Air pollution in Ukraine as seen from space: the effects of the war

Study based on the Copernicus Sentinel 5p satellite imagery

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Air Pollution in Ukraine as seen from Space: The Effects of the War

Main editor: Mgr. et Mgr. Simona Bočková
Authors: Mgr. Bc. Roman Bohovic, Ph.D., Mgr. Bc. Matúš Hrnčiar, Mgr. Mikuláš Muroň, Mgr. Jan Chytrý, Martin Skalský, Ing. Marcela Černochová, Olexiy Angurets, Mgr. Jan Labohý.

Language versions: English, Ukrainian
English proofreading: Stephen Fisher
Photo: Majda Slámová, Arnika, Environmental Monitoring Centre Dnipro
Graphic design: Jakub Němeček
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Contents

Abbreviations and acronyms

Av. Re. Krym – Avtonomna Respublika Krym (Autonomous Republic of Crimea)
BAT – best available technologies
CO – carbon monoxide
CO_2 – carbon dioxide
EEA – European Environment Agency
EU – European Union
GIS – geographic information system
HCHO – formaldehyde
HDX – The Humanitarian Data Exchange
IOM – International Organization for Migration
NO_2 – nitrogen dioxide
$PM_{2.5}$ – particulate matter 2.5 micrometers or less in diameter
PM_{10} – particulate matter 10 micrometers or less in diameter
SP5 – Sentinel 5P
SH – Sentinel Hub
TROPOMI – TROPOspheric Monitoring Instrument
WHO – World Health Organization

Glossary

region – the term used in this report for the administrative division *oblast*
district – the term used in this report for the administrative division *raion*
macroregion – the term used by IOM as a spatial unit for measuring internally displaced people (IDPs) due to the conflict in Ukraine; utilized in a similar regard in this report
Eastern macroregion – macroregion consisting of the Kharkiv, Donetsk, Luhansk and Dnipropetrovsk regions
Southern macroregion – macroregion consisting of the Mykolaiv, Kherson and Odessa regions[1]
Northern macroregion – macroregion consisting of the Poltava, Cherkasy, Kirovohrad and Vinnytsia regions
Central macroregion – macroregion consisting of the Sumy, Chernihiv, Kyiv and Zhytomyr regions
Western macroregion – macroregion consisting of the Khmelnytskyi, Ternopil, Chernivtsi, Ivano-Frankivsk, Zakarpattia, Lviv, Volyn and Rivne regions

[1] Av. Re. Krym has not been included in the IDP count in the IOM report (see source: IOM, 2022).

Key findings and highlights

The war in Ukraine – (besides the obvious tragic impact on human lives and destruction of the infrastructure of the country),has led to significant damage to the environment, including air pollution. This report examines and summarizes the change in air pollution since the start of hostilities with a focus on nitrogen dioxide (**NO_2**). This pollutant is characterized by a high degree of correlation with anthropogenic activities.

Satellite data shows **an overall reduction in NO_2 concentration** over the territory of Ukraine between the pre-war period and current war period. On average, there was **a decrease of 9.4% for the whole country**. In general (in the pre-war period), the distribution of NO_2 is relatively even, with several regions (Kyiv, Donetsk and Zaporizhzhia) having much higher concentrations than the rest of the country. Higher concentrations are mostly in the largest urban areas and in industrial and coal mining regions.

The **largest decrease for the period of the war,** (over 30%), can be seen in and **around large urban areas and industrial centres** such as Kyiv, Kryvyi Rih and Zaporizhzhia and in places where entire cities were destroyed, and residents moved away (what can be termed as the long-term front line). **This study confirms that the key influence on air pollution in Ukraine is, or was, caused primarily by the outdated heavy industry based on coal combustion.** While in no way is it intended to downplay the tragic effects of war, both human and environmental, even the unquestionable horrors of war do not have as devastating an effect on air quality as the operation of obsolete industrial technologies and equipment in peacetime.

A relationship between war-inflicted migration and the decrease in NO_2 concentrations has been demonstrated. These NO_2 changes were observed in macroregions, the spatial units utilized by the International Organization for Migration (IOM) for counting internally displaced people (IDPs) (by place of origin) (IOM, 2022). **Macroregions with the highest shares of IDPs experienced the highest decreases in NO_2 concentration**. Since the conditions experienced through war, have a major impact on society, many people left their homes. This led to a decrease in economic activity and traffic in the monitored area. The largest relative share in the decrease in pollution could be seen in Kyiv (city) and the Eastern macroregion (Kharkiv, Donetsk, Luhansk and Dnipropetrovsk regions).

No long-term increase in the concentration of NO_2 was found for the sites associated with explosions, e.g. on the infrastructure due to war activities**.** This is probably because the chosen methodology did not allow these impacts to be uncovered. The measurement of NO_2 using the TROPOMI sensor of the Sentinel-5P satellite is not sensitive enough to record the growth of individual daily explosions. Shelling activity could only be loosely detected even in a much shorter-term, as shown by an early-war analysis by Zalakeviciute et al. (2022).

Also, no connection was found between a one-time daily increase in NO_2 concentration values and the shelling of Ukrainian cities. This can be caused by the resolution of the sensor (3.5 × 5 km). After an explosion, polluting substances are dispersed into the wider environment due to prevailing weather conditions. Satellite overpass is rarely aligned with the event and the sensor is thus unable to detect increased values. Fluctuations in NO_2 concentrations occur daily even under normal conditions, and it is therefore not possible to clearly determine whether a short-term increase in values is related to an explosion or it is caused by the current prevailing weather situation. It is also important to mention that NO_2 is not one of the main substances released into the atmosphere during explosions.

The effect of war on NO_2 pollution should, however, not be underestimated. The explosions may extend to the igniting of industrial objects, infrastructure, and the natural environment which then become a serious source of emissions. The country saw a 77-fold increase in forest fires during wartime compared to 2021, 70% of which were caused by combat activity (Angurets et al., 2023). Since this study was conducted on a regional to country scale, extensive forest fires as a direct result of shelling could not be easily identified, wherefore narrower periods both before and during the war would have to be investigated in more detail. Moreover, large amounts of NO_2 enter the atmosphere from military machinery movements and personal vehicles of those refugees fleeing, and subsequently from alternative means of heating due to power outages (Angurets et al., 2023). It is thus recommended to leverage other methods of estimating air pollutants (e.g., assessing wet and dry deposition) to fully assess the impacts of the war.

The study recommends a set of activities to support air pollution quality in Ukraine after the war.

These include enhanced pollution monitoring and conducting a thorough assessment of post-war air pollution sources and impacted areas to establish a baseline for effective measures.

It is also recommended to implement EU-based energy efficiency rules in areas such as building renovations, industrial upgrades, and smart transportation solutions to reduce energy consumption and emissions. Enforcing pollution control technologies, strict emission standards, and incentivizing industries to adopt low-carbon processes will contribute to reducing industrial emissions.

Furthermore, establishing green funding programs with grants and subsidies could support the adoption of clean technologies and sustainable production practices. Strengthening regulatory agencies, allocating resources for inspections, audits, and penalties for non-compliance should ensure effective enforcement of air quality standards.

Additionally, directing post-war reconstruction towards sustainable industrial production and energy generation, discouraging new coal-fired power plants, and promoting cleaner energy sources will be vital. Enhancing transparency in making air quality information easily accessible to the public is also important.

By implementing these recommendations, Ukraine can rebuild its economy while fostering a sustainable future with improved air quality and environmental well-being.

Introduction

In 2020, World from Space and Arnika conducted a study on the impact of industry on air pollution in Ukraine (Bočková et al., 2020), investigating the concentration distribution of six pollutants (NO_2, CO, CO_2, HCHO, PM2.5 and PM10). It was found that the majority of NO_2 pollution concentrates in industrial and large urban areas, especially the Dnipropetrovsk, Kyiv, Zaporizhzhia regions or were brought by the movement of polluted air from Poland over the north-western Ukrainian border. Related studies, such as Angurets et al. (2023) and Soroka et al. (2022) elaborate on the war effects on air quality.

