (11-38%), reflecting Russia's pre-war engagement with both Europe and Asia.

After the invasion, the western regions near Ukraine experienced an economic contraction, with border provinces showing NTL reductions of 10 to 58.8% (Figure 6). In contrast, eastern regions, with provinces facing the Pacific and those bordering China, showed increases of 8 to 18.56% in radiance. This spatial pattern illustrates Russia's economic reorientation away from Europe toward Asia in response to direct military impact, Western sanctions and the severing of economic ties.

The cumulative change from 2019 to 2025 provides a perspective on the transformation of Russia's economic geography (Figure 7). Many regions show positive growth over this six-year period, demonstrating the resilience of the Russian economy. However, the western border regions near Ukraine exhibit negative growth rates, ranging from -52% to -6%, while eastern regions show growth ranging from 31% to 64%.

The comparison of pre-war and post-war growth rates in Figure 8 gives the clearest evidence of the reorientation of Russia's economic geography. The western regions show worse economic performance after the invasion than before, with differences in growth rates ranging from -85 to -14 percentage points. The eastern regions have differences ranging from -20 to +6 percentage points.

3.1.4 Shifting centre of gravity of the Russian economy

The spatial redistribution of economic activity can be further analysed by examining the trajectory of the centre of gravity of Russian economic activity, as derived from NTL data. This is shown in Figure 9. Between January 2019 and January 2025, the center of economic gravity moved approximately 245 kilometres eastward, with the movement occurring after the February 2022 invasion. This eastward trajectory provides a summary metric that captures the impact of several concurrent processes reshaping Russia's economic geography.

This reorientation of Russia's economic center of gravity reflects the country's geopolitical pivot away from Europe and toward Asia. The pace and magnitude of this shift suggest that the war and sanctions have accelerated a geographic restructuring of the Russian economy that may have implications for trade patterns, infrastructure development, and regional economic trajectories in the future. The eastward movement visible in NTL data aligns with documented trade reorientation, with Russia's trade with China increasing by 29.3% to $190.27 billion in 2022, and trade with India growing by 121.4% to $30 billion in the same period.

Figure 5 Russia: Subnational NTL growth (pre-war)

The figure shows regional economic growth in Russia before the Ukraine invasion (January 2019-2022). Growth is balanced across the country, with both western and eastern regions showing positive trends. Border regions with Ukraine and Baltic states display growth, while resource-rich areas in Siberia and the Far East show increases, reflecting Russia's pre-war economic orientation between European and Asian markets.

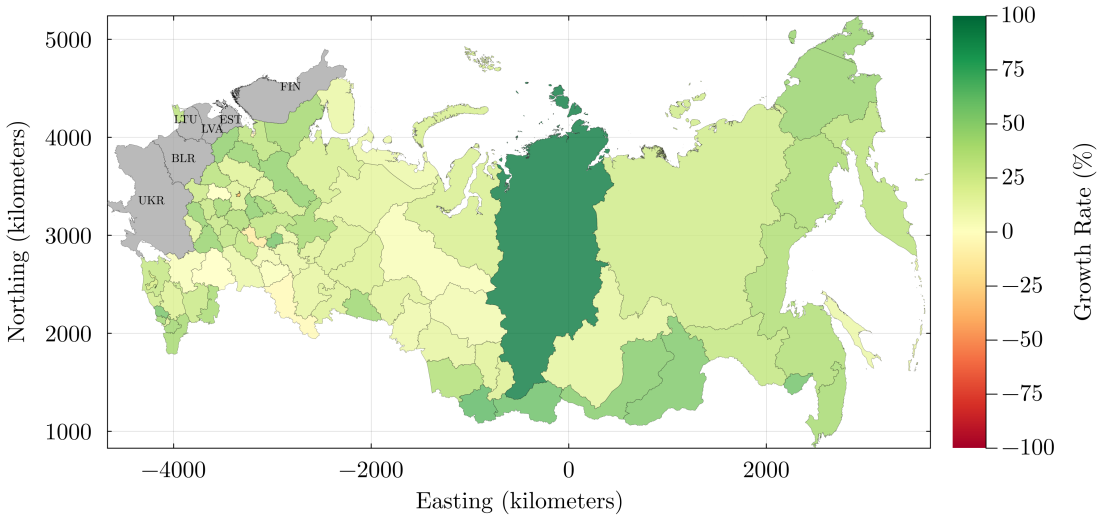
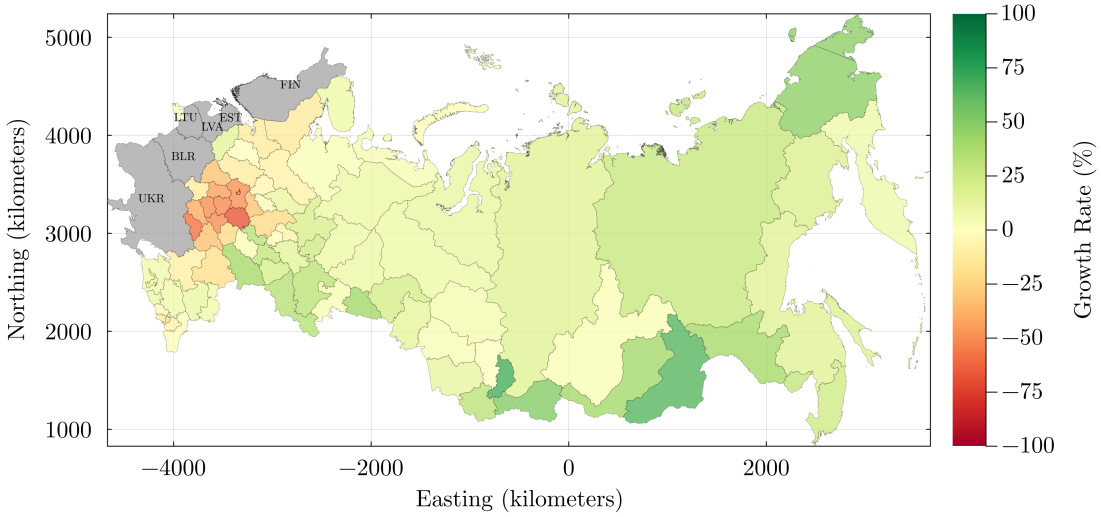


Figure 6 Russia: Subnational NTL growth (post-war)

The figure shows Russia's regional economic shifts after the invasion (2022-2025). Western regions near Ukraine experienced contraction, while eastern regions showed continued or accelerated growth. This pattern illustrates Russia's economic reorientation away from Europe toward Asia



The center of gravity analysis provides evidence that Russia's adaptation to Western sanctions has included a spatial dimension, with the country's economic orientation shifting eastward as it pursues new markets, trade routes, and economic partnerships.

3.1.5 Gas production in Russia

The Yamal-Nenets Autonomous Okrug produces approximately 90% of Russia's natural gas and is an indicator of the health of Russian gas production and exports. Official statistics show fluctuations in national gas production since 2019. The NTL analysis of this region provides an alternative perspective. Figure 10 presents the aggregate NTL for Yamal-Nenets, measured in January of each year after filtering out outliers from gas flaring. By removing these flares, the remaining light signature reflects economic activity and spillovers associated with the gas industry, such as infrastructure development and local services.

This shows an upward trend in economic activity associated with gas production, with NTL radiance increasing by approximately 35.05% between January 2019 and January 2025. This growth has continued throughout the war period, with a flattening in the growth curve observed in January 2023 before resuming its upward

Figure 7 Russia: Subnational NTL growth (2019-2025)

The figure shows the cumulative economic changes across Russia from 2019-2025, spanning both pre-war and war periods. Many regions show positive growth, demonstrating economic resilience. Western border regions near Ukraine exhibit negative growth, while eastern regions show adaptation and growth.

