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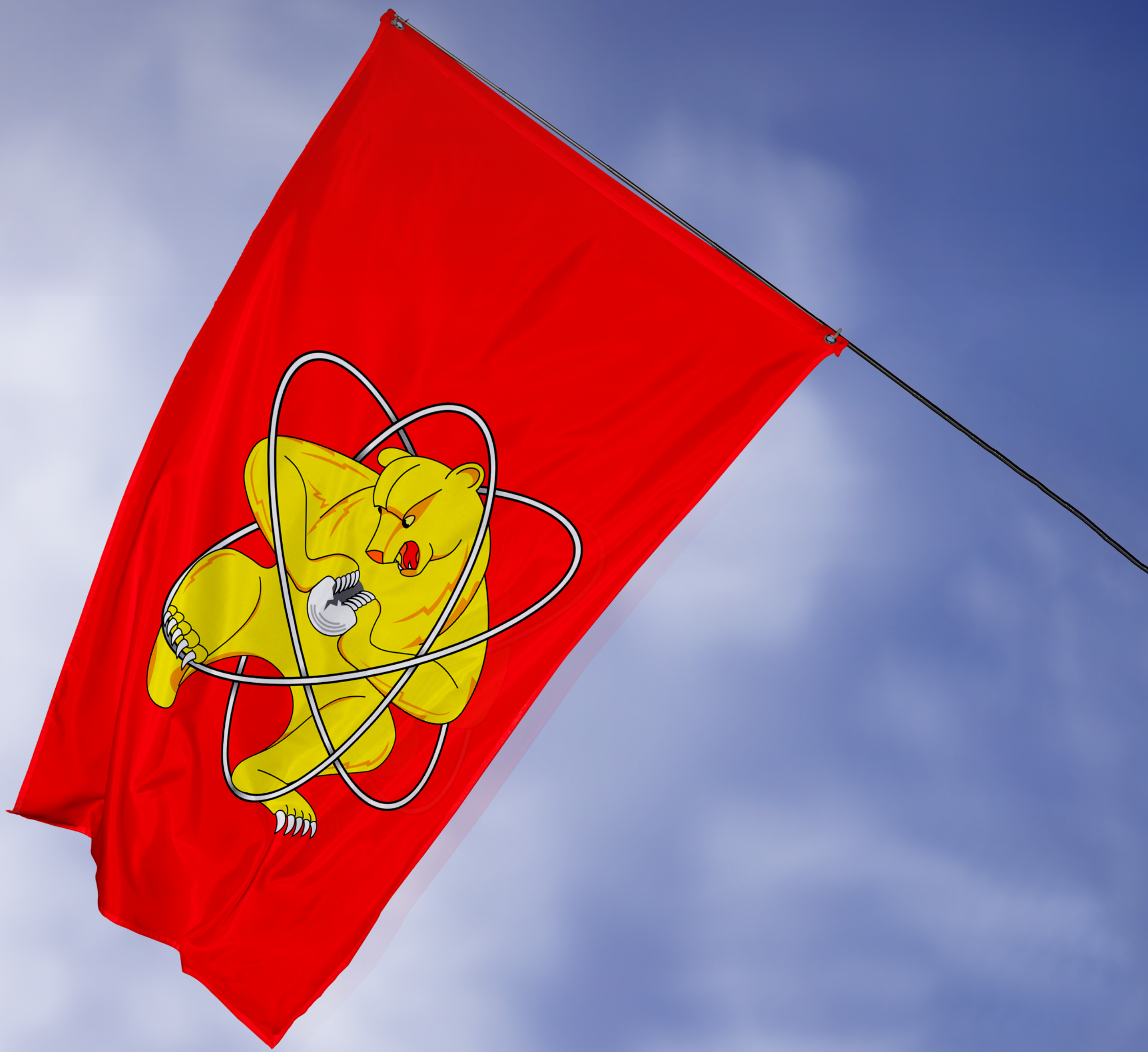

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Abstract: During the Soviet era, closed cities were off-limits to foreigners and unauthorized citizens. After the dissolution, many closed cities opened or were abandoned, but some Russian "ZATOs" (*Закрытое административно-территориальное образование*) kept their closed status. This paper investigates the different development patterns of closed cities compared with normal cities. Absent city-level economic information, we employ satellite nighttime light data to infer economic activity. We find that some ZATOs have thrived in the post-Soviet environment, which we attribute mainly to substantial human capital and Russian government support. Ukrainian counterparts have been more likely to decline, both because of an absence of government support and being cut off from the Russian military-industrial complex.

Keywords: Soviet and Post-Soviet Economic History, Satellite Nighttime Light Data, Urbanization, Closed cities

JEL codes: P25, R12, J10, N34, N94, O18

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On the cover: The flag of Zheleznogorsk, Bear Splitting Atom.
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1. Introduction

During the cold war, especially with the space and nuclear arms races, the Soviet Union built many new cities with special functions, including high-tech research, military, and nuclear power-related work. The USSR also turned some pre-existing cities into such functional cities. Given their strategic importance, the USSR sought to hide these cities from their ideological and geopolitical rivals: NATO, and especially the USA. Thus, these cities were closed to foreigners and in some cases even unauthorized Soviet citizens. After the collapse of the USSR, some “closed cities” faced severe funding cuts and became ghost cities. Other, typically larger cities opened up and survived. In still other cases, closed cities were designated as closed administrative-territorial formations (ZATOs): these cities retain some restrictions, but also enjoy federal funding and other policy support. In this paper, we explore the fates of different types of closed cities both in Russia and Ukraine and point to forces driving heterogeneous outcomes.

The strategy of declaring many existing cities “closed” and building large numbers of additional ones seems to have been unique to the Soviet Union (and now to the Russian Federation, which has continued the practice, albeit with modification). The United Sates has military test sites and closed small cities (notably, Los Alamos, NM, and Oak Ridge, TN) to outsiders during the Manhattan Project, but had had nothing on the scale of the USSR/RF. The same is true for China and other countries. The USA, China, France, and Great Britain have military-related research institutes that are closed, but generally they are either on restricted military bases or in open cities.

Precisely why the Soviets and Russian successors took to secret, closed cities with such unique enthusiasm is a matter of speculation. The obvious reason is that they were an outgrowth of the Gulag system and ultimately related to Stalin’s and other Soviet leaders’ deep paranoia and mistrust of the encircling capitalist world (Siddiqi, 2022; Rowland, 1996). However, this does not explain why other communist regimes did not follow a similar practice. One conjecture, consistent with Glazyrina (2000), is that the relative sophistication of the Soviet military-industrial complex distinguished the USSR from other regimes, as did the remoteness (and hence need to start from scratch) of the rare earths and other mineral and resource deposits that their defense sector needed. Moreover, the Soviet Union was distinct from other countries, communist or capitalist, by its extreme militarization: Easterly and Fischer (1995) cite estimates of the post-1970 defense burden as a share of GDP ranging from 14 to 16 percent – vastly greater than for any plausible comparators. Finally, the USSR may have suffered from a “first mover disadvantage.” It built its military-industrial complex during an era when remoteness was useful for maintaining secrecy: by the time China began to follow suit, spy satellites had made this strategy obsolete (and also have made this paper possible).

Ultimately, Russia and most other former Soviet economies ultimately made reasonably successful transitions away from communism, albeit to an array of settings that range from free market economies to government-controlled economies and societies in which the state still controls the “commanding heights.” However, there seems to be virtually no analysis of how the militarized, closed cities transformed. That is the subject of this paper.

Due to their strategic importance and generous funding during the Soviet period, we anticipate that these cities have superior physical and human capital stocks and, if favorably located, would realize relatively rapid development after the dissolution of the USSR. However, many also faced adverse conditions. Closed cities, especially those with single urban functions (termed *monogoroda*, or company towns) that opened up in response to a collapse in demand, could be expected to face a difficult transition period. However, while ZATO cities eventually received Russian government funding, they still faced restrictions on foreign investment. With ZATO cities’ advantages and disadvantages, these cities' potential different development patterns merit exploration, especially with respect to single-function versus general cities, and government funding versus potential foreign investment.

In the absence of detailed economic time series data we need an alternative measure of economic activity to track the post-Soviet outcomes of Soviet closed cities and their comparators. An obvious alternative is provided by satellite nighttime light data.[1, 2] After intercalibrating across satellites and time of photographs, our results suggest that the luminosity sums plausibly capture Russian GDP trends. By extension, the luminosity count of urban lights should indicate local economic activity. With measures of both luminosity sum and count (number of bright locations), we can explore city development as well as physical expansion or contraction. While the dataset spans from 1992 to the present day, covering the whole period after the collapse of the USSR (which occurred on December 25, 1991), we are limited by not knowing anything about luminosity before the collapse. This is problematic insofar as we are unable to establish parallel trends for comparators. However, since few cities received substantial help during the immediate, chaotic transition period, linking cities with similar initial conditions and immediate post-Soviet patterns is a plausible alternative. Thus, we use 1992 data as a starting point, and focus on cities' development during the economic decline (1992 – 1998), recovery and rapid growth (1999 – 2007), financial crisis (2008 – 2009), recovery (2010 – 2012), and relative stagnation (2013 to present) periods.[3]

The results suggest that, compared both with adjacent cities and similar cities, Russian ZATO closed cities generally have better initial conditions and better development in overall economic activities and urbanization. In contrast, Ukrainian closed cities experience slower development than their pairs. Russian closed cities kept receiving government support after the USSR's collapse, reflecting their military and research importance for Russian government, while Ukrainian closed cities did not. This difference indicates that for single-function cities, government funding proved essential during the transition away from Soviet socialism.