The war in Ukraine has led to numerous losses of human lives and the destruction of property, with environmental damage being another serious consequence of the war that cannot be disregarded. Armed conflicts harm the environment in numerous ways. There is damage to ecosystems and terrain when moving military equipment and fighting; attacks on industrial plants cause leaks of toxic substances into the soil and air. In addition dangerous substances enter the atmosphere through the destruction of infrastructure and buildings. Based on the estimates (Havránek, 2022), **200 – 400 million tons of CO2** (calculated based upon concrete, asphalt and steel) entered the atmosphere in this way in 2022. This is roughly the equivalent of France's annual CO2 emissions (approx. 300 million tonnes in 2019) (CEOBS, 2022b).

The war has had many impacts including the impact on air quality. This report summarizes the change in air pollution during the wartime period with a focus on nitrogen dioxide. Due to the risk of missile attacks during the war, economic activity, and the movement of residents even outside the front itself are restricted during daylight and night hours. Therefore, there occur two different situations in terms of air pollution at one time (Protopsaltis, 2012). During explosions, toxic substances are released into the air, the type of which depends on both the type of the projectile and the place where it explodes. Targeted attacks on critical infrastructure and industrial facilities will result in the release of a large amount of chemicals into the atmosphere. Depending on weather conditions, emissions can migrate over large

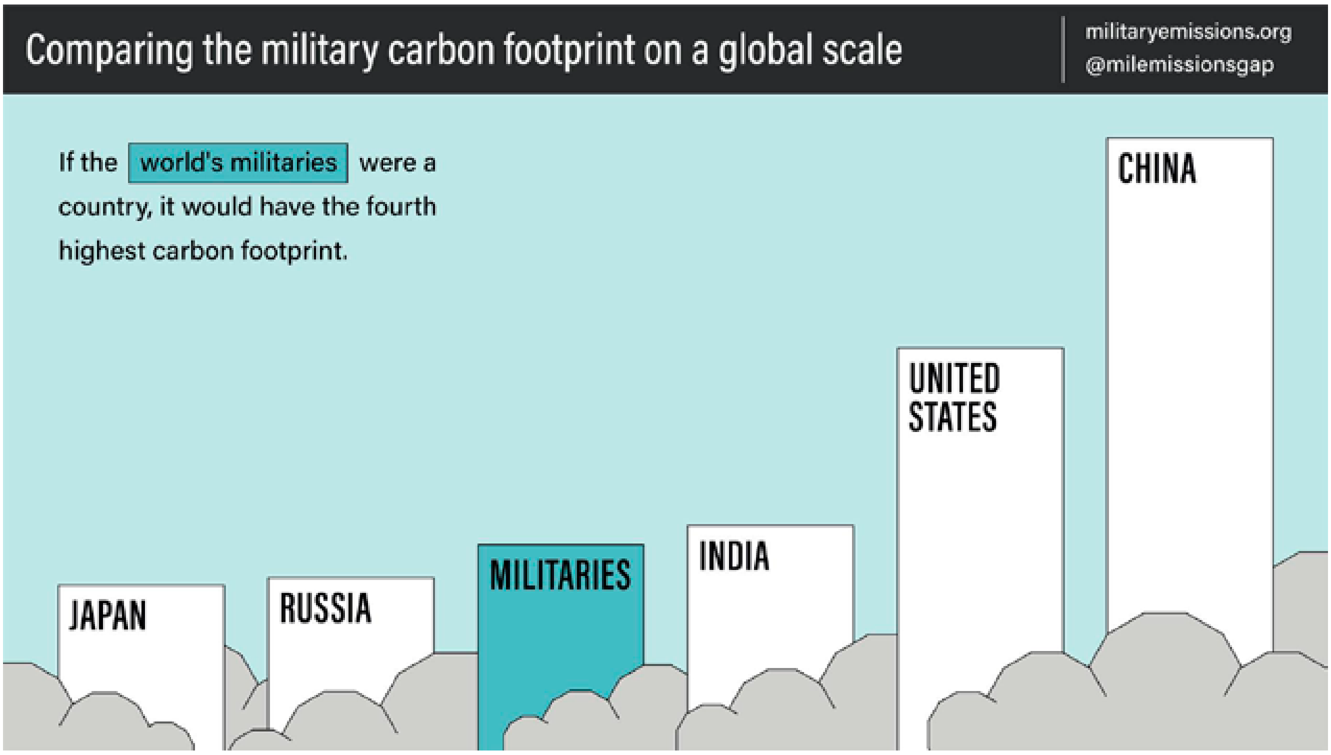

***Fig. 1:** Comparing the military carbon footprint on a global scale (CEOBS, 2022a).*

distances (Melas et al., 2000). Military activities in general cause significant pressure on the climate. According to CEOBS (2022a), the total global military carbon footprint is approximately 5.5% of global emissions. If **military activities** are compared with country effects, it would represent **the fourth highest national carbon footprint** in the world. (Fig. 1)

This report provides a basic data analysis of the time series of NO_2 concentrations from the Sentinel-5P satellite for the entire territory of Ukraine. In 2021, we conducted a study that focused on analyzing air pollution in Ukraine and identifying the key polluters (Bočková et al., 2020). In this report, we are shifting our focus to the changes in air pollution during the war era.

The current state is compared with the normal pre-war state. The analysis of the impact of selected war operations is included. Air pollution is examined in selected time periods, which are then compared to each other. Satellite data for the war period is analyzed between the date of the 24/2 and the 30/11 2022. To determine the impact of the conflict in Ukraine on the atmosphere and air pollution, this period is compared with the pre-war period. The pre-war period contains data from the date of 1/4 to the 30/11 2018 (Sentinel-5P provides data from April 2018 onwards) and from the date of 24/2 to the 30/11 (2019, 2021). In 2020, there were significant impacts of the COVID-19 lockdown on air pollution (EVERIS & World from Space, 2021) where many places recorded decreases in pollution resulting from the limited movement of residents (transport) and the shutdown of industrial facilities. The year 2020 was thus excluded from the pre-war analysis.

Nitrogen dioxide (NO_2)

Nitrogen dioxide (NO_2) is an important trace gas present in both the troposphere and the stratosphere; however, it is also a key atmospheric pollutant produced by anthropogenic

Main human sources of NO_2

- motor vehicle exhaust emissions
- coal-fired power stations emissions
- petrol and metal refining production

activities. According to WHO (2000), higher nitrogen dioxide levels can lead to respiratory infections and reduced lung function and growth; it is also linked with increased symptoms of bronchitis and asthma. Interaction of NO_2 with water and other chemicals in the atmosphere leads to the formation of acid rain, causing changes in forests and aquatic ecosystems.

Nitrogen dioxide and anthropogenic activities

According to the European Environment Agency (EEA) 2022 Air Quality report (2022), **road transport** is the principal source of nitrogen oxides, responsible for 37% of emissions. Other sources of NO_2 are **petrol and metal refining**, electricity generation from **coal-fired power stations**, manufacturing industries and food processing. The natural source of the gas comes from **microbiological processes in soils, wildfires, and lightning**.

Since increased NO_2 concentrations can be used as an indicator of areas with high population density (transportation, domestic heating) or industrial activities, a decrease in pollution values may indicate a decrease in industrial activities or depopulation. When the economic activity of the population stops, concentrations decrease quickly. This fact has been proven by several studies (Virghileanu et al., 2020) focused on investigating the effects of the COVID-19 lockdown on air pollution in multiple countries. In a state of war, the reasons for the decrease in economic activity differ considerably, but the net effect of pollution decrease remains.