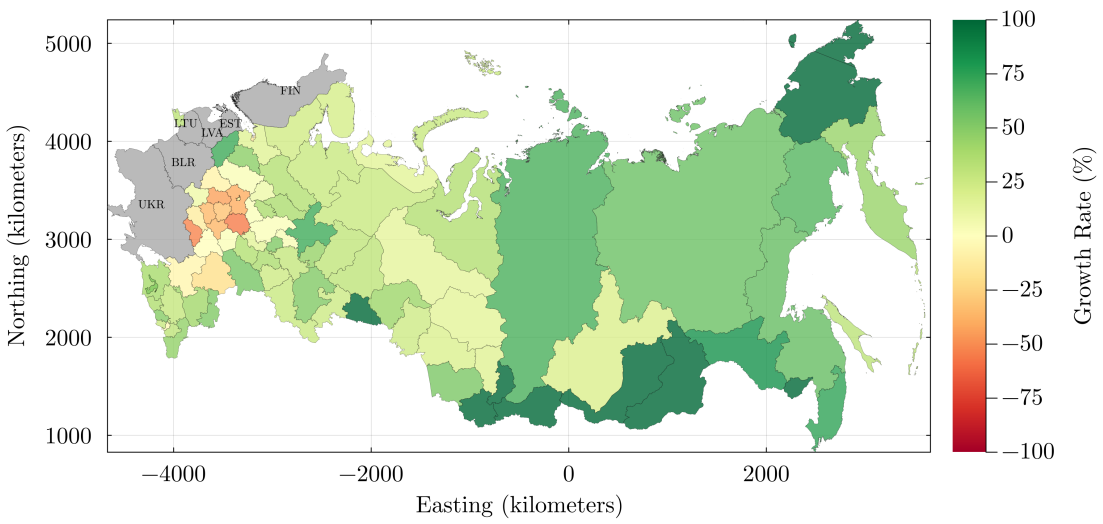


Figure 8 Russia: Difference in pre-war and post-war growth

The figure compares the pre-war and post-war growth rates, highlighting regions where economic trajectories have changed since the invasion. This shows the economic impact of the war on regions close to Ukraine and the western border. There is a decline in radiance in these areas, while eastern regions show continued growth or stability. This shift reflects Russia's economic reorientation away from Europe and toward Asia.

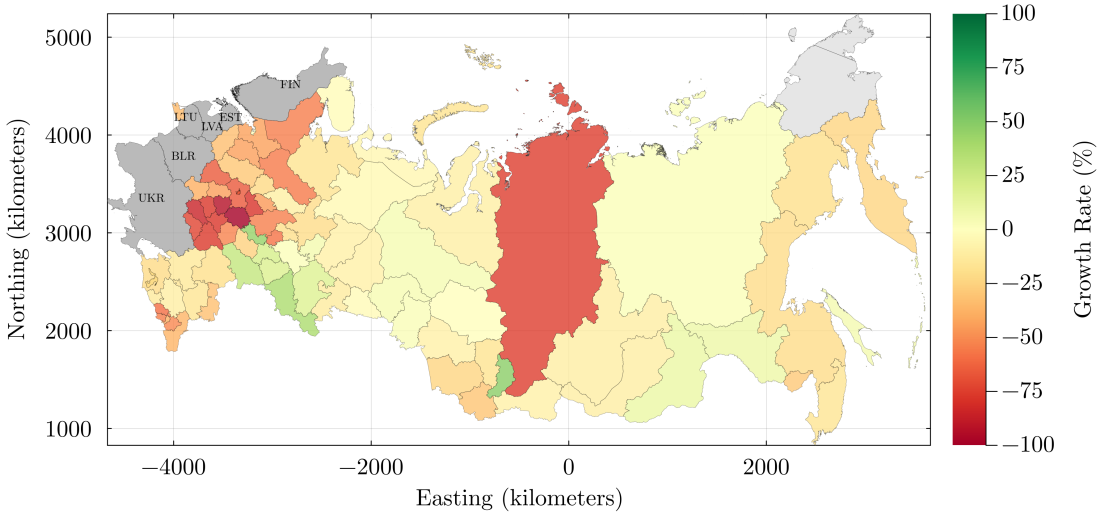
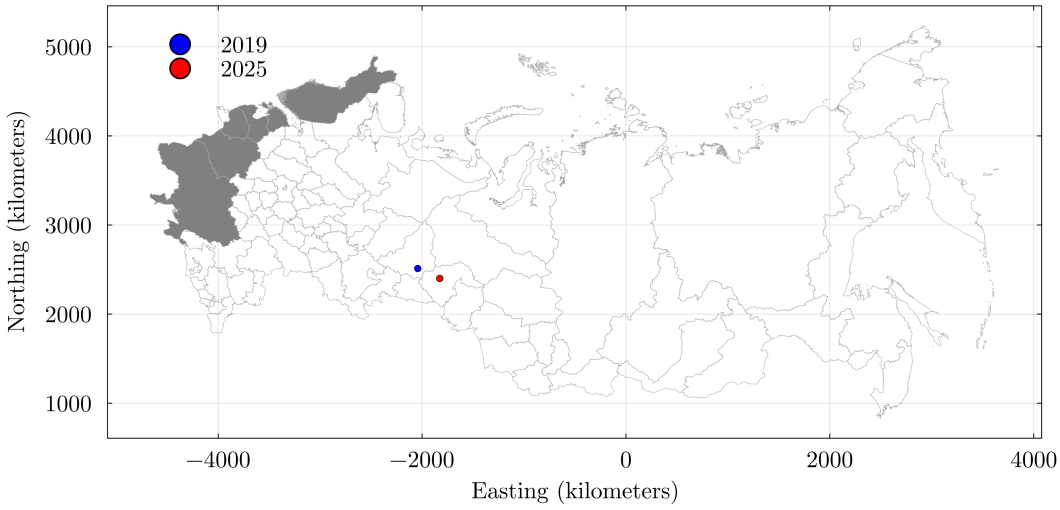


Figure 9 Shifting centre of gravity of the Russian economy (map)

The figure shows the change in Russia's economic center of gravity between January 2019 and January 2025. Over this period, the center of economic gravity shifted eastward, indicating a reorientation of economic activity towards Asia. Neighboring countries are shaded in grey to provide geographic context.



trajectory in 2024 and 2025.

In conventional statistics about Russian gas production, the total dry gas production is believed to have fallen from a peak of 732.64 BCM in 2021 to 613.45 BCM in 2023, a reduction of approximately 16.26%. Similarly, Russian pipeline gas exports to the European Union—the largest market for Russian gas—dropped by approximately 84.77% by 2024 compared to pre-war levels (Keliauskaitė et al., 2021) with Russian gas blockages and European efforts to reduce dependence on Russian energy. Capacity that would have been used to send gas through Nord Stream 2 was stranded through destruction of this pipeline.

The continued growth in economic activity in Yamal-Nenets despite these production and export declines suggests adaptation in Russia's gas sector. Exports to China via the Power of Siberia pipeline grew by 454.39% in 2023, with further capacity expansion underway (Gazprom, 2023). Additionally, Russia has accelerated development of LNG export capacity, which offers flexibility in reaching global markets beyond the constraints of pipeline infrastructure (J. Henderson, Yermakov and Connolly, 2024). The capital expenditures associated with building LNG capabilities in Yamal-Nenets Autonomous Okrug would trigger off improved NTL.

The resilience of the Yamal-Nenets region also reflects the priority that Russia has placed on maintaining its hydrocarbon production capacity despite sanctions. This suggests that the gas sector remains a source of government revenue and geopolitical leverage, leading to investment in both extraction infrastructure and the supporting economic ecosystem visible in NTL signatures.

3.2 Ukraine

3.2.1 Aggregate radiance of Ukraine

The impact of the Russia-Ukraine war on Ukraine's economic activity is evident in Figure 11, which presents the time series of Ukraine's aggregate NTL measured each January from 2019 to 2025. This annual snapshot approach allows for seasonal comparison while avoiding the data gaps that occur during summer months due to the region's high latitude.

The data reveals a decline in luminosity following the Russian invasion in February 2022. Compared to the January 2022 pre-war baseline, the January 2023 measurements show a reduction of approximately 67.55% in aggregate radiance, reflecting the profound impact of the conflict on Ukraine's infrastructure and economic activity.

While the data indicates a modest partial recovery in 2024 and 2025 (a gain of

Figure 10 Aggregate NTL time series of Yamal-Nenets Autonomous Okrug (measured in January, after outlier filtering)

This figure shows the economic activity in Russia's gas-producing region after filtering out radiance values from gas flaring. The upward trend reveals economic growth in Yamal-Nenets despite Western sanctions targeting the energy sector.