Closed cities have received virtually no attention in the academic literature in economic geography. The closest paper to ours by far is Schweiger et al. (2022), which focuses on Russian science cities (*naukogrady*). They also use satellite data, though for a much smaller time span, and match treated with untreated cities. Science cities and closed cities share much in common, though closed cities inherently have less information, making matching sketchier, and limiting the richness of analysis. Mihkailova (2012) explores Soviet city growth, linking it to gulag proximity – an important feature for many but not all closed cities. Again, she focuses on cities that were not secret, expanding her dataset dramatically, but limits her analysis to determinants of growth.

2. Background

2.1. Closed Cities

During the Soviet era, designated closed cities restricted visits by foreigners and in some cases even unauthorized citizens. Typically, such cities had military functions or were engaged in highly classified research, often related to nuclear weapons. Most of these cities "opened" slightly before or after the collapse of the USSR, and some were subsequently abandoned due to the absence of further funding. However, some cities, mainly in Russia, remain closed even today, and the Russian government continues to have closed administrative-territorial ZATO formations.

1 Appendix A discussed the prior literature on nighttime light data as well as the Russian-language literature on Soviet closed cities and their ZATO successors.

2 Appendix B describes satellite nighttime light data and closed city information in detail.

3 Appendix C provides additional information on Russian and Ukrainian economic trajectories.

Russia's ZATO cities are governed by Russian Federation law 3297-1 from 1992 "Concerning the closed administrative-territorial entity" (*Закон РФ от 14.07.1992 N 3297-1 [ред. от 07.02.2011] «О закрытом административно-территориальном образовании»*). Its general provisions state that residents of these areas are placed under special living conditions for security reasons. In exchange, under the section "Social guarantees and compensation for citizens living or working in a closed administrative-territorial unit," the law stipulates that all citizens living and working in these places will receive "general social compensation," which includes supplemental benefits with respect to wages, job security, and state insurance. Furthermore, based on the law's budget formation section, the Russian government is committed to using a portion of the federal budget to fund the enterprises and related facilities for socio-economic development in these areas. However, the "Special Regime for the safe operation of enterprises and (or) facilities in a closed administrative-territorial entity" section restricts foreign investment and other activities related to foreign people and organizations; air flights also are limited. In sum, the development of ZATO has advantages (Russian government support), but it also contains disadvantages (restrictions on foreign investment).

Because of their former and current military or research functions, closed cities also should have inherited both advantages and disadvantages as well. The obvious advantage is that these cities should have had more advanced factories and research facilities, and more experienced, highly-educated workers. Conditional on a non-remote location, such higher physical and human capital stocks could have helped these cities to achieve more rapid recovery and development, as did relatively superior infrastructure.

Offsetting these potential development advantages, closed cities also faced disadvantages stemming from their isolation in some cases and single industry/company town emphasis, especially in smaller ZATOs. After the USSR collapsed, demand for military-related output decreased sharply. Since these cities' main outputs were for the military, the transition should have been especially challenging. General funding reductions accompanying the USSR's dissolution exacerbated this problem, especially for science-related closed cities. Russian R&D expenditures decreased from 2 percent in 1990 to 0.74 percent of total (and shrinking) GDP in 1992 (Schweiger et al., 2022). For example, Protvino was the main city carrying out elementary particle physics, and benefited from Institute for High Energy Physics' scientific program. However, such funding was curtailed after the collapse of the USSR, causing outflows of scientists. In addition, these cities were almost exclusively tied to the Soviet economy and had few international linkages, and such as there were further weakened after the USSR's dissolution. This problem should have been especially acute for the development of formerly closed Soviet cities outside Russia as defense sector links disentangled. This adverse shock was further exacerbated by huge e spending decline outside of Russia, which continues to have high military spending, and Belarus, which is a close Russian ally. In contrast, closed cities located in Ukraine had virtually no economic contacts with the Russian military-industrial complex after the seizure of Crimea and Russian-sponsored uprising in the Donbas in 2014. While Ukraine expanded its military capacity following 2014, its efforts do not appear to have been extended to its formerly closed cities.

In sum, both the heterogeneity and the mix of advantages and disadvantages facing Soviet closed cities following the dissolution of the USSR invite a closer exploration of their outcomes. We anticipate that scientific research or production centers whose output could convert to civilian uses would have revived relatively quickly. Those unable to restructure and which did not receive revenue support from the current Russian government are likely to experience longer stagnation or decline.

3. Methodology

3.1. Nighttime Light Luminosity Intercalibration

Although satellite nighttime light data can capture the spatial changes in luminosity over the years, using unadjusted data directly is problematic. Satellite changing and aging, along with contamination of unwanted light (Henderson et al., 2011), are primary challenges. Moreover, Zhang et al. (2016) find that cloud coverage and longer summer days caused data collection failure in the high-latitude zones for satellite F142002, including Russia. Figure 1 shows the enormous missing data collected by F142002, compared with F152002 in Russia. These missing values also include some cities in our sample. Consequently, we drop F142002 data and only use F152002 to measure 2002 luminosity.

Figure 2 shows the inconsistent data collection due to the satellites changing and aging using the Russian luminosity sums. For example, data collected by F18 generally indicate higher luminosity than data from other satellites, and value differences from different satellites for the same year also reflects collection inconsistency. Therefore, inter-calibration between different years and different satellites is required to produce a consistent results.

Our procedure follows Elvidge et al. (2009). They select a region with minor luminosity changes and a relatively wide luminosity range (Sicily), and also select a satellite/year with the highest luminosity sum (F12/1999). Then they use a second-order regression model: the value of each pixel in the selected area of other satellite years serves as the independent variable; the value of the corresponding pixel of the base year is the dependent variable (Elvidge et al., 2009). To find a base region for inter-calibration of Russian satellite data, we note Sicily's economic properties over 1992-2008: its population is relatively stable, and luminosity changes are minor. We then seek a comparably stable site in the former USSR and at higher latitude. From Macrotrends, Volgograd emerges as the city with the smallest population changes among all big cities. Therefore, we select Volgograd as the base region and F12/1998 as the base year based on Elvidge et al.'s selection criteria. Appendix Table D.1 shows the results of second-order regressions, which then serve as the adjusting coefficients. The adjusting equation, where i represents a specific pixel, is simply:

$$Adjusted\_Luminosity_i = \beta_0 + \beta_1 \; Luminosity_i + \beta_2 \, Luminosity_i^2$$

Based on the adjusting coefficients above, we inter-calibrate values for all satellite years. Figure 3 shows adjusted luminosity sums for Russia. After adjusting, variation across satellites is greatly reduced, as are time trends. Indeed, there is no clear luminosity trend other than for the crash of the 1990s. However, data collected by different satellites for the same year still differ slightly, and we average the values in the empirical work that follows.

Given our focus on urban luminosity, it is important that inter-calibration corrects luminosity differences in urban areas. Yi et al. (2014) also confront this problem and ultimately select an urban light threshold of 8, meaning that all pixels whose luminosity is less than 8 are set to be null. We also select a value of 8 as the urban light threshold, thereby reducing noise from occasional natural lights in rural areas. Adjusted urban luminosity values for Russia are shown in Figure 4, both in total numbers and on a natural logarithmic scale.

These figures reveal three economic periods of Russia after the collapse of the USSR. From 1992 to 1998, when the Russian economy suffered from catastrophic decline, the luminosity trend is negative. Values then fluctuate around a strongly rising trend from 1999 – 2008, reflecting economic recovery. Thereafter, luminosity declines in 2008 reflecting the global financial crisis; full recovery follows; after 2010, the values go down and fluctuate, reflecting economic stagnation. While we do not report numbers here, it is evident that, given Russia's substantial real GDP growth after the transition period, GDP divided by any luminosity measure would have risen sharply, reflecting the huge wastefulness of the Soviet economy.

3.2. Comparing Closed Cities with Other Cities

Based on the population boundary of cities or urban settlements, this paper focuses on 27 closed Russian cities, including Protvino, Snezhinsk, Tryokhgorny, and 24 others. All of these 27 cities are ZATOs of moderate size. It seems likely that the ZATO sample ended up excluding larger cities as these ended up opening because of their size and heterogeneity, while the very small closed cities were too small and likely solely for military use, and hence were not worth maintaining or turning into a ZATO.

Some closed cities belong to the fourth administrative level (town/city), making it impossible to define clear boundaries. In such cases, we use third-level administrative regions[4] (raions/urban-type settlements – that is, US county equivalents) to which they belong, based on their longitude and latitude information. All closed cities are measured at the raion level for comparability purposes.

To compare the potential different development patterns of closed and ordinary cities, we pair each closed city with two sets of third-level administrative regions: adjacent cities and similar cities. Paired adjacent cities must share borders with their paired closed city, and they are generally raion pairs. Being adjacent, these cities are highly likely to share similar geographical features and local policies, which means that trend differences mostly should be driven by former or current closed status. Similar but non-adjacent cities are paired with a closed city based on the nighttime light data of F10/1992. We follow several principles when pairing: a raion is only paired with raions; urban-type settlements only pair with urban-type settlements; a raion around a major city will generally pair with raions around other major cities; a coastal city is paired with other coastal cities; and each closed city will pair with one to three closest similar cities. These steps to ensure geographical similarity increase the likelihood that closed status is the dominant reason for differences that emerge.