Conversely, an increase in NO_2 values can occur after an explosion. However, it is difficult to assess the change in the pollution

Main human sources of NO_2 during wartime

- **Military activities:** Military activities such as the use of explosives, artillery fire, and military vehicles can emit NO_2 into the atmosphere.
- **Industrial activities:** During wartime, industries may continue to operate to support the war effort, which can lead to increased emissions of NO2 from sources such as power plants, factories, and refineries.
- **Transportation:** Military vehicles and transport of troops and supplies can also contribute to NO_2 emissions.
- **Destruction of infrastructure:** Damage to buildings, roads, and other infrastructure during conflict can also release NO_2 into the atmosphere due to the burning of materials or other chemical reactions.

source for an area with high economic activity. In 2020, a massive explosion took place in the port of Beirut, destroying a significant part of the capital's buildings. Although a cargo ship full of ammonium nitrate exploded, the impact on atmospheric NO_2 loading was limited to a few days and a few kilometres along the coast. One day after the explosion, concentrations of NO_2 over Beirut increased to about 1.8 mol/m^2. Nevertheless, a few days before the explosion, values 2.5 times higher were documented, related most probably to emissions from car and ship transportation (Farahat et al., 2022).

It is also necessary to mention that NO_2 is not among the main substances released into the atmosphere during explosions. During the destruction of entire cities, a cloud with scattered particles enters the atmosphere, possibly containing ground cement, glass fibres, asbestos, lead, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated furans and dioxins (Velázquez, 2022).

In war zones, there is often a drop in NO_2 concentrations related to the occupation of the territory, with a subsequent decrease in the economic activity of the population, as has happened since 2013 in Iraq (Ministry of Environmental Protection of Israel, 2015). In cities occupied by the so-called Islamic State, such as Tikrit and Samarra, armed conflict has left marks manifesting decreases in NOx pollution. A drop in NO_2 concentration by 40 to 50% has been recorded over Damascus and Aleppo in Syria since 2011 (Lelieveld et al., 2015). A civil war began that year, resulting in over 6.6 million people fleeing their homes. This has had a strong impact both on society and the economy.

Data and Methodology

Sentinel-5P

Sentinel-5P mission (S5P) is a satellite devoted to atmosphere monitoring, launched in October 2017 as part of the EU Copernicus Programme. It carries the TROPOMI spectrometer (TROPOspheric Monitoring Instrument) covering wavelength bands between the ultraviolet and the shortwave infrared. SP5 measures gases such as NO_2, ozone, formaldehyde, SO_2, methane, carbon monoxide and aerosols daily with a spatial resolution of about 5.5 km x 3.5 km (7 km to 5.5 km until August 2019).

Sentinel-5P level 2 (L2) data products were used with "quality assurance value" pixels under 0.5 filtered out. The quality assurance value is an important parameter that reduces the seamless coverage of the areas of interest by S5P data and the proposed methodology takes it into account.

Outline of processing

The basis of the analysis is a comparison of the pre-war and wartime (starting in February 24, 2022), concentration of NO_2 in atmosphere for the entire territory of Ukraine. To obtain more detailed results, values are also analysed and calculated to both the regional and the district level. The impact of significant explosions, aimed mainly at critical infrastructure, has been determined. In these cases, significant short-term increased concentrations of NO_2 in the vicinity of the explosion were expected. In this report, changes in NO_2 concentrations for the selected attacks on infrastructure objects were compared with the long-term pre-war and wartime averages and with the nearest observable period to the day of the explosion. Buffets in the vicinity of the explosion with a size of 1 km were used for the analysis, so that the influence of the external environment is minimized as much as possible. Changes in NO_2 concentrations were also compared to socio-economic parameters, especially depopulation. Migration data were obtained from IOM resources via HDX (IOM, 2022) for the so-called macroregions, referring as late as to November 2022. To determine the short-term changes of NO_2 concentrations, a 14-day analysis in selected districts was carried out for the pre-war and war period.

QUOTE: The distribution of satellite-measured air pollution considers anthropogenic sources as well as results of naturally occurring processes.

SP5 satellite data products are usually measured in mol/m² units. The TROPOMI NO_2 product gives the total atmospheric NO_2 column between the surface and the top of the troposphere (tropospheric column) (ESA, 2023).

When using SP5 satellite data, it is important to consider the difference in the way values are measured. Health limit values are usually given in the units used for ground-based measuring instruments. Therefore, converting values from satellite imagery (mol/m²) to ground-based units (µg/m³) is not recommended (Kira, 2016).

Quality flags and observation frequency

It is important to understand that the quality of accessible pixels is highly dependent on weather conditions, sensor errors and other parameters, such as cloud cover.

S5P revisit time for Europe (including the area of Ukraine) is more than once a day with scanning overlaps at higher latitudes due to a near-polar, sun-synchronous orbit of the satellite. The processed data thus comprises all available satellite measurements. "Using all available data" means: combining data from several satellite orbits with varying grid sizes and orientations. To address this, all S5P satellite observations were downscaled to obtain a regular grid with a resolution of **1km × 1km**. Data was automatically pre-processed and downloaded to a cloud space using our proprietary Python scripts. Final processing steps were executed on a desktop GIS.

Results

Basic analysis

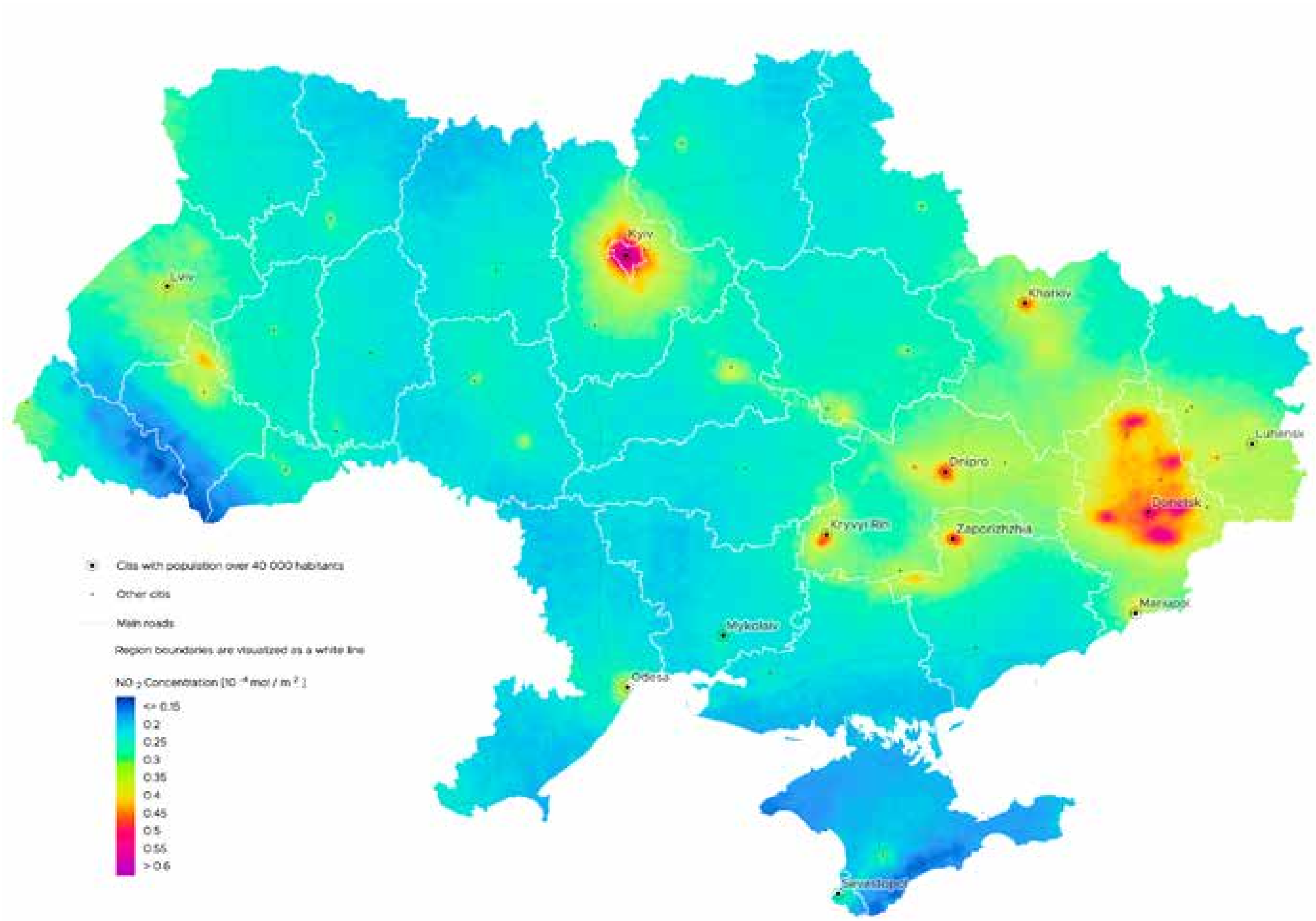

Fig. 2: *Average concentrations of NO_2 in Ukraine for the pre-war period obtained from the Copernicus S-5p satellite data (Copernicus Sentinel data (ESA, 2022; modified); OpenStreetMap contributors, 2022).*