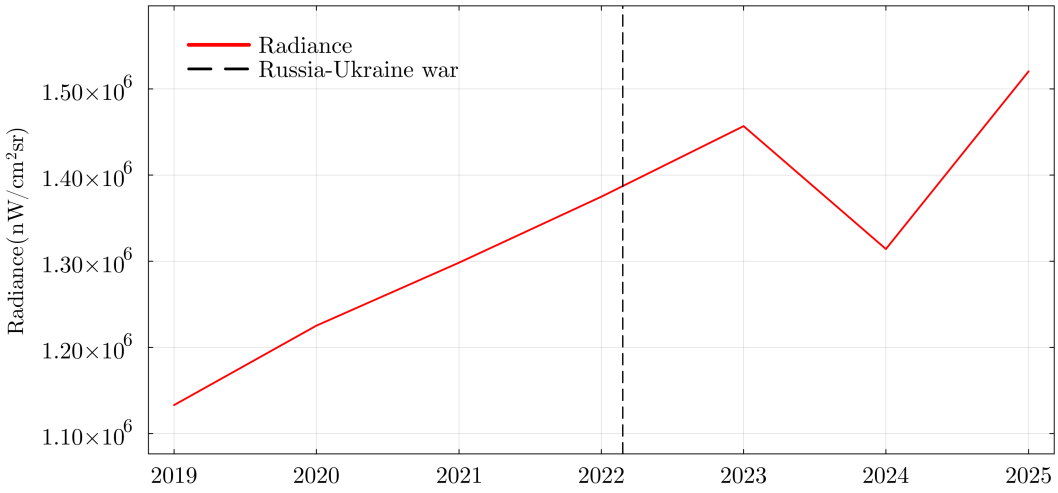
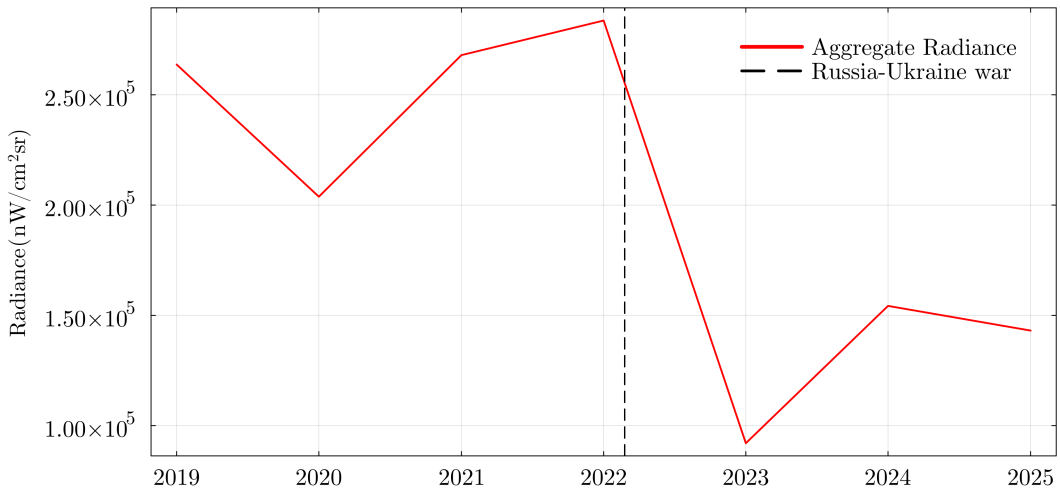


Figure 11 Time series of aggregate NTL of Ukraine (measured in January)

The figure shows the time series of Ukraine's aggregate NTL from measured at January, from 2019 to 2025. There is a decline in the aggregate radiance of the country following the onset of the Ukraine-Russia war in early 2022 reflecting the impact of the conflict on economic activity. The partial recovery in 2024 and 2025 remains well below pre-war levels.



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55.47% from the low of 2023), radiance levels remain substantially below pre-war values, reaching only about 50.45% of the January 2022 levels by January 2025.

3.2.2 Subnational trends in Ukraine

Figure 12 displays the subnational aggregate radiance in January 2019, representing the pre-war baseline, which is useful for assessing the impact of the war on regional economies. Figure 13 shows the map for January 2025, highlighting the widespread decline and economic disruption. Analysis of subnational NTL growth reveals the profound impact of the war, as shown in Figures 14, 15, and 16. The difference in growth rates before and after the invasion is stark (Figure 17), and the westward shift of Ukraine's economic centre of gravity is evident in Figure 18.

Examining the subnational economic impacts of the war across Ukraine reveals several patterns. The pre-war baseline map (Figure 12) shows the concentration of economic activity in major urban centers as is found in most countries, with an accent on Kyiv, Kharkiv, Dnipro, Odesa, and the industrial regions of eastern Ukraine. By January 2025 (Figure 13), there was a marked reduction in radiance across the entire country, with severe dimming in eastern and southern regions that

have experienced direct combat, occupation, or that have proximity to the front lines.

The subnational growth maps allow us to quantify these changes more precisely. During the pre-war period from January 2019 to January 2022 (Figure 14), most regions showed modest growth in luminosity, indicating economic expansion. The post-invasion period from January 2022 to January 2025 (Figure 15) shows a different pattern, with widespread and severe reductions in NTL intensity throughout the country, including in western regions that were not directly exposed to combat operations.

The cumulative change from January 2019 to January 2025 (Figure 16) illustrates the overall economic transformation during this six-year period. Nearly all regions display negative growth in NTL intensity, with the most severe contractions (a 56.35% reduction) in the eastern and southern regions closest to the front lines or under Russian occupation. Even in western regions, relatively removed from direct combat, there are substantial reductions in NTL intensity, reflecting the nationwide impact of the conflict through disrupted supply chains, population displacement, and perhaps blackouts.

A particularly revealing analysis comes from examining the difference in growth rates between the pre-war and post-war periods (Figure 17). This comparison highlights the economic trajectory change attributable to the war, controlling for pre-existing trends. While most regions experienced an acceleration in economic decline after the invasion, the rate of dimming varied significantly: some areas experienced a decline after the war began, whereas others saw the pace of decline slow or stabilise.

The westward shift in Ukraine's center of economic gravity (Figure 18) provides a summary metric of this geographic redistribution of economic activity. This westward movement of approximately 29.7 kilometres between January 2019 and January 2025 reflects both the disproportionate economic damage in eastern Ukraine and the relative preservation of economic capacity in western regions.

3.3 NTL near the battlefront

We separately analyse the NTL data for the set of 'disputed territories'. These are the region of Donetsk, Kherson, Luhansk, Zaporizhia, Crimea, and Sevastopol, which represent areas of contestation and shifting control during the Russia-Ukraine conflict, and therefore, the site of active conflict. Analysing NTL patterns in these regions could provide insights into the economic consequences of the conflict in territories experiencing occupation, changing governance, and combat operations.

Figure 12 Ukraine: Subnational aggregate radiance (log scale) — Jan 2019

The figure shows the subnational distribution of NTL across Ukraine in January 2019. This provides a baseline for assessing the impact of the war on regional economies and infrastructure.

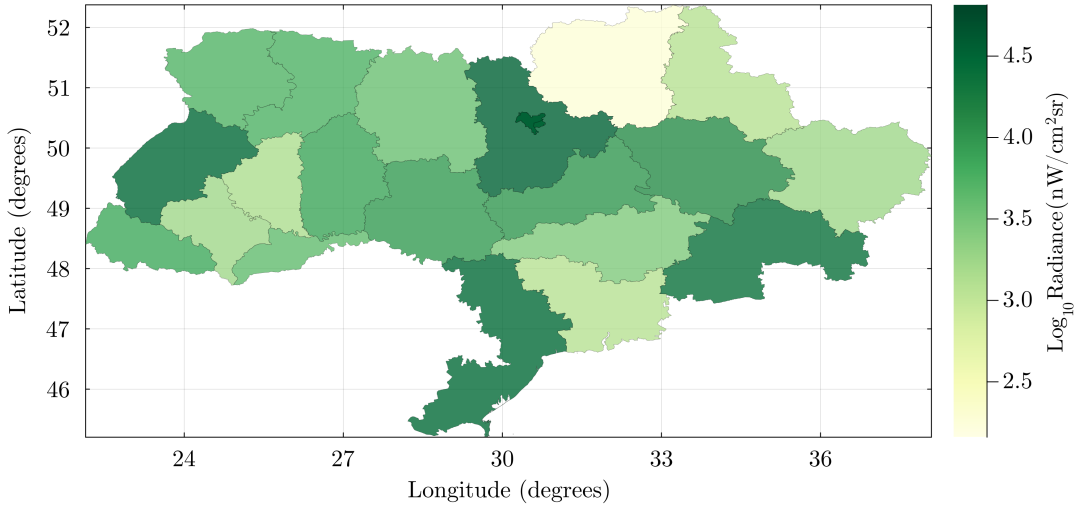


Figure 13 Ukraine: Subnational aggregate radiance (log scale) — Jan 2025

The figure displays the subnational distribution of NTL across Ukraine in January 2025. Compared to the pre-war baseline, there is a reduction in radiance. This highlights the economic disruption experienced throughout the country.