Figure 5 provides examples of selecting adjacent cities and similar cities. The left ones are the closed cities; the middle ones are their adjacent cities; and the right ones are their similar cities. Figure 6 shows all closed cities with their two-type paired cities (in blue) in the nighttime light data.[5]

Having matched "treated" closed cities with two sets of untreated comparators, we then use fixed-effect models to determine whether significant different development patterns exist between closed and paired cities. The regression models:[6]

$$LULS_{iy} = \beta_0 + \beta_1 CI + \beta_2\ year_y + \beta_3\ PC_i + \gamma_{1\times k}\, OI_{i,k\times 1} + \epsilon_{iy}$$

- $LULS_{iy}$ measures ln values of urban light estimators, including the urban light luminosity sum[7], and urban light counts[8] of year *y*, for city *i* in year *y*.

4 The first level refers to countries, and the second level refers to federated states. The Russian urban-type settlement is a special type of division, originally from the USSR. It looks like a city or town without a suburb. In the subdivision boundary information we used, the urban-type settlement is considered at the same level as the raions.

5 Appendix E provides a complete list of closed cities and their paired adjacent cities and similar cities.

6 Regression model and results using the values of urban light estimators without ln scale are provided in Appendix F.

7 The urban light luminosity sum adds up all the luminosity values of all light pixels whose values are greater than 7 (the urban threshold), inside of the city/raion boundary. We use this luminosity sum as an approximation of overall economic performance.

8 The urban light count is the count of the light pixels whose values are greater than the urban threshold inside the boundary. We use the urban light count to measure city expansion.

- *CI* is the closed city indicator = 1 if it is or contains a closed city, and = 0 otherwise.

- β_2 measures the time fixed effect.

- β_3 measures the geographical region fixed effect, where PC_i refers to the paired closed city.

- *OI* is a vector of other indicators for urban-type settlement, TripAdvisor presence (a market of closedness), and science city status.

4. Results and Discussions

4.1. Closed City Locations

Figure 7 provides a closed city distribution map. Green pins designate closed cities outside of Russia; blue pins represent Russian closed cities; orange pins represent Russian cities that are only closed for foreigners.

The closed city list and the distribution map exhibit several notable features. Soviet closed cities existed in Azerbaijan, Belarus, Estonia, Kazakhstan, Kyrgyzstan, Latvia, Moldavia, Russia, Tajikistan, Ukraine, and Uzbekistan. We do not observe closed cities in Armenia, Georgia, Lithuania or Turkmenistan. Figure 8 shows the clear distinction between Latvia and Lithuania. A second striking distinction appears around the Black Sea area (Figure 9). These distinctions may result from missing data, differing historical backgrounds, differing natural resources, and duplicate functions of some areas. Figure 9 offers a typical example of a duplicate function. Sevastopol, the naval base of the USSR Black Sea Fleet, limits the importance of other Black Sea naval bases, displacing prospective closed cities around the Black Sea in Georgia. Similarly, naval bases in Estonia and Latvia should suffice for the defense of the Baltic Sea, obviating the need for one in Lithuania.

Distance from Russia also may help explain the absence of closed cities in Armenia, Georgia, Lithuania, and Turkmenistan, and for the small number of closed cities in Kyrgyzstan, Moldova, Tajikistan, and Uzbekistan. Absence of a shared border makes transportation costly while their perceived remoteness also would have been unattractive to the largely Russian scientific and technical staff. It is also possible that the Soviet military-industrial complex feared that remote sites would be more vulnerable to spies, especially with a US presence nearby in some cases.[9]

Also noteworthy are the differences in closed cities' functions across constituent Soviet republics. Save for in Russia and Kazakhstan, closed cities were mainly military in nature. For example, most closed cities in Belarus were related to nuclear missile sites and defense systems. As for Kazakhstan, the number of closed cities is the second largest among the former Soviet members, and their functions vary greatly. The first atomic and thermonuclear bombs of the USSR were tested in Kurchatov; Gvardeisky hosted a Soviet agricultural research institute, which may relate to the development of the biochemical weapons (or, more benignly, dryland farming crop yields): the research centers there now focus on the development of COVID vaccines; and the Baikonur cosmodrome is located near Tyuratam in southwestern Kazakhstan.

9 Reasons also may be idiosyncratic. The small lakeside city of Karakol (Przhevalsk in Soviet times) has been the site of both Russian-Kyrgyz military exercises (see Caravanserai 2018 10 12) and an anti-submarine weapons test base (see globalsecurity.org 2019 12 02). However, Karakol is also a major ski resort, and tourism is more important than torpedoes to the local economy.

A third essential characteristic is that, while some closed cities were placed in former existing cities or towns, the majority of them were newly built to serve specific scientific or military functions. Such a division also is related to the location selection of closed cities. For the pre-existing type, a primary reason for choosing the city is historical background, such as having a pre-existing research institute or military facility. An archtypical example is Vlasikha, Moscow Oblast, Russia. In 1928, the Vaccine-Serum Laboratory of Military Sanitary Directorate of the Red Army was built there; later, it became the Red Army's Biotechnical Institute. Although this institute was closed in 1937, the remaining infrastructure function still made this city attractive to Soviet managers. Geographic location added to the city's choice as a closed city. Vlasikha is close to Moscow, and during WWII, it was the critical area for the Battle of Moscow. After WWII, proximity plus facilities made it a natural choice to serve as the headquarters of the Strategic Missile Forces. Another example of the pre-existing type is Ostrovnoy, Murmansk Region, Russia. In 1915, during WWI, construction of a naval base was undertaken. In 1981, Ostrovnoy became a closed city because of its naval base, and now this city serves as the headquarters of the Northern Fleet.

Newly-built closed cities mainly were constructed after 1945, and especially between 1950 and 1960. Compared with pre-existing cities, which mostly are closed due to their military roles, the functions of newly-built closed cities vary. In addition to military cities, cities related to aerospace, nuclear energy, biochemistry, or even high-level physics were built during this period. An example is Protvino in Moscow Region. Protvino is one of the largest physics research centers in Russia, and is home to the "U-70," the largest proton accelerator when it was built in 1960. The construction period of these cities coincides with the Cold War's first phase, with their functions corresponding to varying areas of USSR-US competition, including the space and nuclear arms races. The Cold War also explains why science-related designation generally overlaps with the four functions listed above, as the Soviets sought to hide information regarding their achievements in these areas from the West.

For these newly-built closed cities, and especially those that did not have a purely military function, natural and human resources appear to have been critical determinants of location. Most obviously, in the case of mining cities for uranium and rare earths, mineral deposits are essential. In addition, building a new city and mining uranium ore requires a large labor force; given the hazards involved, forced labor often was preferred. Prisoners in regular prisons or Gulags were the target human resources, as they could be forced to work and, from planners' perspectives, incurred a low opportunity cost. As Figure 10 shows, many closed cities are located near prisons or Gulags, which corresponds to such intuition, and which has been documented at length in Mihlailova (2012). Zvezdny, which was built in 1956 close to a Gulag in Perm Oblast to provide nuclear technical support for the Soviet defense system, is a typical example.

4.2. Adjusted Urban Light Luminosity with Country-level Macroeconomic Trends

After computing adjusted urban light luminosity values and using adjusted coefficients from Appendix Table B.1, we compare them to Russia's macroeconomic and demographic patterns, including population, urban population, CO2 emissions, electric power consumption, and GDP (Figure 11). We also compute another version of adjusted urban light luminosity values with adjusted coefficients from Elvidge et al. (2009) Appendix G compares adjusted and unadjusted urban light luminosity values.

Aggregate Russian urban light luminosity sum (ULLS) closely follows trends in electric power consumption and GDP, while correlations with population, urban population, and CO2 emissions are much weaker. While Figure 11 shows a clear trend on population and urban population, their growth rates are tiny, especially when compared with the growth rates of total urban light luminosity. thereby leading to weak correlations with ULLS. The weak luminosity-CO2 emissions link likely reflects large structural changes in the Russian economy and, specifically, the rise of services relative to manufacturing.

4.3. Comparing Closed Cities with Other Cities

In the following analysis, with regression tables appearing in Appendix H, we focus primarily on Urban Light Luminosity SUM and Urban Light COUNT as dependent variables. Appendix I provides descriptive statistics for these measures' growth rates. When regressing Urban Light COUNT, we exclude closed urban-type settlements and cities paired with them because their COUNT values tend to equal the numbers of pixels in these areas, so we simply use the luminosity SUM value to approximate the GDP of these cities. We also included some Ukrainian closed cities in the regression discussed in Appendix J and conducted the placebo test (Appendix K).

4.3.1. Regression results matching Closed and Adjacent Cities

Table H.1 provides regressions that match closed cities in Russia with nearby comparators. It emerges that urban lights of closed cities are brighter than those of their nearby third-level administrative regions, implying that closed cities tend to be among the most developed areas around their locations for the whole period after the USSR's dissolution. On average the closed cities generate 86% more urban light compared to their adjacent cities. Based on results from Section 4.2, this difference implies that closed cities yield 50% or more GDP in comparison with nearby matches. An obvious reason is Russia's ZATO policy, as federal funding provides infrastructure and other support for these cities. However, ZATO cities also may benefit from pre-existing features, including favored funding during the Soviet period.

Coefficients on both urban settlement and science city-related indicators significantly differ from zero. The ULLS coefficients for the urban-type settlements dummy are negative because they generally have smaller areas compared with raions, which cover entire districts. The results also indicate that the science-related closed cities generate (or consume) 32% more urban light than other closed cities. It is unsurprising that science-related closed cities are generally more developed: they attracted a more educated labor force that had higher opportunity costs of resettling, and hence demanded better initial conditions. Their higher human capital levels also may enable them to bounce back and then thrive more effectively following the USSR's collapse.