The average concentrations of NO_2 in Ukraine in the pre-war period (excluding winter seasons) can be observed in Fig. 2. The average concentration of NO_2 in the entire territory of Ukraine in the monitored period reached 0.286 10^{-4} mol/m². The highest concentrations of the pollutant are mainly located around large cities and in the vicinity of industrial regions. The main centres of pollution are in the city of Kyiv and in the Kyiv, Donetsk, Kharkiv, Dnipropetrovsk, Ivano-Frankivsk and Lviv regions.

The average concentration of NO_2 in Ukraine in the war period is displayed in Fig. 3. It can be observed that there was a pollution decline throughout the territory. The average concentration of NO_2 over the whole territory of Ukraine decreased to 0.259 10^{-4} mol/m². That represents an average decrease of 9.4%. The largest decrease in absolute values was recorded in the eastern regions (including large agglomerations of Kharkiv, Luhansk, Donetsk, Dnipro and Zaporizhzhia) and for the city of Kyiv.

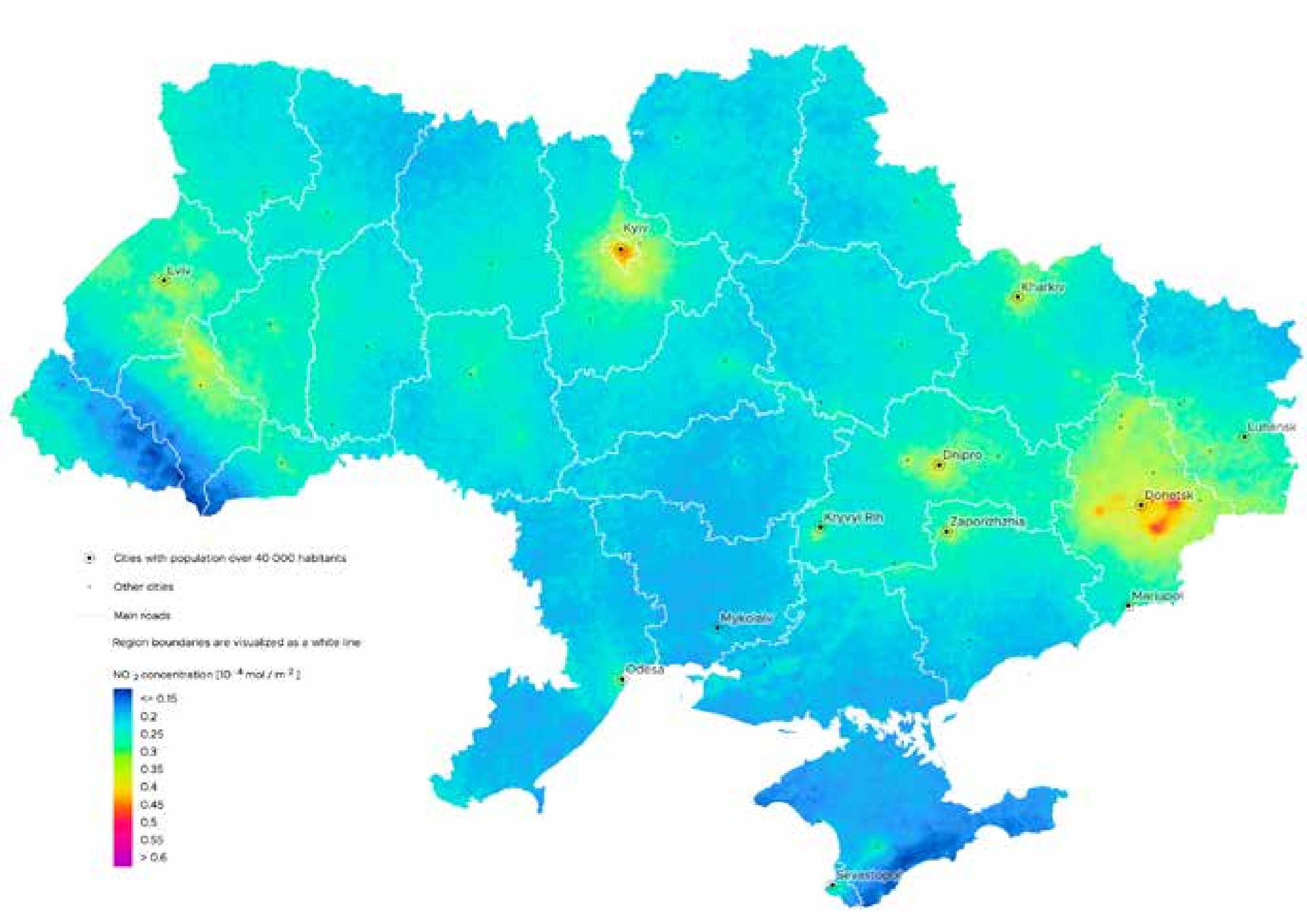

Fig. 3: *Average concentrations of NO_2 in Ukraine for the war period (Copernicus Sentinel data (ESA, 2022; modified); OpenStreetMap contributors, 2022).*

Fig. 4 shows the difference between the pre-war and war period expressed as a percentage difference between the processed satellite data visualized in Fig. 2 and Fig. 3. In contrast to the western part of Ukraine, a general decline in NO_2 pollution can be seen in the eastern part. The largest decrease (over 30%) is seen in and around large cities such as Kyiv, Kryvyi Rih and Zaporizhzhia, but less so in smaller cities, for example, those in the Donetsk region. In the north of the region, a significant reduction may be related to a decrease in the economic activity of the population due to war. For example, 80% of the population of Slovyansk (located in the middle of an area where there has been a significant decrease in NO_2 pollution) was evacuated before June 2022 (The New Voice of Ukraine, 2022). Also, other depopulated places are located in this area, such as Bakhmut, where 90% of inhabitants have left the city since the beginning of the war (France24, 2022).

Fig. 5 shows the average concentrations of NO_2 in Ukrainian regions in the pre-war and war periods. A decrease in NO_2 concentrations can be observed in almost all regions. The highest relative and absolute decreases can be observed in the Kyiv (city) – 29% and 0.17 10^{-4} mol/m^2. A high decrease was also recorded in the regions of Dnipropetrovsk (18%; 0.06 × 10^{-4} mol/m^2), Luhansk (16%; 0.05 × 10^{-4} mol/m^2), Donetsk (15%; 0.06 × 10^{-4} mol/m^2), Kirovohrad (15%; 0.04 × 10^{-4} mol/m^2), Poltava (14%; 0.04 × 10^{-4} mol/m^2) and Kharkiv (13%; 0.04 × 10^{-4} mol/m^2).