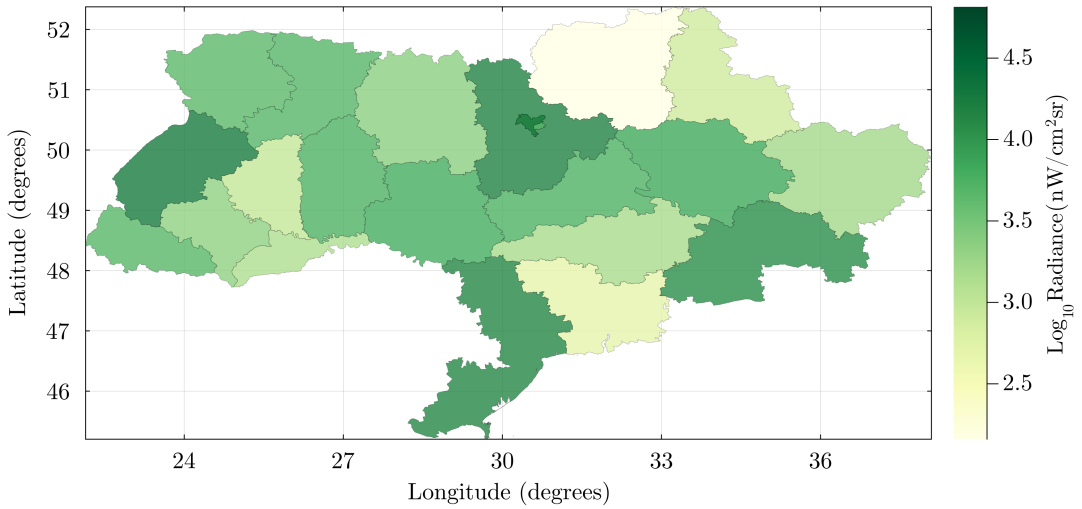
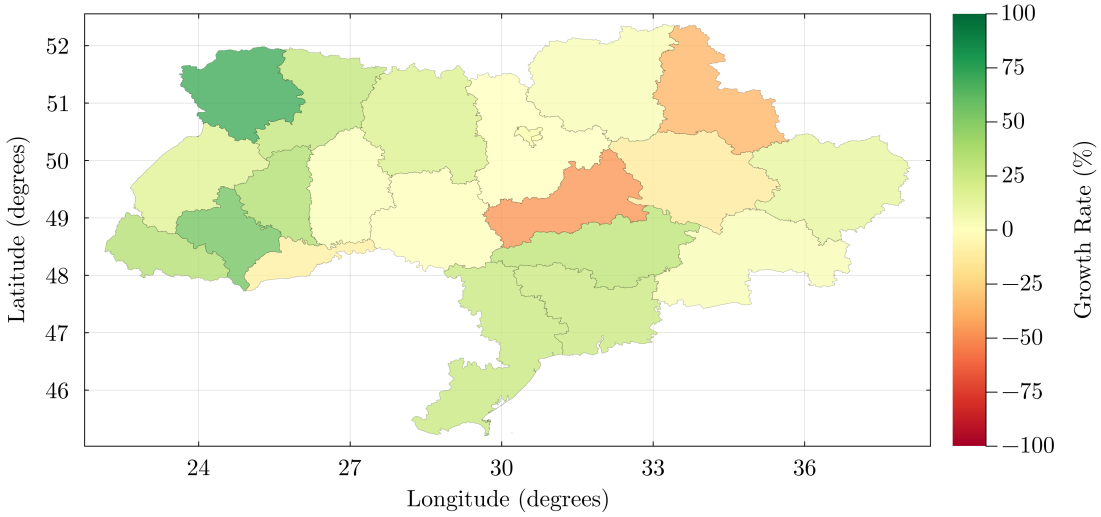


Figure 14 Ukraine: Subnational NTL growth (pre-war)

The figure illustrates the spatial pattern of economic change in Ukraine during the pre-war period from January 2019 to January 2022. Most of the country shows increase in luminosity (light to dark green areas), indicating economic expansion.



There may be an important impediment to using NTL data to infer the dynamics of economic activity in these regions. Every army has a substantial operation in terms of field camps for soldiers, kitchens, hospitals, depots for supplies, and the logistics operations of moving food, fuel, ammunition, and soldiers while taking the casualties out. This operation is likely to create light at night, which would be picked in the NTL measurement, but it cannot be interpreted as being related to the economy that is found in a normal location.

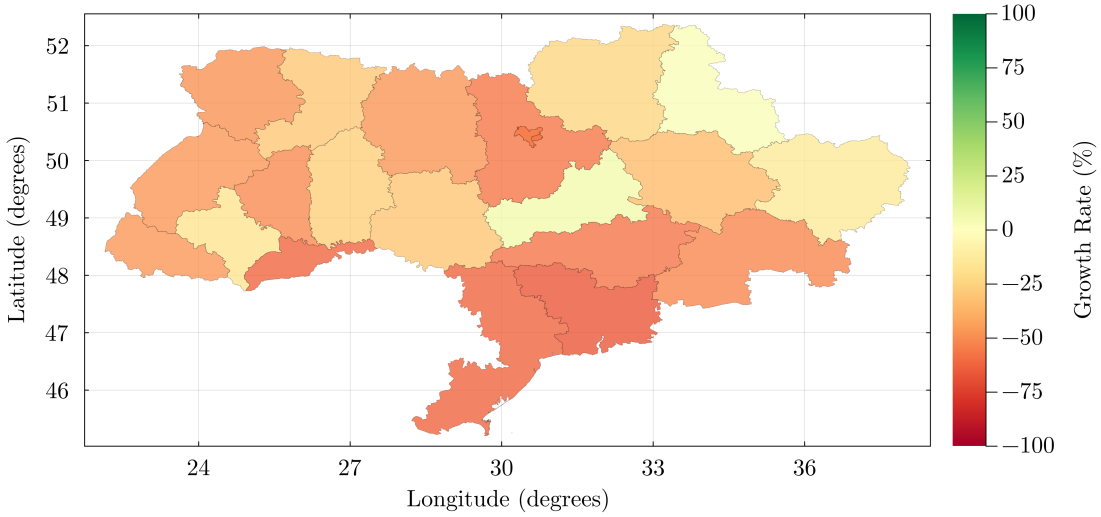
3.3.1 Aggregate radiance in the disputed territories

Figure 19 presents the aggregate NTL for these territories measured each January from 2019 to 2025. Prior to the invasion in 2022, the aggregate radiance shows fluctuations, with Crimea and Sevastopol (under Russian control since 2014) showing stability, while Donetsk and Luhansk (experiencing conflict since 2014) show variability.

By January 2023, there was a decline of approximately 0.306% from January 2022 levels. The disputed territories showed a recovery by January 2025, with levels approximately 5.24% higher than the January 2022 pre-invasion baseline. This pattern likely reflects several concurrent processes: damage in some areas balanced

Figure 15 Ukraine: Subnational NTL growth (post-war)

The figure presents the pattern of economic change in Ukraine during the war period, January 2022 to January 2025. The map reveals negative growth in NTL intensity throughout most of the country.



by Russian investment in infrastructure in territories under consolidated control, (particularly Crimea, where economic integration with Russia has been a priority) and war-related placement of logistics and personnel in these locations.

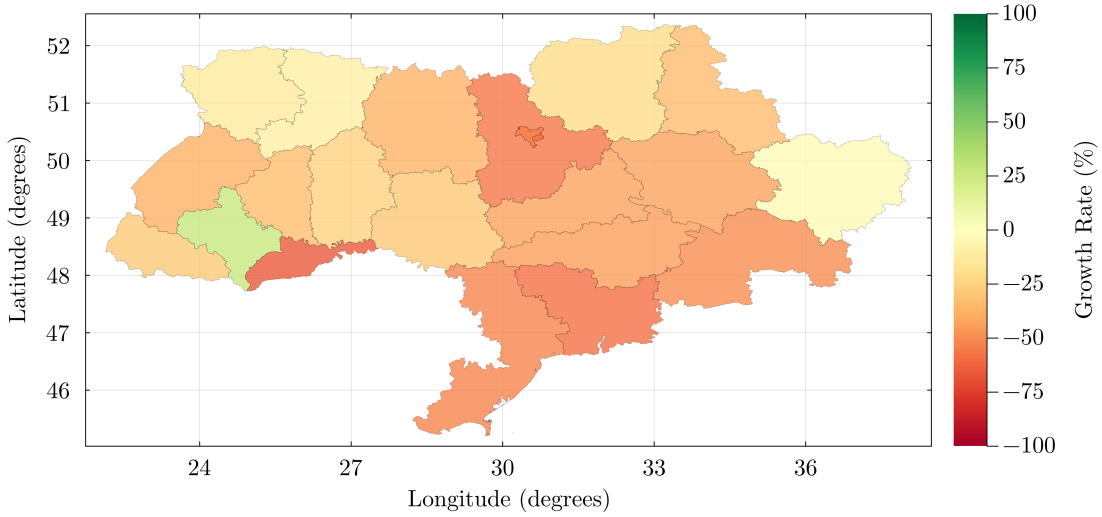
3.3.2 Subnational trends in the disputed territories

The subnational trends within the disputed territories underscore the varied economic consequences of the conflict.[4] The analysis reveals a territorial divide, with Crimea and Sevastopol showing stability and growth, reflecting Russian investment, while other regions like Donetsk and Luhansk display more negative trajectories due to direct combat and shifting control. This pattern highlights how outcomes are shaped by physical destruction, governance, and occupying forces' priorities.

[4] A detailed examination of these trends, including maps of radiance levels and growth rates, is available in Appendix A.