Finally, we use a dummy variable indicating presence on www.TripAdvisor.com to indicate the current closeness status of the closed cities. The coefficient is not significantly different from zero, showing that the partially or fully open (formerly) closed cities have no measurable development difference from closed cities that have remained closed. Virtually by definition, truly closed cities cannot have a TripAdvisor.com presence, and it is both easier and more accurate to identify status this way rather than searching through documents.

Table H.2 provides results from urban luminosity COUNT measures. Results are similar to the SUM measures in Table H.1, though the science-related city variable loses significance. More specifically, on average, closed cities have 69% more illuminated urban area compared with their adjacent cities, while the science-related closed cities generally have the same urban areas as other closed cities. Counterparts to Tables H.1 and H.2 but only using 1992 values for SUM and COUNT measures, respectively, appear in Tables H.3 and H.4.

Table H.3 reveals that closed cities' initial conditions differ markedly from their surrounding areas when the urban-settlement indicator is included. However, other terms are insignificant, suggesting that closed cities are similar but hardly identical to adjacent cities, and being a science-related closed city does not confer a further advantage. Comparing Tables H.1 and H.3 also suggests that, since the coefficient on closedness increases and becomes significantly different from zero in more recent years, the advantage of being a closed city was sustained rather than being an initial advantage that wore off. Indeed, the advantage of being a science-related closed city does not reflect initial conditions at all, showing that science-related closed cities enjoyed better development prospects after the collapse of the USSR but not at the outset.

Table H.4 indicates that the closed cities have more lit urban area than other cities, although only at a 90 percent confidence level. Moreover, the TripAdvisor indicator and science-related indicator coefficients are not significantly different from zero. Comparing COUNT values in Tables H.2 and H.4 again shows that closed cities expanded faster than adjacent cities. While the patterns regressions themselves do not offer a causal mechanism, it is not difficult to speculate as to the reasons. Most plausibly, as Russia moved toward becoming market economies, and residence restrictions via the *propiska* internal passport system were lifted, people sought to move to cities in search of better jobs and social infrastructure, and the most developed cities in their regions were the obvious targets. This relative attractiveness would have been further enhanced by the Russian government policy of providing more funding to formerly closed cities and regions, further attracting both in-migrants (and firms). Besides, being science-related does not make a city more urbanized. Although these cities are likely to have higher initial development levels and the best schools in their regions, which attracts migrants, they may also face the problem of being science-related. Jobs in these cities may have higher skill requirements, making them less attractive to those migrants with relatively low education levels, which will count for a significant proportion of rural populations.

4.3.2. Regression Results Matching Closed and Adjacent Cities

Table H.5 shows that on average the closed urban-type settlements and districts containing the closed cities are 34.2% brighter than their similar urban-type settlement and raion matches throughout the entire post-Soviet period. The positive closed city coefficient implies that they generally are more developed than their paired cities (with pairing based on having similar initial conditions). Science-related and urban settlement indicators now lose significance (cf. Table H.1), presumably because of improved matching: science-related closed cities are paired with initially more developed cities. Curiously, the Trip Advisor indicator becomes significant and negative, implying that full or partial openness is associated with lower luminosity. However, the small number of those without a Trip Advisor listing and idiosyncratic factors may account for the surprising sign, as we discuss in Appendix L.

Table H.6 is consistent with Table H.5 save for the science-city term, which becomes negative and significant. The result indicates that the urban areas for closed cities are 29% brighter than their initially similar pairs. However, the negative Trip Advisor term is counterintuitive, as it suggests that opening up is disadvantageous. Again, comparing these results with coefficients based on adjacent city, the reverse sign may be related to some influential points because the data size of the TripAdvisor indicator and sci-related indicator is small (Appendix L); it also may be the case that unobserved regional heterogeneity is even more important than city baseline luminosity similarity. As for the negative coefficient for the science-related indicator, the reason in the adjacent cities remains applicable – namely, the higher requirement for residence in these places.

Tables H.7 and H.8 demonstrate that initial conditions in 1992 do not appear to differ between closed cities and their matched pairs. By implication, the significant differences in Tables H.5 and H.6 should be related to the policy implemented in or affecting these closed cities after the collapse of the USSR. The results also imply that the ZATO-status and support law did in fact help affected cities develop more rapidly, even in the absence of foreign funds.

4.3.3. Closed vs. Adjacent and Similar Cities in Different Economic Periods

After the collapse of the USSR, Russia has experienced five main economic periods: economic decline (1992-1998), recovery and rapid growth (1999-2007), the global financial crisis period (2008-2009), financial crisis recovery (2010-2012), and slow growth or stagnation (2013-present).

Soviet-era closed city status appears to have conferred a large, positive advantage in all five periods (Table H.9). Throughout the whole five periods, the urban luminosity sum of closed cities is 70% higher than that of their adjacent cities, implying that their overall economic performance should be more than 50% greater. This is also true when the luminosity measure is the count of illuminated areas rather than the sum of pixels (Table H.10). The urban areas for closed cities are also more than 50% larger than their adjacent cities among all five periods. Indeed, the remarkable feature of these regressions is the stability of the closed city coefficient. However, for both sum and count, the coefficients in 2010 – 2012 are the lowest throughout the whole post-Soviet era, indicating that the financial crisis had higher adverse effects on the closed cities, so they need more time to recover from it. The urban settlement indicator is also consistently negative with stable values.

However, in contrast to Table H.1 covering the entire post-Soviet period, the coefficients for science-related cities mostly are not statistically different from zero, with the exception being 1999-2007. Such results show that science-related closed cities are more outstanding during the boom period. As for other periods, all coefficients are positive but not significant, possibly because of the smaller sample size of science-related closed cities.

Tables H.11 and Table H.12 match economically similar cities. They exhibit similar results as the full post-Soviet period regression, though coefficient values are only 30-40 percent as large as for the neighboring city comparison. Table H.11 coefficients become insignificant for 2010-2012 due to increased standard deviations. Similarly, the results from Table H.12 are generally the same as the full period regression, again save for the 2008-2009 and 2010-2012 periods. This could be a consequence of the reduced sample size, but it also is possible that different closed cities behaved fairly differently during the economic shocks. Overall, it seems apparent that the set of advantages conferred on closed Russian cities have persisted across time and economic conditions.

5. From Ubiquitous Webcams to Radioactive Paradise

While regressions reflect differences in average outcomes, it is difficult as well not to be struck by the heterogeneity of outcomes of closed Soviet cities. This section briefly discusses a few examples to give a sense both for what closed cities were (and are currently) like, and to emphasize the range of outcomes.

As mentioned above, Protvino (Wikipedia links provided here and elsewhere) is a high energy physics research center 100 km south of Moscow. On the edge of the Moscow suburbs, it has and continues to offer a pleasant white-collar, research center atmosphere. A history (with great photos) can be found on the city’s website, while the tripadvisor.com site suggests a comfortable and eclectic if slightly remote setting not dissimilar to what one might find in Bowling Green, Kentucky, USA, which in fact is one of its sister cities. Protvino’s population surged from 13,000 in 1970 to 34,500 in 1989, and has since stagnated. This stagnation is captured in its luminosity patterns, which mirror those of its matched cities – the difference being that luminosity sums are 2-3 times greater in Protvino than in the four matched.

In contrast, the plutonium-producing military-industrial complex city of Zheleznegorsk ("iron mountain") lies nearly 3,400 km east of Moscow. While it currently has ZATO status (and is not on TripAdvisor), the city's remarkable website offers a choice of 10 web cams (and a fun description of the checkpoints, with photos, can be found here). The city's population rose from 86,200 in 1979 to a peak of 97,500 in 1992; it has since gradually declined, mostly after 2009, to just under 82,000. While its luminosity declined in the 1990s, luminosity actually has risen by about 15% since 2009. A similar pattern exists for nearby comparator as well as matched cities – except that Zhelenegorsk is about three times and 1.5 times as luminous, respectively.

Ozyorsk , another closed ZATO plutonium-producing city in the Urals some 1,438 km from Moscow, has had a more tragic past than Zhelezegorsk: in 1957 a liquid atomic waste container exploded at the Mayak plant, releasing vast amounts of radioactive material as detailed in the Emmy-nominated documentary *City_40*. A postwar city built from scratch, early demographic and economic data are unavailable, but it must have grown rapidly. 1996 population was recorded as 89,200; 2020 population had fallen to 78,440. After declining, recovering, declining again in 2008 and again in 2012, luminosity in 2018 is virtually the same as in 1992. However, unlike Zhelezegorsk, there is virtually no difference in luminosity levels or trends in Ozyorsk and its similar matched cities. A plausible conclusion, and consistent with Tavolga's (2020) report Radioactive paradise (*Радиоактивный рай*), is that the city is dying out, but may be sustained by central government transfers.

At the other end of Russia, some 6,445 km from Moscow in maritime Primorskii Krai, lies the port of Bolshoi Kamen. A naval base and shipyard, it was founded after the Second World War, and has had alternately closed and opened (most recently, in 2015, but no TripAdvisor site exists). Unfortunately, the city is most known for the explosion of a nuclear submarine in nearby Chvazhma Bay in 1985 (described in Hoffman, 1988; Sivintsev, 2003, reassures readers that this was not remotely like Chernobyl – though there appear to be roughly 100 other aging nuclear subs in the area). While early population data are unavailable, it appears from the 1989 census that the population was just under 66,000; since the early 1990s the population has fluctuated around 40,000, gradually declining to 38,000 after 2012. These patterns likely reflect a large population exodus from remote regions following the dissolution of the USSR and end of the internal passport system, offset by increased Russian military expenditures. However, in terms of overall luminosity, Bolshoi Kamen has considerably underperformed both adjacent and similar matched cities. Its peak luminosity was in 1993 and, while for a city like Protvino, luminosity in recent years is about 60% greater than 1992-93 (and 20% greater for Zheleznegorsk), Bolshoi Kamen's is about 20% less.