The difference in the average concentration of NO_2 in Ukraine between the pre-war

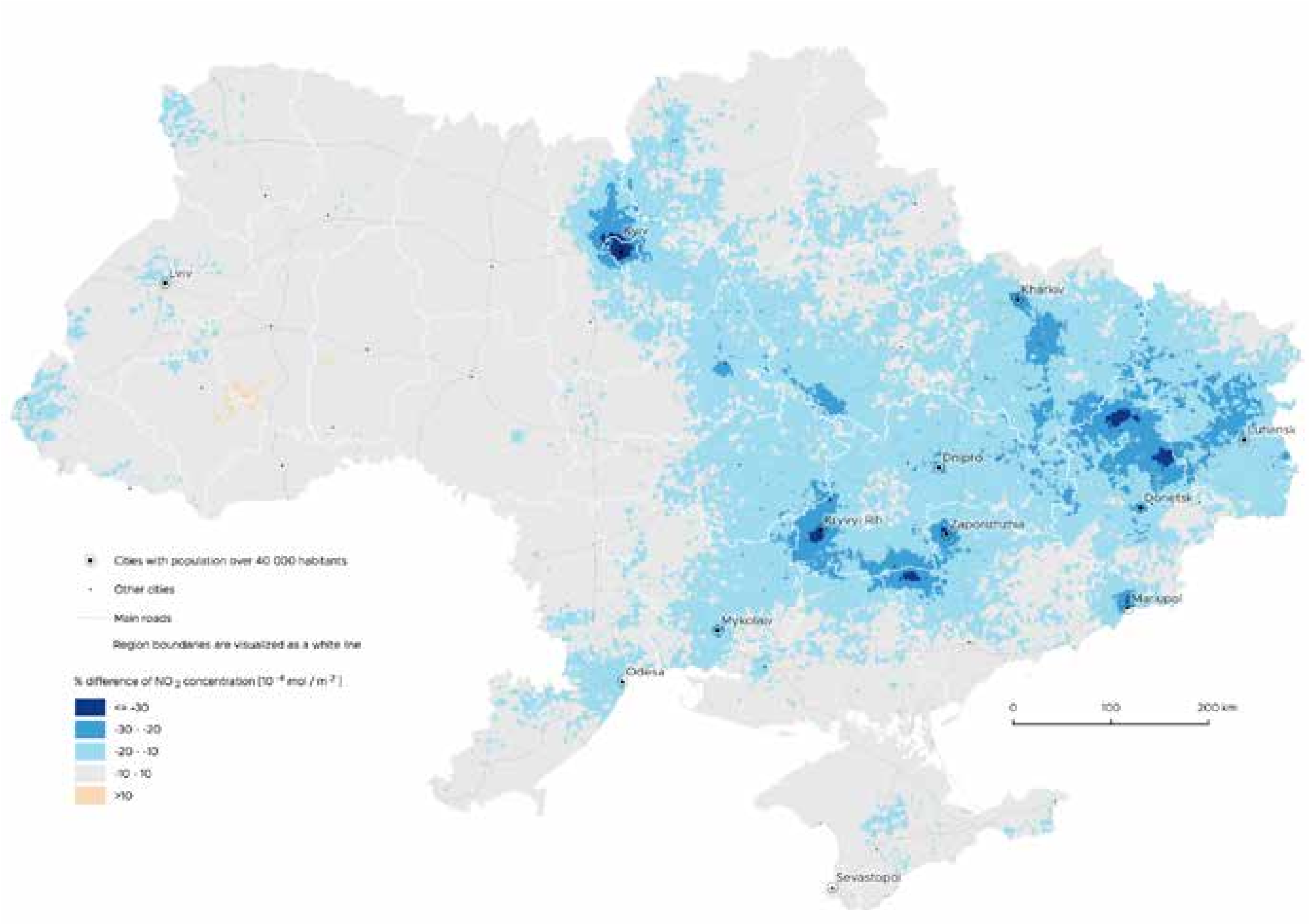

***Fig. 4:** Difference in average concentration of NO_2 in Ukraine between the pre-war period and the war period (Copernicus Sentinel data (ESA, 2022; modified); OpenStreetMap contributors, 2022).*

period and the war period calculated per district can be seen in Fig 6. The highest average relative reduction by over 40% can be seen in the districts of the city of Kyiv; Kharkiv region – Kharkiv, Kupiansk, Izium; Luhansk region – Starobilsk, Sievierodonetsk, Alchevsk; Dnipropetrovsk region – Kryvyi Rih. The table in Fig. 8 can be considered for comparative purposes.

The table indicates the relative average change of NO_2 concentration in 14-day periods in selected districts of Ukraine between 24 February and 31 November between the pre-war period and the war period. It should be noted that the results may be affected by external influences during the acquisition of satellite data, and such short-term higher/lower values may deviate from real in-situ values. Nonetheless, a decrease in values for different 14-day periods can be clearly identified. In general, it can be said that the differences in values occur more in the winter, spring, and autumn months, when the NO_2 concentrations generally reach higher values in absolute numbers, than in the summer months. During winter months, pollution (from the heating season and traffic) is often trapped in the lower layers of the atmosphere due to climatic conditions. 14-day changes in NO_2 concentrations may also be related to population migration due to war. This is particularly the case in Kyiv and larger cities, where the number of inhabitants fluctuated when the security situation worsened or, conversely, when returning to a relatively calmer period.

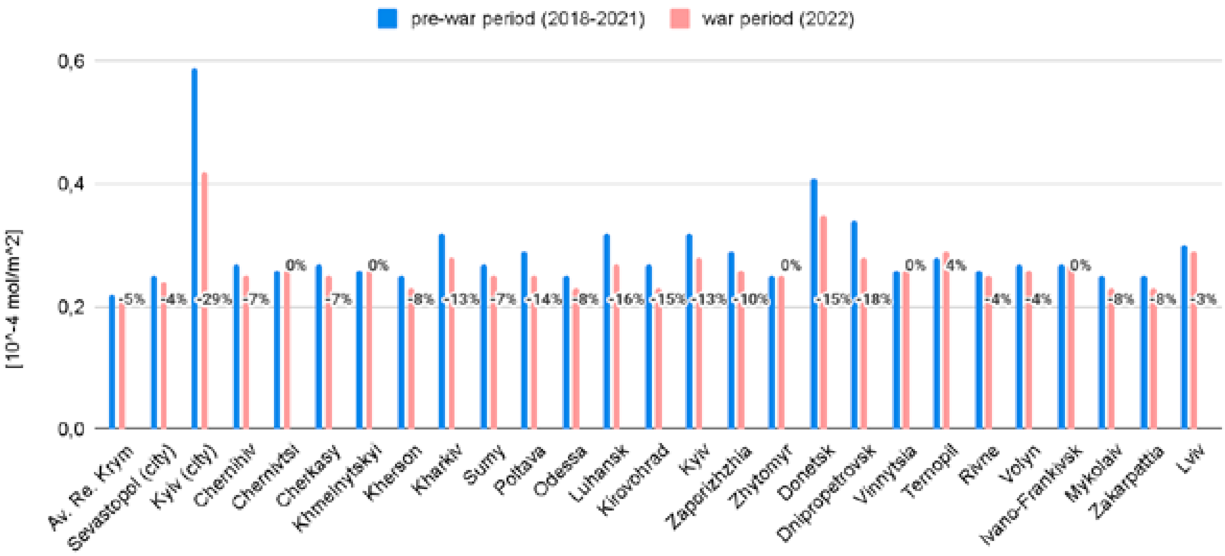

Fig. 5: *An Average concentration of* NO_2 *in Ukrainian regions for the pre-war period and the war period. For every region percentage change is calculated and visualized in the graph (Copernicus Sentinel data (ESA, 2022; modified)).*