Figure 16 Ukraine: Subnational NTL growth (2019-2025)

The figure provides a view of Ukraine's economic transformation over the study period from January 2019 to January 2025. The map shows reduction in NTL, with most regions displaying negative NTL growth.



4 Conclusion

The war in Ukraine is an important geopolitical milestone for the world. Economic measurement using NTL has not processed a large scale conventional war before.

Every strategic war of attrition is shaped by the performance of the economy. For this very reason, both sides have an incentive to reduce transparency about the performance of the economy. This calls for an emphasis on alternative data such as NTL data. We do not suggest that NTL data is a perfect measure of economic activity. It has its strengths and weaknesses. We view this paper as a component of the alternative data literature that has emerged around the Russia-Ukraine war.

Further, a new kind of strategic warfare has arisen, with standoff weapons on both sides through the course of this war. This has important implications for the economy operating in the rear. The use of standoff weapons has introduced a new dimension to strategic warfare not seen in the Eastern front in the World War II. We have to delve into the details of the working of the economy of both countries and not just the aggregate NTL data.

The key findings of this paper may be summarised as follows.

Figure 17 Ukraine: Difference in pre-war and post-war growth

This figure illustrates the change in subnational NTL growth rates between the post-war (January 2022 to January 2025) and pre-war (January 2019 to January 2022) periods. While most regions saw a decline in NTL from 2019 to 2025, the rate of dimming varied: some areas experienced a decline after the war began, whereas others saw the pace of decline slow or stabilise.

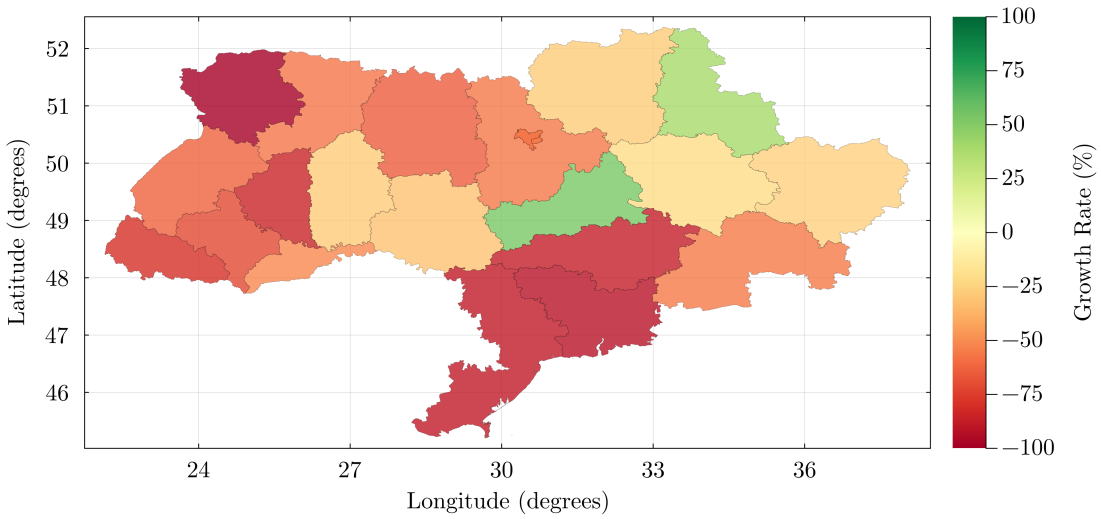
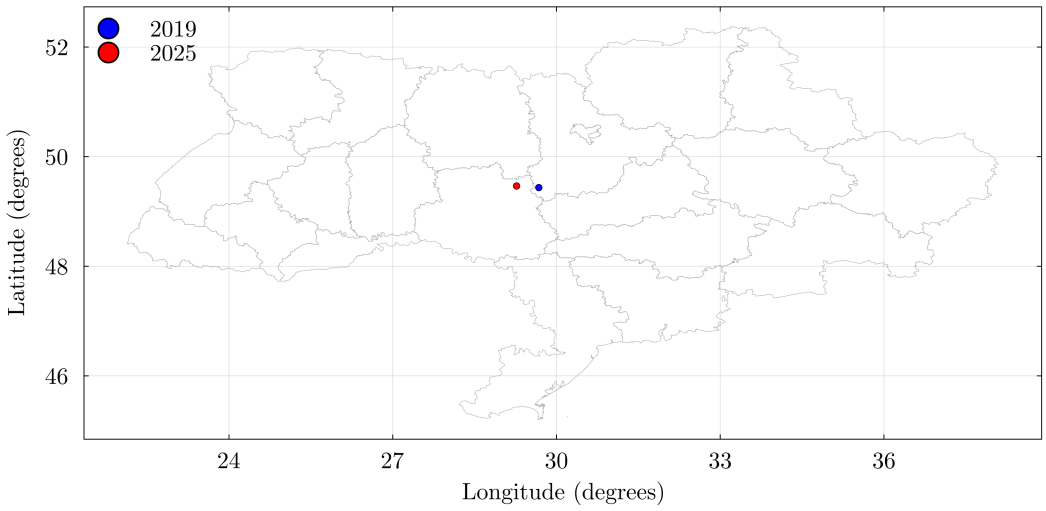


Figure 18 Shifting centre of gravity of the Ukrainian economy

This figure highlights the westward shift in Ukraine's center of economic gravity between January 2019 and January 2025. The map visually captures how economic activity has concentrated towards west, reflecting the impact of the war on regional economic dynamics.



Aggregate economic impact The aggregate NTL for Russia shows roughly 0 growth from 2022 to 2025 (Figure 2). In contrast, there has been a drop in aggregate NTL of 67.55% for Ukraine in the same period (Figure 11).

In Russia, gas production in the Yamal-Nenets Autonomous Okrug, a region which continues to show strong economic activity (Figure 10). This runs against conventional views that Russian gas exports have declined sharply, which can help explain the lack of a drop in the Russian economic activity as measured by NTL data.

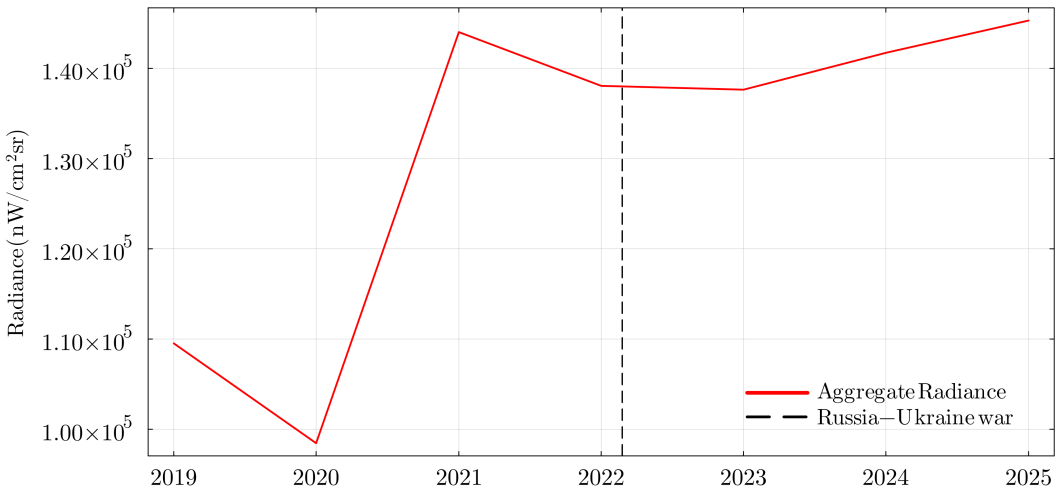
For both countries, 2023 was a low point, after which there has been some recovery.

The economy near the front The oblasts where the war is taking place, have fared surprisingly well on the NTL data (Figure 19).

An implication of this for economic activity, may reflect a limitation of the NTL data in the context of understanding a battlefront. It is likely that the economic impact of the logistics tail of armies in action (which makes light at night) exceeds the adverse impact of destruction of the productive economy.

Figure 19 Time series of aggregate NTL of the disputed territories (measured in January)

The figure shows the aggregate NTL time series for the disputed territories, measured in January of each year. The area shows an increase in aggregate NTL.



3

The footprint of standoff weapons A growth reversal is visible in locations within Russia that are hundreds of kilometres inside the Ukraine border (Figure 8). The radiance in the regions of Russia near Ukraine contracted by 10-58.8%, while eastern regions maintained growth of 8-18.56%.

Reversal of gains from trade A growth reversal is visible in Russian locations near the border with European countries, which have imposed sanctions more completely, as opposed to the border with other countries (Figure 8).

Changing economic geography The Russian economy has shifted East, away from Europe and the war (Figure 9). In contrast, the Ukrainian economy has shifted West, away from the war zone (Figure 18).