Russia's closed cities included many that ringed major political-industrial centers, most notably Moscow. However, a large fraction was remote, and were designed with a sole, military-industrial complex purpose. They generally exist intact today, and even those that remain closed have informative websites (though their quality varies enormously, and appears to be positively correlated with economic development), are the subject of both prosaic stories and (until recently) media exposes, and appear in official statistical data. This is not the case for Ukraine's militarized settings: the sites generally have closed, and, as the settings are closer to historically developed settings, they largely have been either abandoned or reabsorbed.

The heterogeneity of formerly closed Soviet cities is striking. Protvino is a prosperous small city with what appear to be high and rising living standards. Elsewhere, the situation is grim, but stable, since growing Russian defense expenditures and a political commitment to maintaining the ZATO network ensure that they will not die out. In short, scattered, stable settlements will persist as long as Russia remains a militarized society.

We use a boxplot to capture closed cities' overall luminosity sum trend by setting 1992 as the base year (Figure 13). The trend basically follows the five economic periods of Russia and Ukraine. The luminosity sums of Ukrainian closed cities are mostly below one, showing that they are not fully recovered from transition. While also suffering from transition, Russian closed cities did much better. They regained their 1992 level in around 2000, and the sums increased significantly during the rapid growth and recovery from the financial crisis periods. The boxplot also shows the heterogeneity of the development of Russian closed cities. They are more similar around 1992, but the discrepancies have increased markedly in the ensuing 27 years, showing their different fates after the collapse of the USSR.

6. Conclusion, Limitations, and Future Work

The Cold War witnessed a contest between the USSR and the US and its NATO allies for geopolitical hegemony and, consequently, both space and nuclear arms races. Soviet leaders, acutely aware of their economic disadvantages relative to the West, poured resources into catching up with and hopefully surpassing their rivals. An important part of their strategy was to both build many closed cities and to convert other cities into closed types that focused on producing technologies and goods for the military-industrial complex. Not surprisingly, they closed these cities to unauthorized citizens and foreigners, trying to hide the information from geopolitical rivals. To maximize control and inaccessibility to outsiders, most of these closed cities were placed inside or near Russia itself. The locations also tended to be near Gulag camps or prisons to get cheap human capital input for building or expanding these cities.

In the absence of demo-economic information, satellite nighttime light data are the only resource to find out how these cities have fared in the post-Soviet environment. Due to changing out and aging of satellites, inter-calibration is required to produce consistent luminosity measures. We then find that the adjusted urban light luminosity sum trend closely tracks Russia's real GDP, enabling us to regard it as a good proxy for economic development.

To assess the advantages or disadvantages of having been a closed city, we match cities both with fairly similar adjacent cities (thereby controlling for regional factors) and with highly similar initial luminosity measures. By exploring sub-periods, we conclude that closed Russian cities have had a persistent advantage in terms of economic development, though we cannot ascribe that advantage to particular forces, or to initial advantages that persisted vs. continued government support. In contrast, we find that Ukrainian closed cities have not had a post-Independence advantage, though again there are multiple possible reasons for this pattern. In this sense, government funding may play a vital role. However, whether such support is actually cost-efficient is still remained to discuss. As Junussova and Beimisheva (2021) note, the use of top-down distribution of subsidies on single industry *monogoroda* (company towns) is inefficient because the support will go to uncompetitive and unprofitable industries. Such inefficient use of government funding is highly likely also to happen in closed cities.

Russia's closed cities tended to be the most developed places in their surrounding areas. These results partially overlap with Limonov and Nesena's (2016) findings that the mining cities as well as the satellite cities of Moscow tend to have higher socioeconomic indices than elsewhere; as we have seen, a large share of closed cities are of this type. (2016) Using the size of illuminated urban areas to measure the urbanization process, these cities are also the most urbanized places in their surrounding areas. However, comparing ZATOs with similar cities whose development and urbanization processes were not different in 1992, we emphasize our finding that subsequent differences emerge and that they favor closed cities. An obvious reason is that the Russian government has continued to provide supplemental funding for ZATO cities, which means that in these places, the benefit from federal funding outweighs the negative effect of the restrictions on foreign funding. As for urbanization and spatial expansion, it may also be because the government provides social compensation to ZATO residents, encouraging people to move in.

The luminosity regressions also demonstrate that science-related closed cities generally are even more developed but less urbanized than other types of closed cities. One plausible story is that science-city residents are more educated than peers elsewhere and are able to use their human capital advantageously, while that also makes it hard for people with low education levels to move in.

It is important to regard our findings as conjectural with respect to underlying causal factors. Small numbers of closed cities and prospective matches also are a limitation. We manually selected similar cities based on baseline luminosity sum and lit areas criteria. However, these criteria only ensure that matched cities have similar geographic properties, and not that all preconditions are observably identical. Furthermore, while the 1992 regression results indicate that their initial differences are not significantly different from zero, 1992 values may have already reflected the negative impact of the dissolution of the USSR, and in any case do not guarantee prior parallel trends. Due to temporarily reduced funding and reduced national importance, the negative effects on closed cities may be more significant than on other cities, affecting similar urban luminosity sums and counts in 1992. An ideal pairing strategy would be one that matches time trends prior to the collapse of the USSR. However, the earliest nighttime light data come from 1992, so we can only hope that the parallel trends assumption is valid. Nor is the 1989 Soviet Census helpful as it does not provide the city-level information to help us pair cities. Due to their closeness status, the Soviet government hid information on closed cities, thereby confounding our effort to match cities with more than the confidence of a single data point.

A secondary problem concerns those closed cities without their own boundary at the fourth-level administrative shapefile, due to the absence of further low-level shapefiles. To address this, we use the data for the whole surrounding district to represent the nighttime light data for them. However, many raions contain more than one city or town, which means that the observed different development patterns also could be driven by the other cities or towns in the same raion. Thus, the accurate conclusion – that raions with closed cities inside developed better than those raions without closed cities, showing that containing a closed city can facilitate the economic growth of the whole region – is a bit weaker than if we could map and compare precise cities. In any event, there is nothing we can do to improve the mapping, and the limitation seems likely to be of secondary importance, given that most raions are dominated by a single city.

In target city selection strategy, we focus on all closed cities with populations between 10,000 to 200,000. This enables us to exclude purely military outposts as well as multi-dimensional cities. However, the majority of closed cities are outside these established boundaries. One extension thus would be to include all cities in the regression model and add categorical variables to represent city level based on population. Adding these cities will not only create a more extensive dataset, but also it is possible to find out whether the development and urbanization of bigger closed cities are more sensitive to closed city heritage than is the case for relatively small closed cities.

There also is scope for further exploring the link between luminosity and economic development. Section 5.2 shows that adjusted urban light luminosity is highly correlated with GDP at the national level. However, whether such links will be strong at the city level or the third administrative level is not guaranteed. It is possible that such a connection is strong for some types of cities (most obviously, industrial cities or transportation hubs) but not for others (government or service centers). Exploring the luminosity-GDP and luminosity-population links for different types and sizes of cities thus should lead to further refinement of the analysis here.

That substantial work remains to be done reflects the fact that very little has been done so far using luminosity data to infer the impacts of policies on regional economic growth. The topic we investigate in this paper – how Soviet-era closed cities fared relative to comparators after the USSR disintegrated – is of obvious interest to those concerned with the fate of "post-socialist" planned economies. However, it also is of broader intellectual interest, since it demonstrates how one can use luminosity data in the absence of good socio-economic information to link large, well-defined government policies at the city level to long-run development outcomes.

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Appendix

Figure 1. Nighttime Light Data by F142002 and F152002 of Russia and Selected Cities