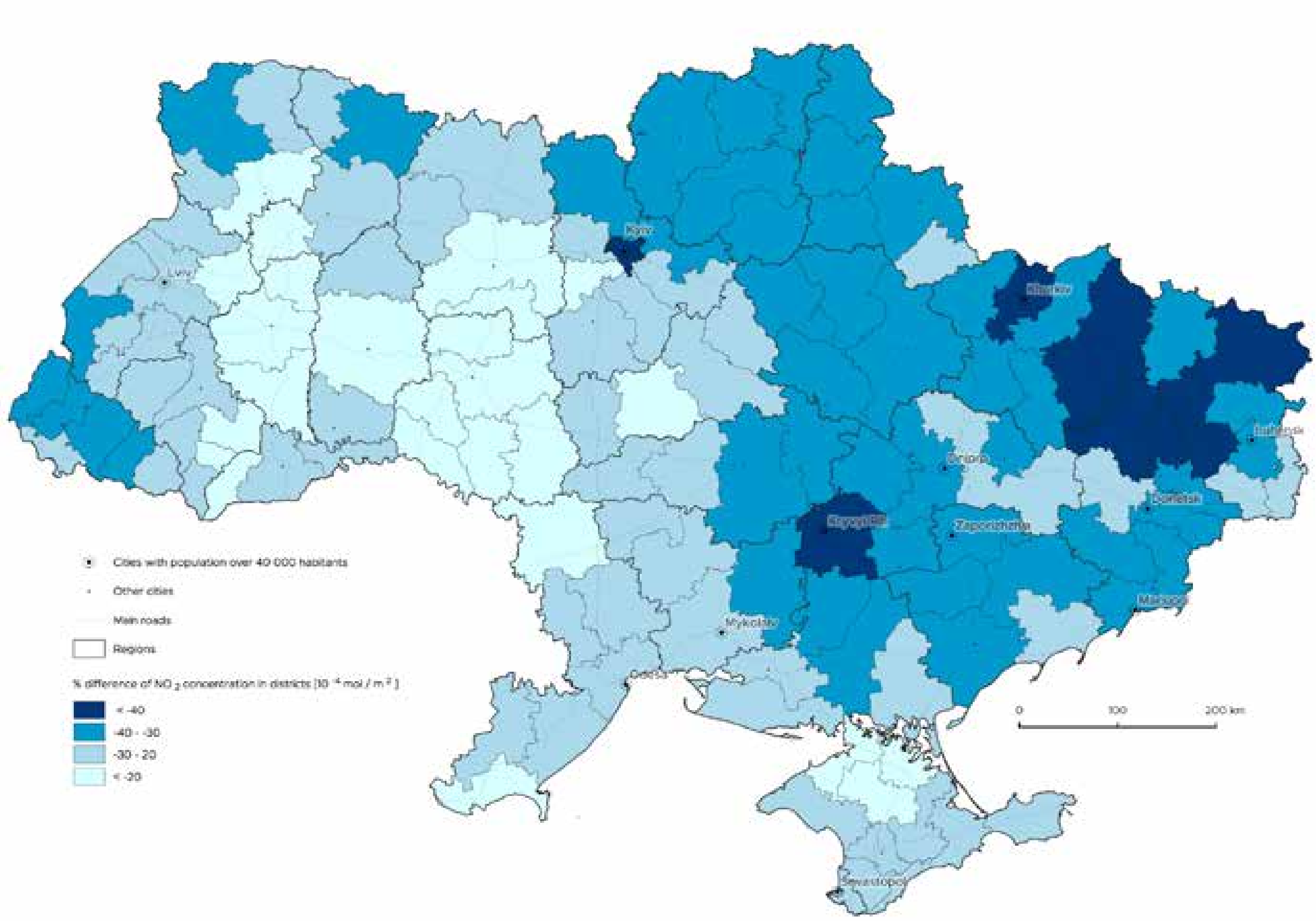

Fig. 6: *Difference in average concentration of* NO_2 *in Ukraine between the pre-war period and the war period calculated per district (Copernicus Sentinel data (ESA, 2022; modified); OpenStreetMap contributors, 2022; administrative divisions with aggregated population (HDX, 2022)).*

The effect of individual explosions on changes in NO_2 concentrations

Fig. 7 traces the differences in NO_2 concentrations for selected locations where significant attacks occurred during the war period.

The results confirm the previous mentions that the concentration of NO_2 is not among the most significant pollutants released during the explosion, respectively it is not easy to detect these short-term events with the TROPOMI sensor.

For most of the investigated locations, there was no increase in NO_2 concentrations during the time of the explosion. On the contrary, lower values than the average value in the pre-war period and the war period are detected on the given day. There was an increase in NO_2 concentrations at two investigated locations. However, in the case of April 18, 2022 (a fire in a warehouse of paints and varnishes in the city of Sumy), there were increased values for the entire territory of northeastern Ukraine. In the second case (June 18, 2022), the increase in values may be related to a military strike on a compound of Sievierodonetsk's Azot chemical plant, however, increased values on this day were detected in several places in Ukraine without an obvious connection.

Attacks On Ukrainian Industrial Facilities				**NO_2 [10^{-4} mol/m^2]**		
number	location	date	event description	pre-war period	war period	event date – max.
1	Sumy	2022-03-18	a fire in a warehouse of paints and varnishes in the city of Sumy	0.31	0.29	0.80
2	Kalynivka	2022-03-24	a Kalibr cruise missile struck the KLO oil depot in Kalynivka, the attack detonated fuel tanks and ignited a massive fire.	0.39	0.32	0.24
3	Chernihiv	2022-03-21	a fire of oil-storage tanks in Chernihiv	0.32	0.26	no data
4	Lviv	2022-03-27	a fuel-storage facility hit by cruise missiles in Lviv	0.40	0.36	0.35
5	Kremenchuk	2022-04-02	a destruction of a key Ukrainian refinery in Kremenchuk	0.34	0.26	0.15
6	Sievierodonetsk	2022-06-01	a fire in Sievierodonetsk's Azot chemical plant	0.39	0.31	0.27
7	Sievierodonetsk	2022-06-18	a military strike on a compound of Sievierodonetsk's Azot chemical plant	0.39	0.31	0.45

Fig. 7: *changes in NO_2 concentration in case of attacks on Ukrainian industrial facilities (Copernicus Sentinel data (ESA, 2022; modified); Faria, 2022; Al-Jazeera, 2022; CEOBS, 2022b).*

The relationship between changes in NO_2 pollution and depopulation

Fig. 9 and Fig. 10 show the relationship between the change in NO_2 concentrations and the decrease in population density due to the state of war. The largest relative share in the decrease in pollution can be observed in Kyiv (city) and the Eastern macroregion (see Fig. 10). Kyiv represents a specific macroregion since its area is limited only to the capital.

The relative decrease reaches the highest value in these regions because the economic activity and the movement of the population throughout the territories were restricted. In addition, the Eastern macroregion also includes areas that have been occupied by Russia since 2014. During the war, there was a restriction on economic activity and the movement of residents to other places. According to IOM (2022), over 4 million (Updated: 4 November 2022) refugees (IDPs – internally displaced people[2]) left the Eastern macroregion of Ukraine during the war and remained on the territory of Ukraine. It can be seen that the largest share of IDPs comes from the Eastern macroregion of Ukraine, both in absolute and in relative values (63% of all IDPs).

A significant decrease in NO_2 concentration was also found in the Southern and Central macroregions (Fig. 10), which are directly located on or near the battlefront. On the contrary, the densely populated Western macroregion achieved a low reduction of NO_2 concentrations, while also having the fewest leaving IDPs, both in relative and absolute numbers. A similar situation occurred in the Northern macroregion whose territory was nevertheless directly occupied by Russian troops for the part of 2022.

[2] The term represents IDPs who resettled within the territory of Ukraine. It may not include residents who emigrated abroad as a result of the war.