There was an eastward shift of the economic center of Russia by 245 kilometres between January 2019 and January 2025. We are able to see maps of levels (Figure 4) and growth rates of subnational NTL (Figure 8) that yield fresh insights into the working of the Russian economy.

The war, and its consequences upon the economic geography of both countries, emphasizes the connections between institutions and regional economic outcomes (Rodríguez-Pose, 2020; Iammarino, Rodriguez-Pose and Storper, 2019). In understanding the economic geography of Russia and Ukraine in the future, there could be two views. On one hand, we may think that in the event of a lasting peace, the economic geography could rapidly revert to its pre-war arrangement. On the other hand, there is the question of path dependency (Boschma, 2023). Perhaps Russia could permanently shift its emphasis away in favour of the East, and Ukraine could permanently look West in its future economic organisation, after a lasting peace.

Future research examining these economies over a longer time horizon, with several additional years of post-war data, would provide more comprehensive insights into the true economic consequences of the conflict and help distinguish between temporary wartime disruptions and permanent structural changes in economic geography. Such longitudinal studies would also help validate the persistence of the geographic shifts we have identified and better separate economic signals from conflict-related noise in the NTL data.

5 Reproducible Research

We provide a Google Colab notebook (Rowe et al., 2020; Patnaik and Mendez, 2024) that enables users to download data, process satellite images, and generate results—including figures and tables—within a single, fully reproducible environment.

The notebook retrieves NTL rasters and shapefiles from Google Earth Engine (GEE). The process involves initialising the notebook in a Python environment to acquire the data. Following the instructions provided, the user then manually switches to a Julia environment for subsequent processing.

When fetching data from GEE, scaling has been done to reduce computation time. To match the results of the paper more accurately, the scale parameter can be controlled to increase the resolution. By resampling, the levels change, but the patterns remain the same.

The notebook is publicly available on Google Colab and is hosted in an open GitHub repository.

Acknowledgments

We are grateful to Evgeny Gavrilenkov for insightful feedback on an earlier draft. We thank Ishi Jain of IIT Kanpur for working on this paper as an intern. We also thank Tilotamma Ghosh of the Earth Observation Group for assistance with queries related to the NTL data. We thank Hasita Pattipaty and Aaryaman Shah for helping on literature review.

Appendices

A Subnational trends in the disputed territories

This section provides a detailed look at the subnational NTL trends within the disputed territories. The maps show variations in radiance patterns from the pre-war period to 2025, illustrating the different economic trajectories across these regions.

Examining these maps reveals a territorial divide in economic trajectories. Crimea and Sevastopol, which had been under Russian control since 2014, show a pattern of economic stability and growth throughout the period. This reflects Russia's investments in these regions, including the construction of the Crimean Bridge and other infrastructure projects designed to integrate these territories economically with Russia.

In contrast, Donetsk, Luhansk, Zaporizhia, and Kherson display varied and negative economic trajectories. Prior to February 2022, these regions showed economic strain from the conflict that began in 2014. After the invasion, areas with fighting showed reductions in NTL intensity, reflecting destruction of urban infrastructure, industrial facilities, and housing, as well as population displacement.

The economic impact appears most severe in areas that have experienced shifting control or combat operations, where infrastructure has been damaged and civilian life disrupted. Areas under consolidated Russian control have some evidence of stabilisation or recovery in certain urban centers by January 2025, though still below pre-2022 levels in most cases.

This pattern of economic change within the disputed territories underscores how the economic impacts of the conflict are shaped by physical destruction, governance patterns, priorities of occupying forces, and pre-existing economic structures in each region.

Figure 20 shows the economic landscape of disputed territories in January 2019, establishing a pre-war baseline. In this period, Crimea and Sevastopol were under Russian control, while Donetsk and Luhansk had war-related disruptions. At the same time, there was a significant scale of Ukrainian attacks upon Crimea.

Figure 21 reveals the transformed economic landscape of disputed territories by January 2025. Compared to levels seen in Figure 20, some regions show an increase in radiance, particularly in Crimea, while others show a decline.

Figure 22 demonstrates the pre-war economic growth patterns across disputed territories. Sevastopol and Crimea show positive growth, while most northern regions show decline or stability.

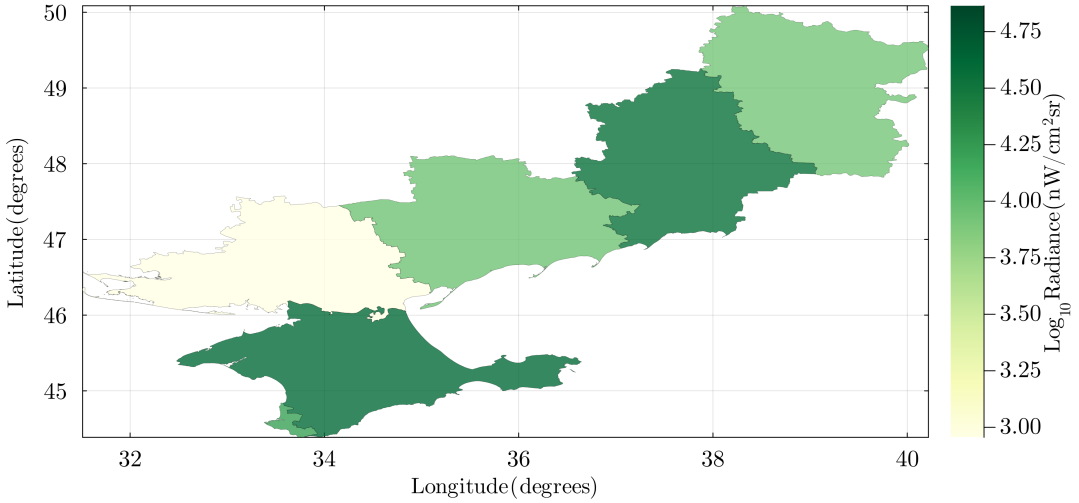
Figure 23 illustrates the post-invasion economic changes in disputed territories from January 2022 to January 2025, showing the varied impact of the conflict across different regions.

Figure 24 displays the cumulative economic changes in disputed territories from 2019 to 2025, spanning both pre-war and war periods. Crimea and Sevastopol show growth, while other regions exhibit varied trajectories.

Figure 25 compares growth patterns before and after the 2022 invasion, highlighting the differential impact of the war across the disputed territories and revealing how economic trajectories have changed since the onset of the conflict.

Figure 20 Disputed territories: Subnational aggregate radiance (log scale) — Jan 2019

The figure shows the subnational aggregate NTL (log scale) in January 2019. This map provides a baseline for the disputed territories before the war.



B Monthly radiance time series

This section presents the monthly time series for aggregate NTL radiance in Ukraine, Russia, and the disputed territories from January 2014 to January 2025. These figures offer a more granular perspective on economic activity, complementing the January to January plots presented in the main analysis.

Figure 26 illustrates the monthly evolution of Ukraine's aggregate nighttime lights radiance from 2014 to 2025. The pattern mirrors Figure 11, showing a significant drop following the 2022 invasion.

Figure 27 demonstrates the monthly pattern of Russia's aggregate nighttime lights radiance over the eleven-year period. Consistent with the January to January analysis, the data reveals relatively stable levels with modest changes.

Figure 28 shows the continuing pattern observed in the disputed territories' monthly aggregate radiance. Unlike Ukraine and Russia, these territories showed growth above pre-war levels.

C Challenges in visualising Chukotka

Plotting the Chukotka Autonomous Okrug for visualisation purposes presents unique cartographic challenges. These challenges arise due to several factors: its high latitude, its geographical position spanning the 180th meridian (which corresponds to the International Date Line), and

Figure 21 Disputed territories: Subnational aggregate radiance (log scale) — Jan 2025

The figure shows the subnational aggregate NTL (log scale) in January 2025. Compared to levels seen in Figure 20, some regions show an increase in radiance, particularly in Crimea, while others showing a decline.

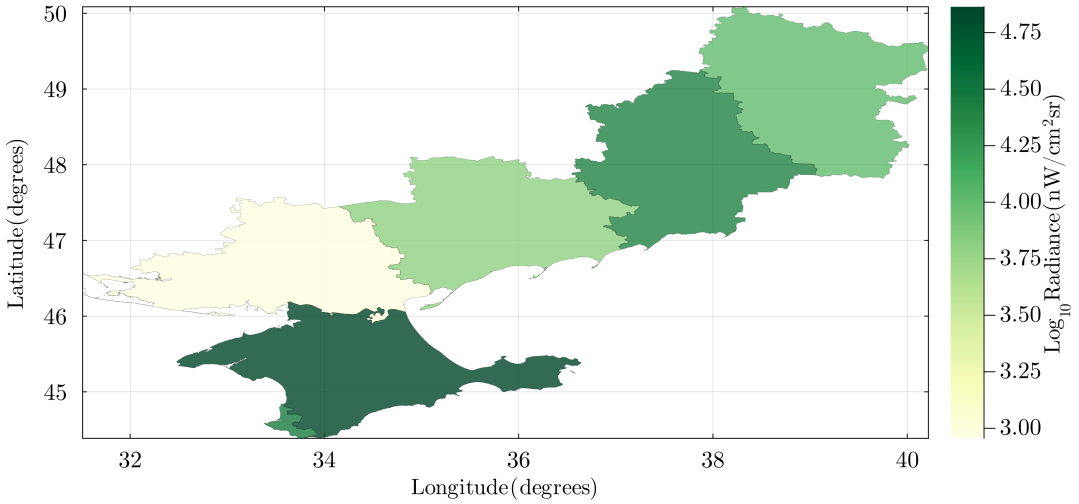


Figure 22 Disputed territories: Subnational NTL growth (pre-war)

The figure shows subnational NTL growth in disputed territories before the war. Sevastopol and Crimea show positive growth, while most northern regions show decline or stability.