F142002 Russia

F152002 Russia

F142002 Selected Cities

F152002 Selected Cities

Figure 2. Unadjusted Luminosity Sum for Russia, 1992-2019

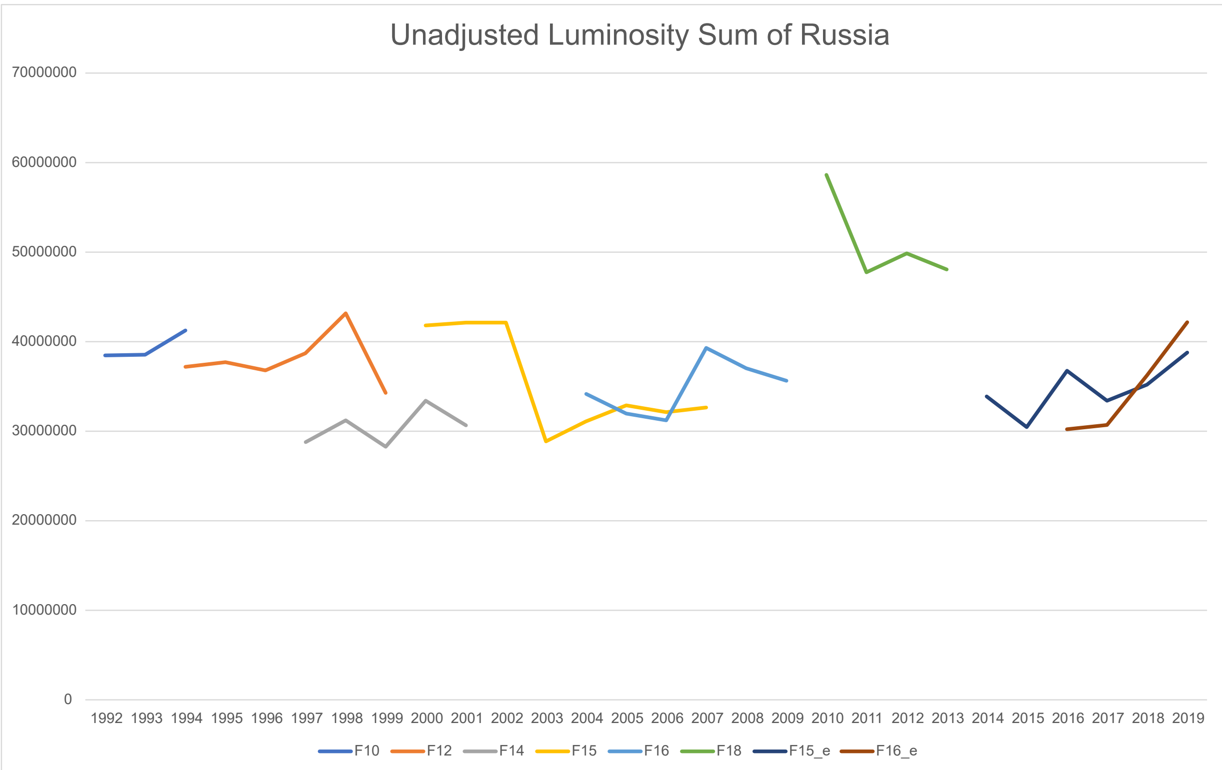


Figure 3. Unadjusted Luminosity Sum for Russia, 1992-2019

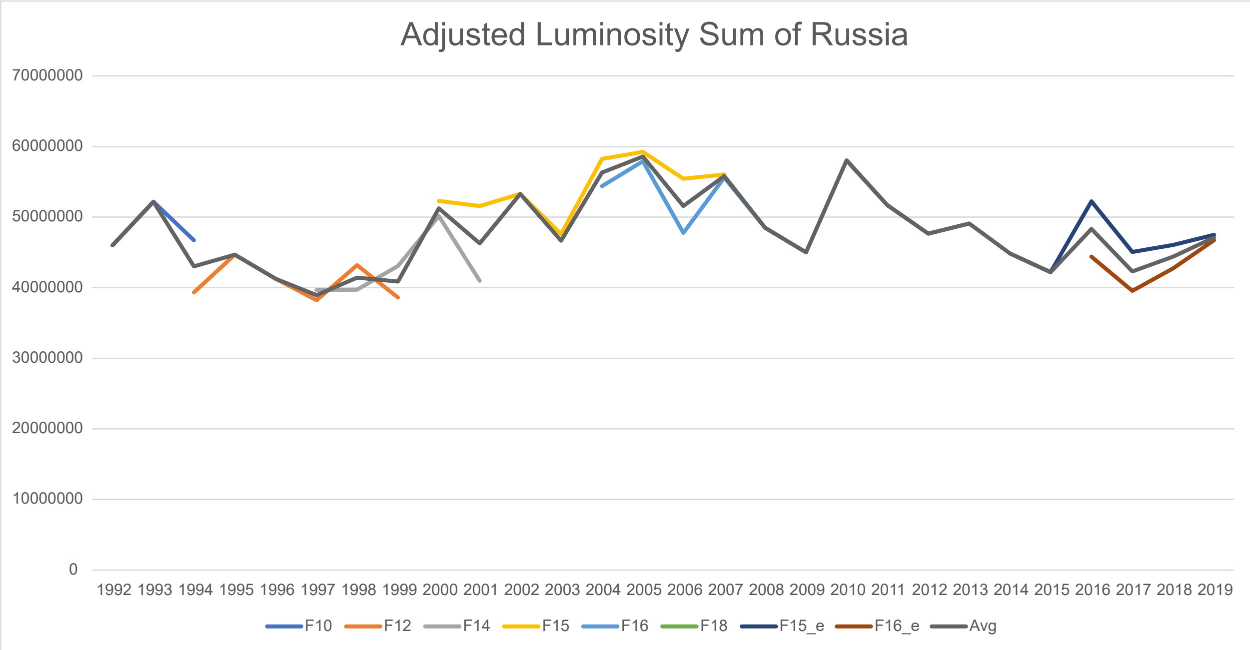


Figure 4A: Urban Russian Inter-calibrated Adjusted Luminosity Sums

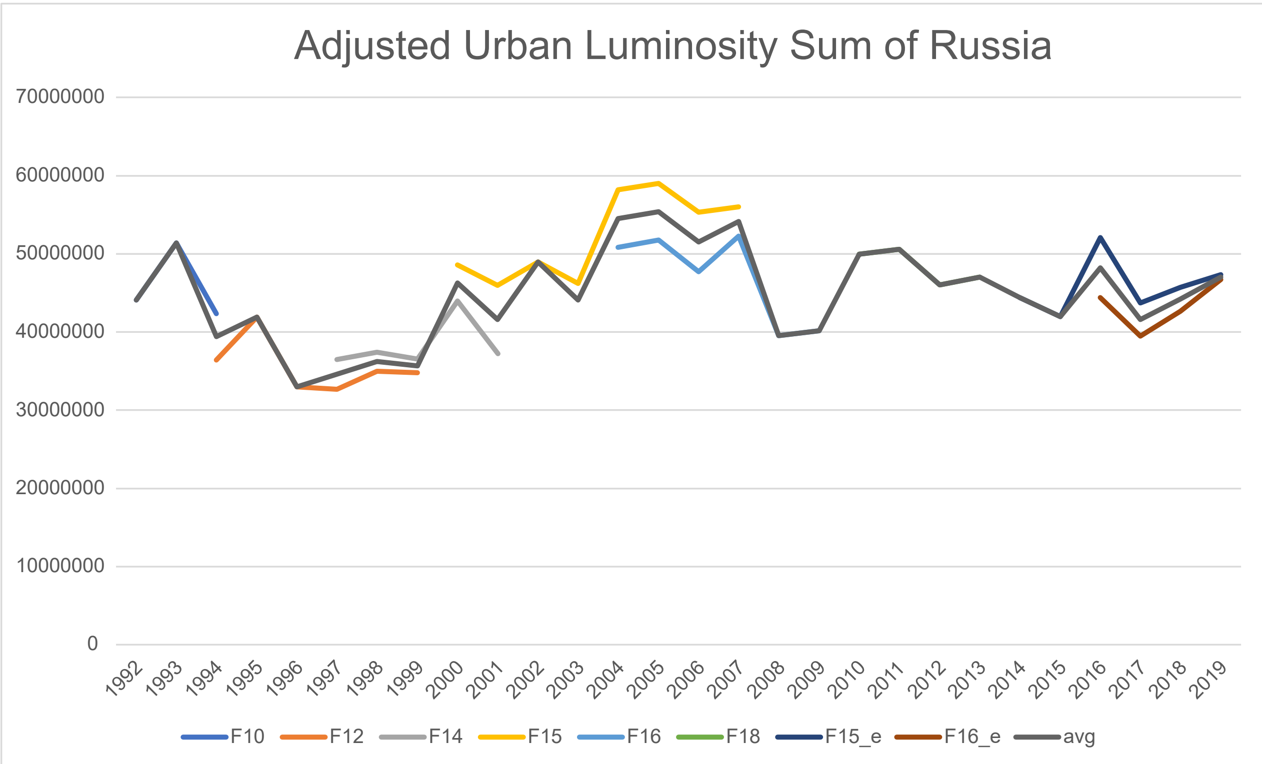


Figure 4b: Urban Russian Inter-calibrated Adjusted Luminosity Sums, ln scale

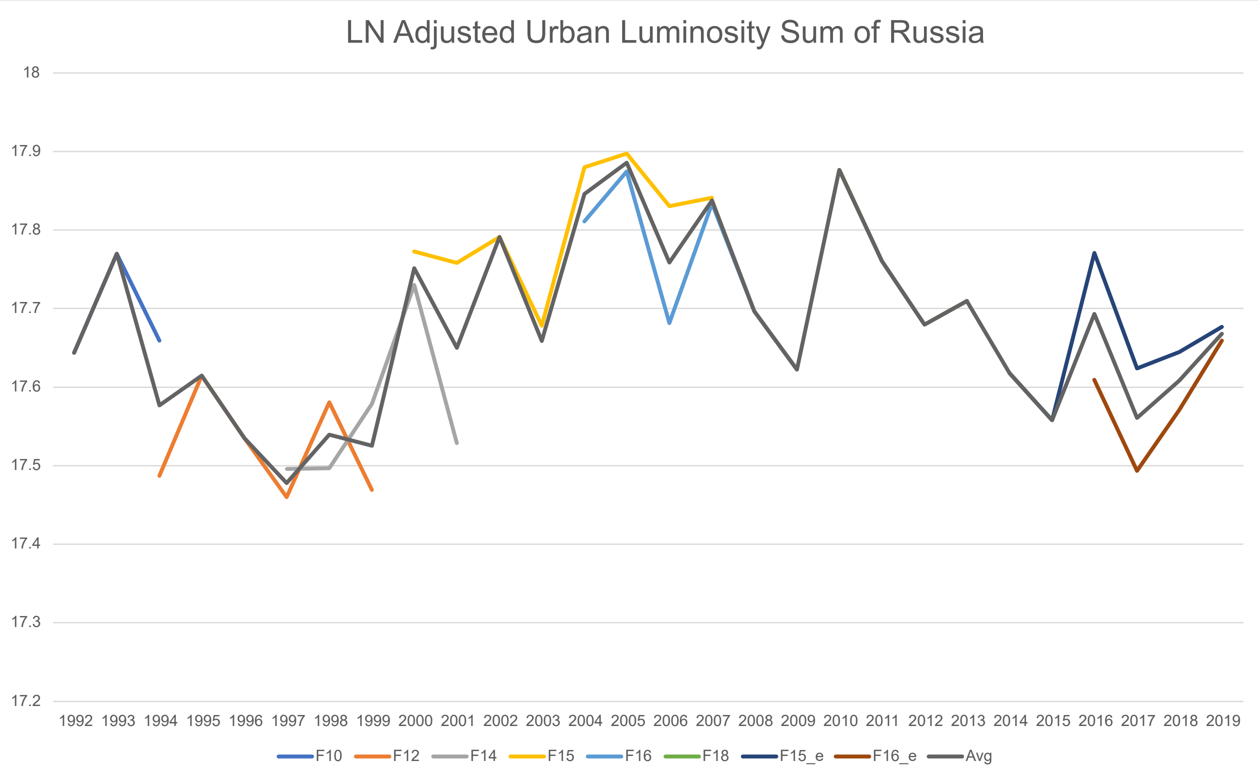
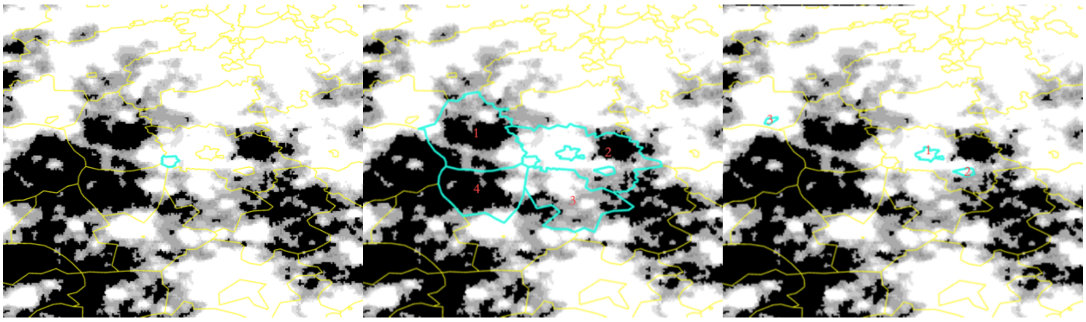
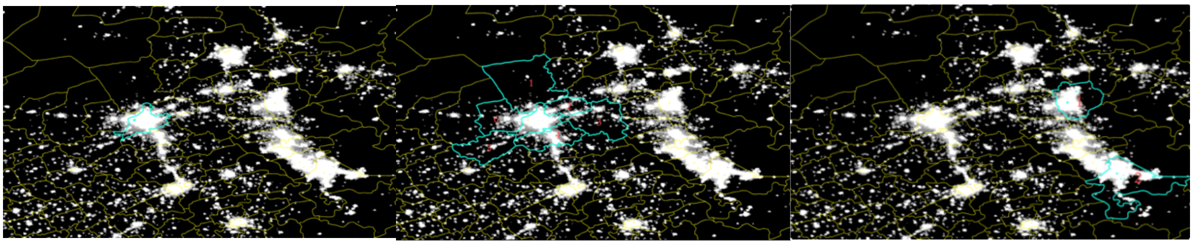


Figure 5: Examples of Selecting Similar Cities