***Fig. 8:** Average decrease of NO_2 concentration in 14-day periods in selected districts of Ukraine between 24 February and 31 November of the pre-war period and the war period) (Copernicus Sentinel data (ESA, 2022; modified)).*

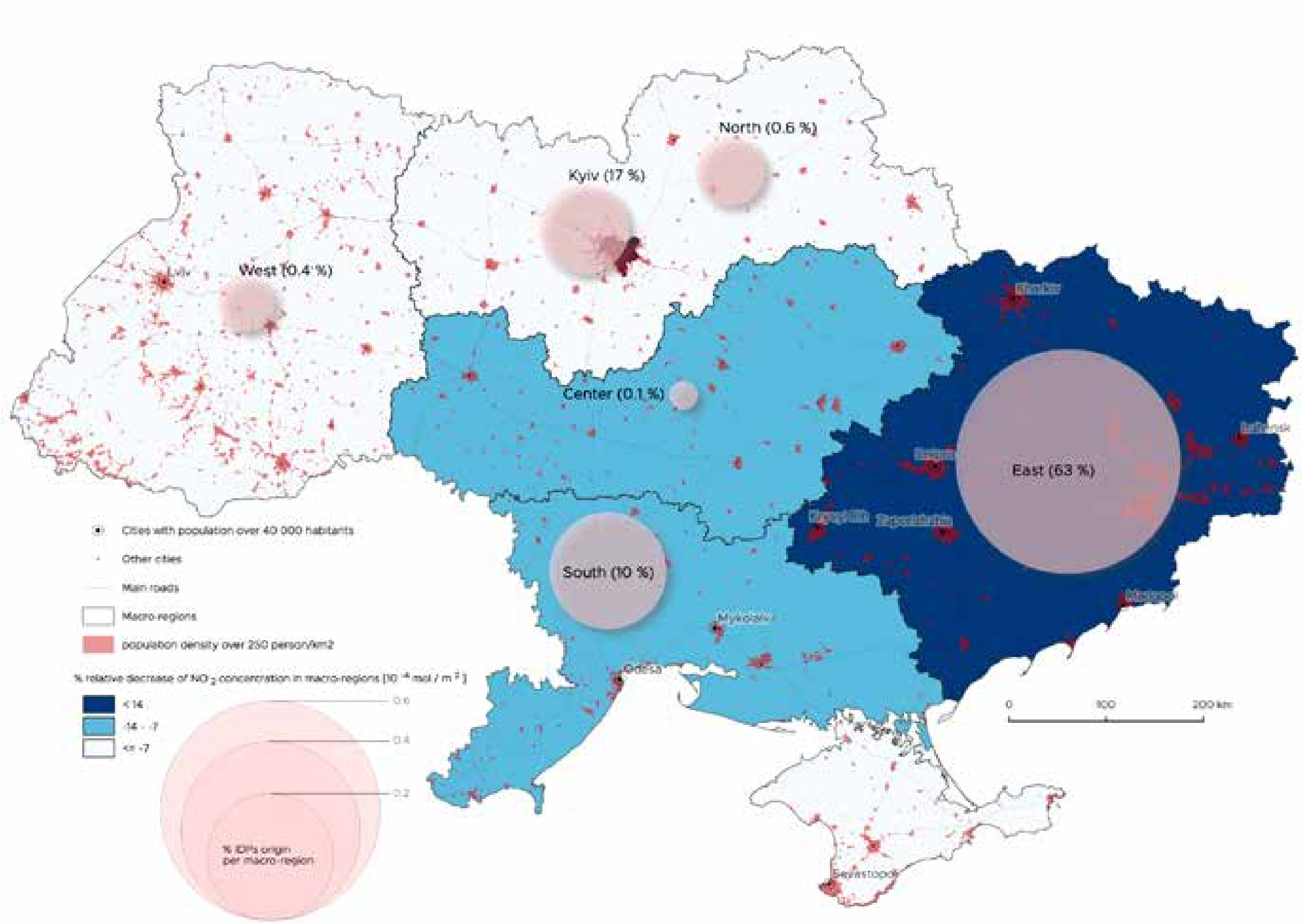

Fig. 9: Comparison of the share of IDPs (by place of origin) coming from individual macroregions and the relative reduction of NO_2 concentration between the pre-war period and the war period calculated per macroregions in Ukraine. The map is supplemented with population density above 250 inhabitants/km^2 (Copernicus Sentinel data (ESA, 2022; modified); OpenStreetMap contributors, 2022; population density (Geo-ref.net, 2022); IDPs (IOM, 2022)).

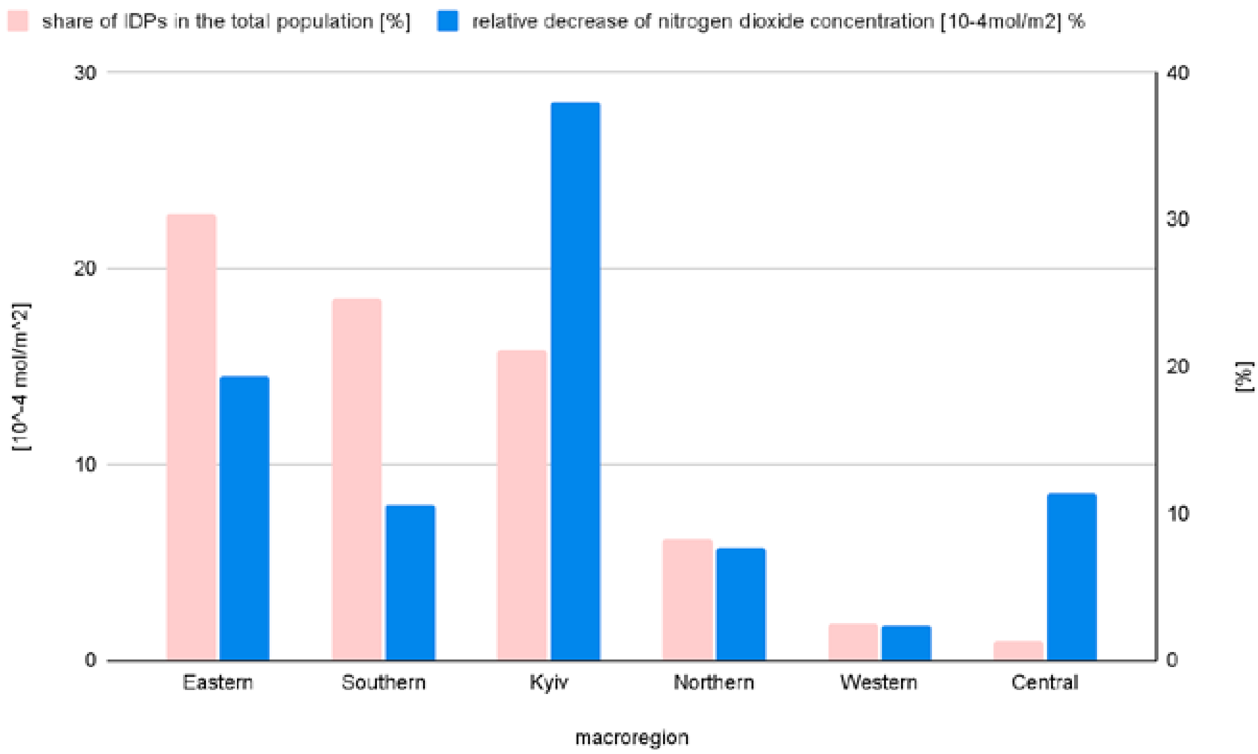

Fig. 10: *Comparison of the share of IDPs in the total population (by place of origin) within macro-regions and the relative reduction of NO_2 concentration between the pre-war period and the war period calculated per macroregions in Ukraine (Copernicus Sentinel data (ESA, 2022; modified); population density (Geo-ref.net, 2022); IDPs (IOM, 2022); aggregated population (HDX, 2022)).*

Recommendations

A green recovery approach can be instrumental in activities to minimize air pollution in Ukraine after the war. By aligning economic recovery efforts with sustainable and environmentally friendly practices, Ukraine can address the post-war challenges and simultaneously promote a cleaner and healthier environment for its inhabitants, thus reduce costs on e. g. healthcare or mitigation of negative impacts of pollution.

Air quality is one of the most important health and environmental factors today and in the future. To improve the quality of life and the environment in Ukraine, coordinated action is necessary on the national, regional, and municipal, industrial, and citizen levels. Moreover, reducing air pollution will directly contribute to fulfilling the UN Sustainable Development goals, as well as the goals of the UNFCCC Paris Agreement on climate change.