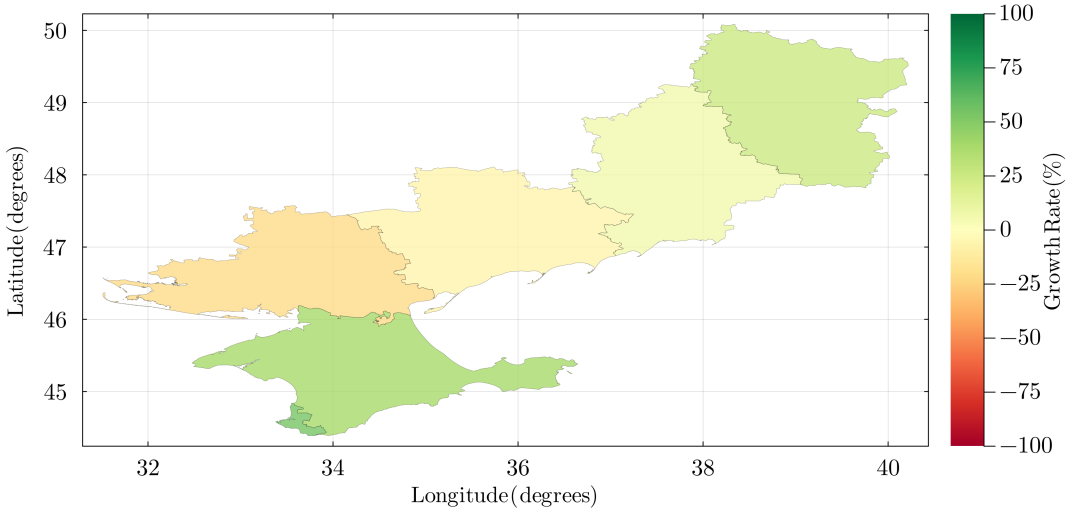


Figure 23 Disputed territories: Subnational NTL growth (post-war)

The figure shows NTL growth in disputed territories from January 2022 to January 2025, after the invasion.

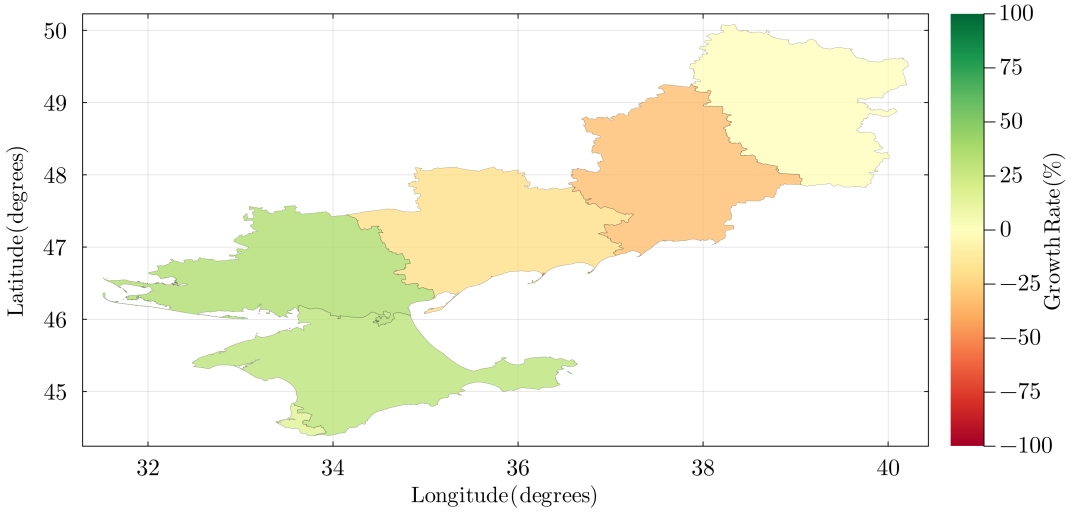


Figure 24 Disputed territories: Subnational NTL growth (2019-2025)

The figure displays the economic changes in disputed territories from 2019 to 2025. Crimea and Sevastopol shows growth.

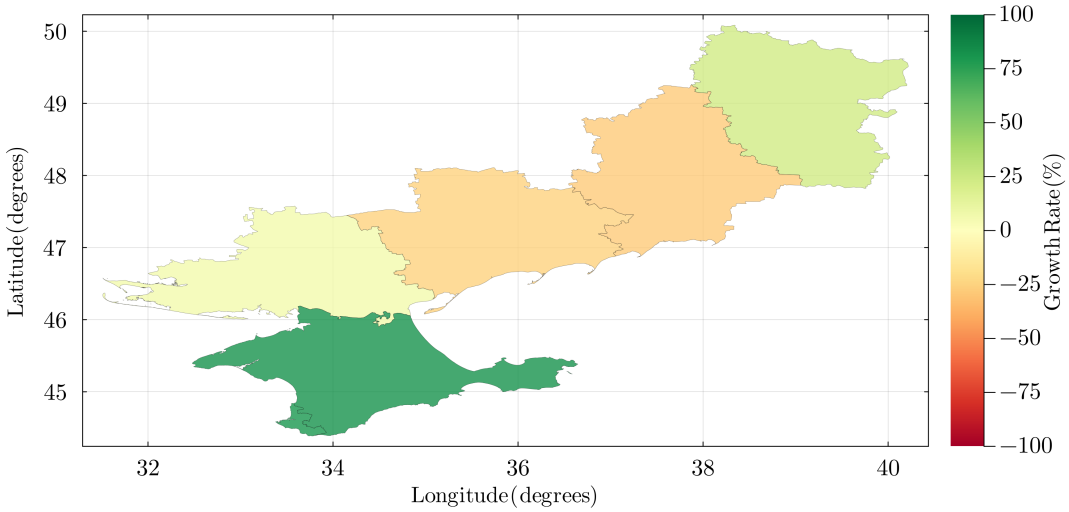


Figure 25 Disputed territories: Difference in pre-war and post-war growth

This figure compares growth patterns before and after the 2022 invasion.

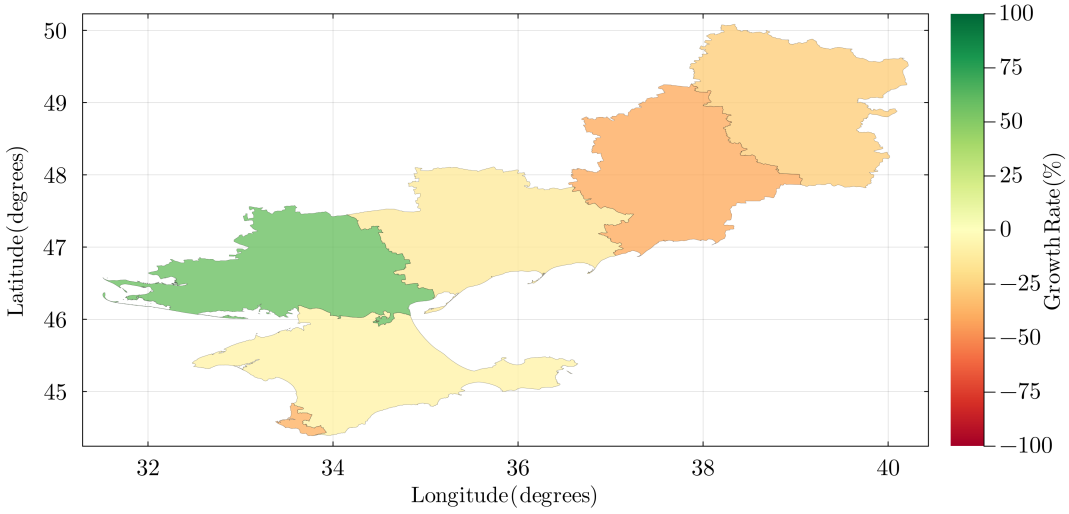


Figure 26 Monthly aggregate NTL radiance for Ukraine, January 2014 – January 2025

This figure illustrates the evolution of monthly aggregate NTL radiance in Ukraine.