Protvino	Zhukovskiy raion (1)	Serpukhov(1)
	Serpukhovskiy raion (2)	Pushchino(2)
	Zaokskiy raion (3)	Obninsk(3)
	Tarusskiy raion (4)	



Novosibirskiy raion

Kolyvanovskiy raion (1)

Moshkovskiy raion (2)

Toguchinskiy raion (3)

Iskitimskiy raion (4)

Ordynskiy raion (5)

Kochenevskiy raion (6)

Kemerovskiy raion (1)

Novokuznetskiy raion (2)

Figure 6: All Closed Cities with Their Two-type Paired Cities

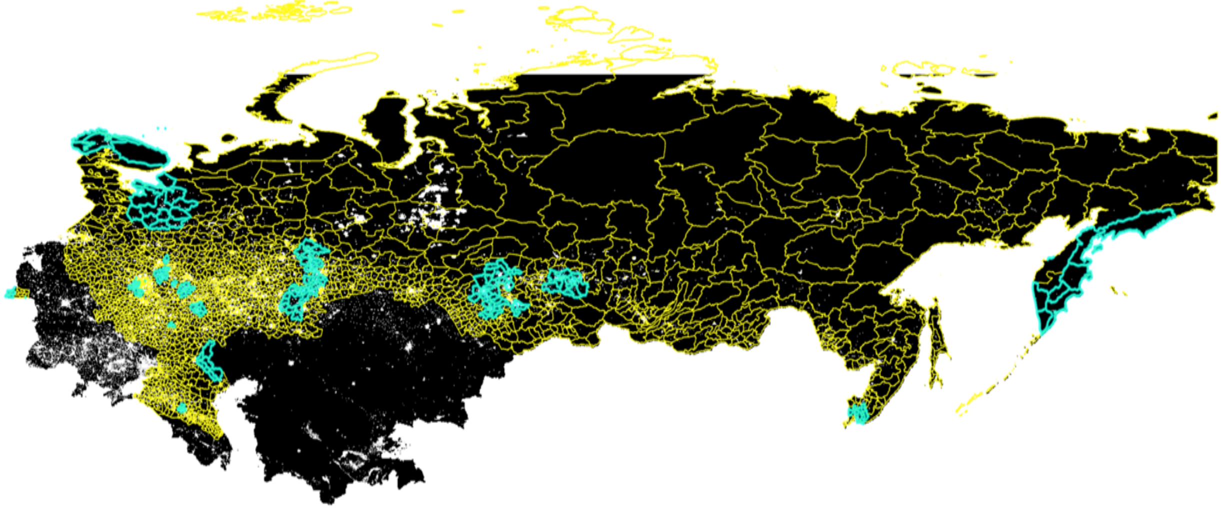


Figure 7: Closed City Distribution Map

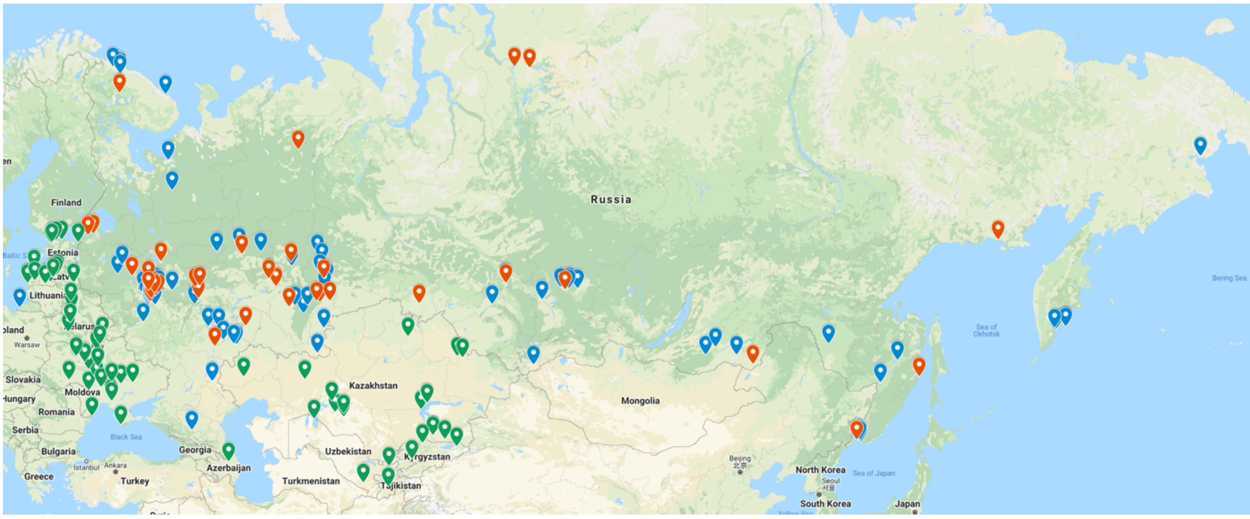


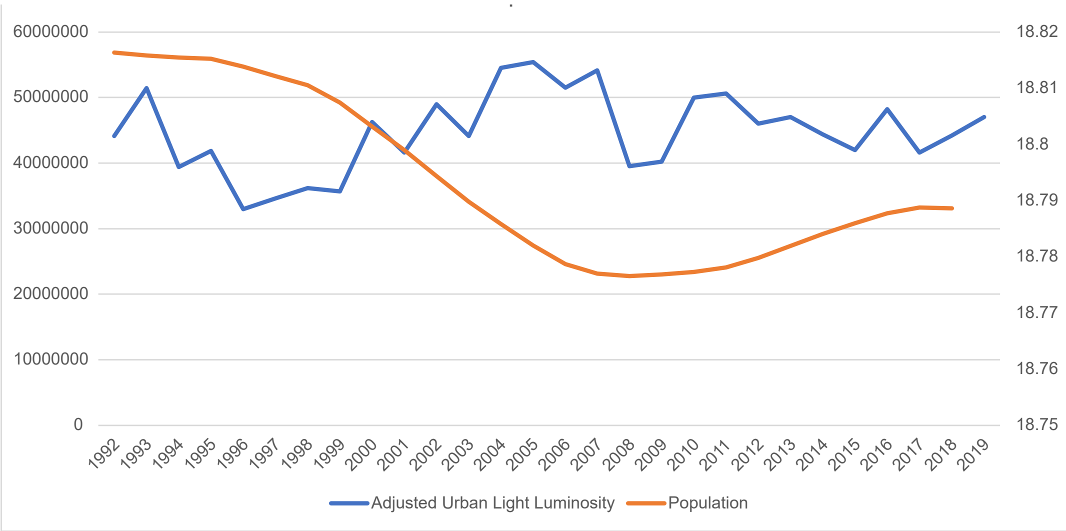
Figure 8: Soviet-era Closed Cities in Latvia and Estonia