Industrial air pollution is one of the environmental priorities in the Association Agreement with the European Union from 2017, which provides for gradual approximation of Ukrainian legislation in accordance with EU environmental rules, policies, and standards, and the development of sector strategies. The following activities are recommended to achieve the proposed objective:

1. Data collection and monitoring

In Ukraine, the long-standing issue behind the lack of comprehensive air quality reporting lies the inefficiency of pollution monitoring by the state authorities. However, new initiatives are emerging, such as the Dnipro Environmental Monitoring Center (https://ecomonitoring.info/) (Pehchevski, 2020) or civic indicative networks such as the EcoCity Public monitoring of air quality (https://www.eco-city.org.ua/).

EcoCity provides affordable monitoring devices, therefore supporting air monitoring projects can be a convenient tool to gain a comprehensive overview of the air pollution status in regions. This helps to prevent exceeding the recommended concentration limits and addresses the responsibility for local air pollution.

It could further provide a valuable basis for building a post-war framework to assure higher standards of air protection. Building an authoritative, preferably certified network besides civic measurements is, nevertheless, still encouraged, as well as continued satellite monitoring.

According to the experience of the EU countries, building a unified system operated by one authority on a national level, which also performs validation of data, seems to be the best option. This system should also be independent of external and political influences. Furthermore, a thorough assessment of the post-war air pollution sources, their impact, and the areas most affected need to be conducted to provide a baseline for planning and implementing further air pollution measures.

On a local scale, ground measurements play a vital role in understanding the sources of pollution and obtaining precise data on pollution levels, particularly in areas with dense populations. Regular utilization of satellite monitoring and data from services like Copernicus Atmosphere Monitoring Service can provide a broader perspective on the overall progress and spatial-temporal changes in pollution distribution.

It is important to complement the process with the use of a Pollution Release and Transfer Register (PRTR). This register should provide a comprehensive summary of pollutant releases from large industrial facilities, allowing for the identification of major pollution sources. The results of air quality monitoring should affect government systems at different levels like state standards of ecological safety, procedures for issuing legal permits for pollutant emissions, or state regulatory policy.

2. Energy efficiency measures

Implementing financial instruments backed by strong energy efficiency rules and obligations based on EU policies in areas such as the renovation of buildings, industries, and transportation sectors can significantly reduce energy consumption and associated emissions.

This includes promoting energy-efficient equipment, retrofitting buildings, and implementing smart transportation solutions, all of which contribute to air pollution reduction. Policy instruments such as audit obligations, technical competence requirements, and implementation of energy management systems need to be used, with a specific focus on efficient district heating and cooling to support clean and decarbonised heat and cooling supply.

3. Emission control measures for industries

It is recommended to implement pollution control technologies, require cleaner production methods, and enforce strict emission standards for industries.

Any financial support and incentives for industries should be tied to the use of the best available techniques (BAT) and the transition to low-carbon processes. Those activities can include grants, subsidies, low-interest loans, and tax incentives for investments in pollution control technologies and sustainable production practices. Establishing green funding programs specifically targeted at reducing industrial emissions and supporting the adoption of clean technologies is recommended to facilitate these activities. Sector-specific roadmaps for emission reduction should outline key steps, milestones, and targets for transitioning. Proper support and technology transfer from international institutions can provide guidance and technical support in the development of these roadmaps and progress monitoring.

Support for research and development initiatives focused on developing innovative solutions for emission reduction in industries will also foster international competition and provide new business opportunities.

4. Emission inventories and plans

Local governments can utilize emission inventories to identify significant sources of air pollutants and guide their actions toward addressing the issue.

Various methods are employed to determine emissions, including continuous monitoring at specific sources, extrapolating short-term measurements to longer periods, and utilizing emission factors. The comprehensive understanding and quantification of local sources of air pollution enable stakeholders to identify key sectors that require rapid and cost-effective mitigation measures. This is particularly crucial for industrial centres and urban areas where emission inventories should precede the planning of targeted interventions.

The development of clean air plans at municipal and regional levels, based on up-to-date inventories, serve as an effective tool for achieving long-term improvements in air quality. These plans should outline specific measures and strategies to be implemented, assuming the local emission sources are identified . Such initiatives involve announcing smog alerts and imposing restrictions on transportation, industrial operations, and public activities.

5. Regulatory frameworks and environmental liability

Enforcement of environmental policies has been a long-term issue for Ukraine and will continue to be so.

To improve the situation, it is recommended to strengthen the capacity of regulatory agencies responsible for environmental protection to effectively enforce air quality standards and regulations.

This requires the allocation of adequate resources, including funding, staffing, and training. Emphasis should be also put on enforcing the legislature, which is bound to advancements against lobbyist pressure and corruption. Regular inspections and audits of industries, power plants, and other pollution sources should be done to verify compliance with environmental regulations. Stringent, but proportional penalties for non-compliance with air quality standards and regulations should raise awareness among industries and the public about the consequences of non-compliance.

6. Renewable energy deployment

The abrupt decline in NO_2 concentrations during the war suggests that industry and especially energy generation remain the major polluting elements in Ukraine.

Coal-fired power plants have recently accounted for providing around 34% of their electricity supply (Pehchevski, 2020). It is thus key to direct the post-war reconstruction of the country towards more sustainable industrial production and energy generation.

The focus must be put on preventing the construction of new coal-fired power plants and the gradual reduction of the share of all kinds of fossil fuels in energy production.

Outdated coal-fired power plants must either be fundamentally modernized or replaced by other resources to help decarbonise the country's economy. To attract business interest in the sector, it is recommended to establish supportive policies, feed-in tariffs, and investment incentives to attract private sector involvement in renewable energy projects.

7. Public awareness and participation

It is recommended to continue raising awareness among the public about the health impacts of air pollution and the importance of individual actions in reducing emissions. To encourage public participation in decision-making processes and involve stakeholders in the development and implementation of air pollution control measures, user-friendly platforms, and tools for accessing and understanding environmental data are crucial.

Ensuring public access to information is crucial, including data from the state air quality monitoring, timely smog warnings, and details regarding the operation of major pollution sources. It is important for the government to actively involve the public in decision-making processes, such as spatial planning, the approval of clean air plans at the municipal and regional levels, as well as conducting Environmental Impact Assessments (EIAs) and permitting procedures for industrial facilities. Public engagement not only has positive effects but also helps overcome potential opposition from the public, political entities, or commercial interests regarding planned pollution reduction measures.

Public awareness campaigns should be implemented to promote positive changes in individual behaviour. These campaigns can encourage actions such as using more sustainable transportation methods, adopting cleaner heating practices in private households, promoting energy conservation, and discouraging the burning of biomass.

By integrating these green recovery activities into post-war reconstruction plans, Ukraine can not only rebuild its economy but also create a sustainable and resilient future with improved air quality and environmental well-being.

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ARNIKA

Arnika is uniting people seeking a better environment. We believe that natural wealth is not only a gift, but also an obligation to save it for the future. Since its foundation, Arnika has become one of the most important environmental organizations in the Czech Republic. We base our activities on three pillars: engaging the public, professional arguments, and communication. Since the beginning, we have led public campaigns both in the Czech Republic and internationally. The organization focuses on nature conservation, toxics and waste, access to information, and public participation in decision-making.
Website: https://arnika.org/

CLEAN AIR FOR UKRAINE
cleanair.org.ua

Clean Air for Ukraine is a joint project of Arnika and an informal network of local nongovernmental organizations from the industrial regions of Ukraine. Our objective is to improve access to information and strengthen public participation in decision-making. A public monitoring network of air pollution, analysis of soil, river sediments, and foodstuffs in five regions, and capacity building programmes for civil society are some of our main achievements. We bring the experience of transformation of the Czech Republic, involve scientists and experts in public campaigns, publish analyses, and suggest solutions.
Website: https://cleanair.org.ua/

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www.worldfrom.space

You can download the study:

More information: www.cleanair.org.ua

EcoCity air quality monitoring station (Arnika archive).

Mobile monitoring station of the Environmental Monitoring Centre, Dnipro (EMC archive).