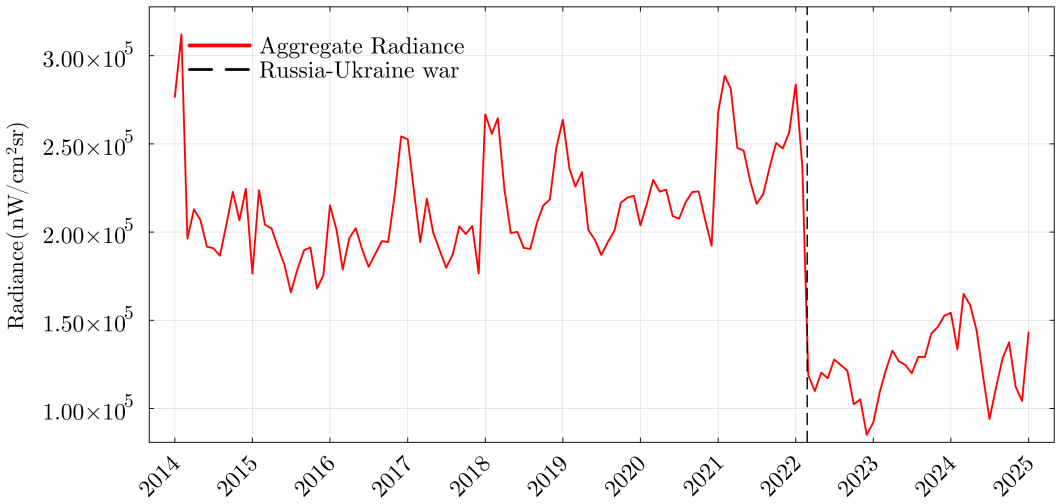


Figure 27 Monthly aggregate NTL radiance for Russia, January 2014 – January 2025

This figure illustrates the evolution of monthly aggregate NTL radiance in Russia.

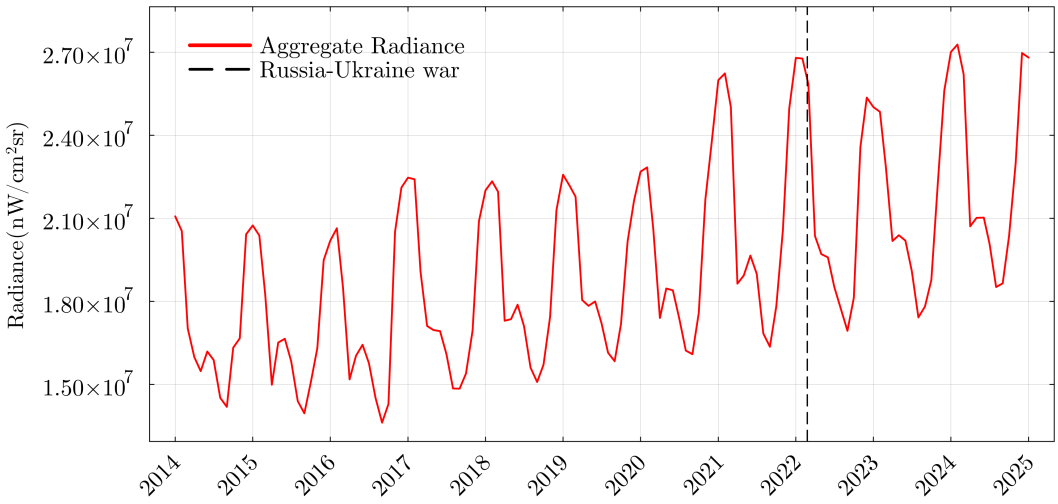
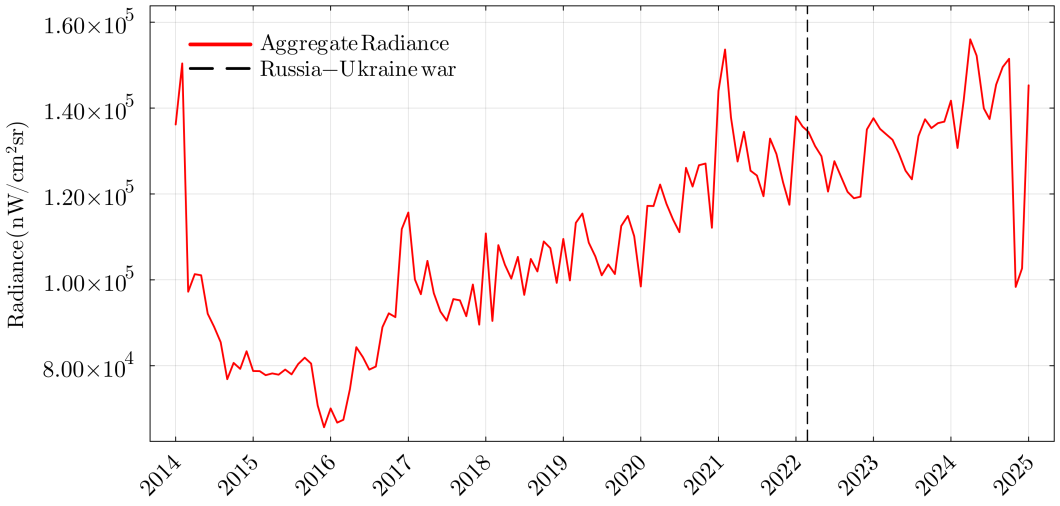


Figure 28 Monthly aggregate NTL radiance for the disputed territories, January 2014 – January 2025

This figure illustrates the evolution of monthly aggregate NTL radiance in the disputed territories.



the inherent distortions that occur when attempting to project a spherical surface onto a flat map. **The Dateline Issue** is a primary challenge, as standard map projections can inadvertently split Chukotka, resulting in parts of the region appearing on the extreme left or right edges of the map, or even wrapping around. This can misrepresent the region's spatial contiguity and negatively impact the visual analysis of data. Our approach to address these cartographic challenges involved careful handling of the region's geometry to accurately calculate aggregate radiance. This process effectively managed the division of Chukotka across the 180th meridian, ensuring that all parts of the region were correctly included in our calculations. For visualisation purposes, we utilised an Albers Equal Area (AEA) projection. This specific projection is particularly suitable for regions like Chukotka because it can be centred in a way that keeps the entire region intact on the map. Furthermore, the AEA projection minimises the distortion of area, which is crucial for thematic mapping and ensuring an accurate representation of geographical data in our visualisations.

D Custom projection for Russia

For our visualisations of Russia, we employ a custom Russia-specific Albers Equal Area (AEA) projection. This projection is based on a shapefile that has been tailored for Russia using the following proj string:

```
+proj=aea +lat_1=50 +lat_2=70
+lat_0=40 +lon_0=100
+datum=WGS84 +units=m +no_defs
```

The use of this custom projection is crucial for accurately representing the vast and latitudinally

Table E.1 Percentile values of NTL radiance for selected urban regions.

The table shows the 99th and 99.9th percentile values of raw NTL radiance for selected urban regions in 2019 and 2025. The threshold is set to capture nearly all genuine urban activity, while excluding extreme outliers. The values are presented in $nW\,cm^{-2}\,sr^{-1}$

Region	Year	99th Percentile	99.9th Percentile
Saint Petersburg	2019	250.62	352.48
Saint Petersburg	2025	336.05	523.17
Moscow	2019	163.02	318.23
Moscow	2025	97.93	304.23
Greater London	2019	98.59	224.24
Greater London	2025	111.53	288.88
Greater Tokyo Area	2019	64.13	129.14
Greater Tokyo Area	2025	67.42	158.73

diverse territory of Russia. It plays a vital role in minimising area distortion across the country, which is an important consideration for quantitative analyses based on NTL data where the area of regions is relevant. In the resulting visualisations generated using this custom AEA projection, the map coordinates are presented as Northing and Easting values instead of simple metric coordinates. These Northing (N) and Easting (E) values are derived from the original geodetic latitude (lat) and longitude (lon) data through specific transformation formulas. The conversion formulas involved are complex and are detailed in EPSG Guidance Note #7-2.[5] While the full set of formulas is extensive, their application ensures precise mapping from the spherical geographic coordinates to the planar representation of the AEA projection used for our visualisations.

E Radiance thresholds and urban brightness

To determine an appropriate upper threshold for radiance values (used to filter out extreme outliers such as gas flaring), we examined the distribution of raw radiance in major cities. Table E.1 shows the 99th and 99.9th percentile values for selected urban regions in 2019 and 2025. This analysis informed our choice of a 100 $nW\,cm^{-2}\,sr^{-1}$ cutoff, which preserves nearly all genuine urban and industrial activity while excluding extreme non-economic sources.

[5]The formulas are detailed at `https://epsg.io/9822-method`

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