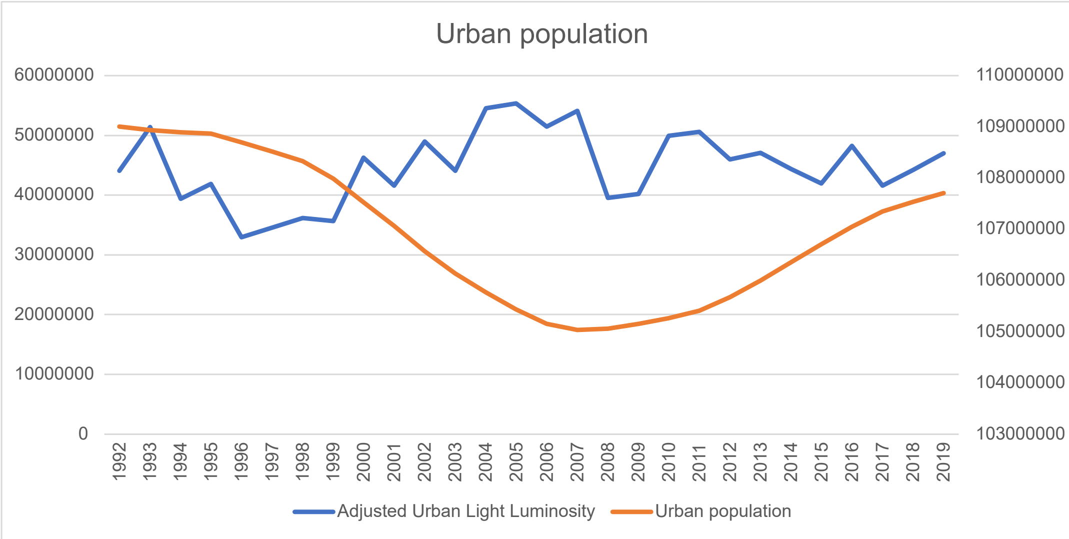
Figure 9: Soviet-era Closed Cities around the Black Sea

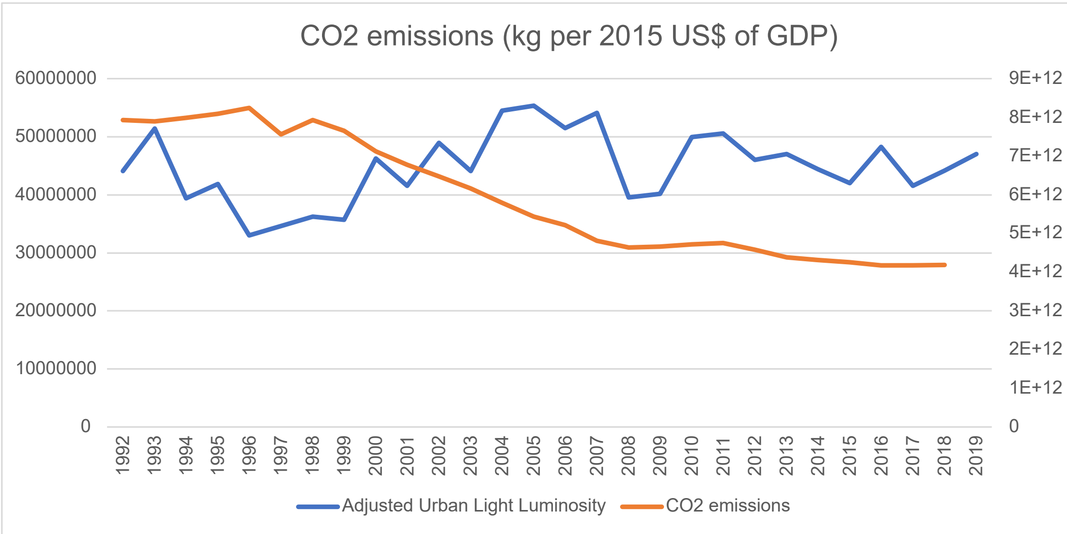
Figure 10: Distribution of Gulag camps throughout the USSR[10]

10 https://gulag.online/articles/mapa-taborovych-sprav-gulagu-a-pribehu-ze-stredni-evropy?locale=en

Figure 11: Urban Light Luminosity and Macroeconomic Trends







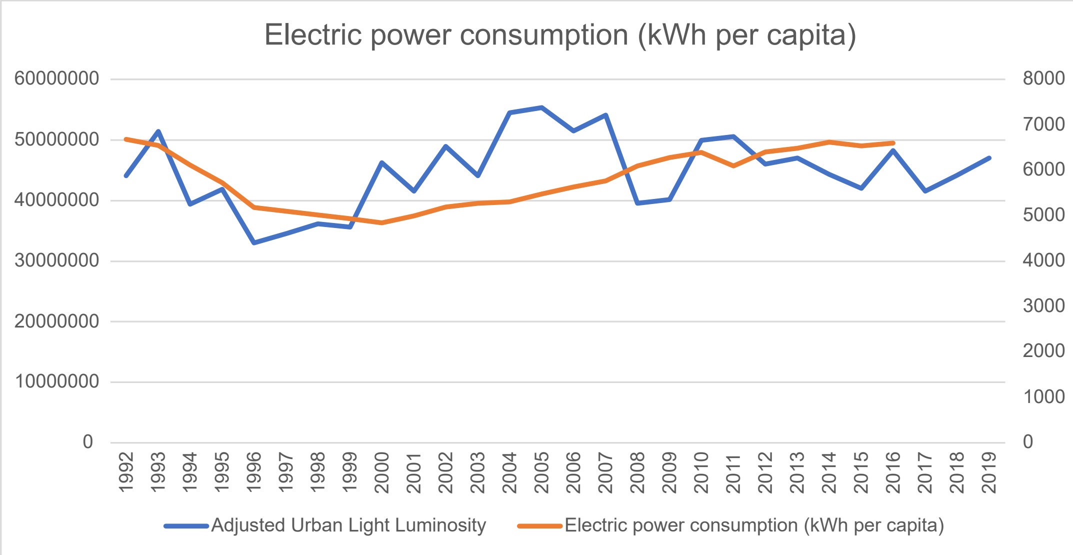


Figure 12: Rolling Urban Light Luminosity Sum Average vs PPP-adjusted GDP

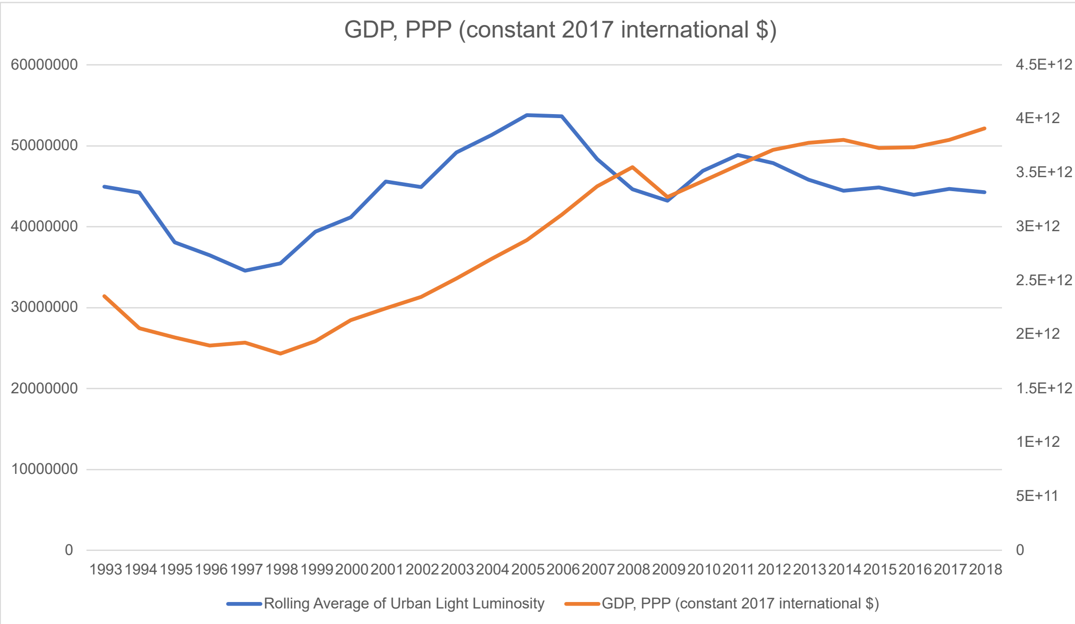


Figure 13: Luminosity of Russian and Ukrainian closed cities relative to 1992