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Integrating research in ecological and climate change educational process: assessment of atmospheric pollution over Ukraine due to military actions

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Abstract. Since the beginning of the aggression of the Russian Federation in Ukraine, education in many Ukrainian universities has been suspended due to security reasons for a certain period. But the war affected not only the forms of education, but also the content: military issues are increasingly reflected in educational courses and research projects. This applies directly to the bachelor's and master's training program in the field of Ecology of the National University of Kyiv–Mohyla Academy. Therefore, the practice of integrating new methodological approaches into educational courses related to the assessment of the impact of hostilities on the natural environment, the assessment of ecological damage, and the restoration of disturbed natural systems has become widespread. Students are also involved in conducting research as part of their bachelor's and master's theses. In this work, we present the results of the assessment of the impact of hostilities on atmospheric air, which was carried out as part of teaching the courses "Meteorology and Climatology", "Geoinformation Systems", "Environmental Monitoring" and others.

Faculty researchers and students extensively analyzed the profound direct and indirect environmental effects of the war in Ukraine. These effects can be attributed to changes in the optical characteristics of the atmosphere, atmospheric pollution caused by the emission of missile and shell detonation products, and the increasing release of greenhouse gases and gas-aerosol impurities. Satellite data were used for this purpose.

Satellite observation of atmospheric concentrations of formaldehyde, aerosol, carbon monoxide, nitrogen oxide, and sulphur dioxide from the Sentinel–5P satellite was an important research method integrated into the educational process. Daily satellite observation data were analyzed using the Google Earth Engine platform for the period 2019–2022. Data were monthly and yearly averaged within the boundaries of rayons (second–level administrative units of Ukraine). It helped to register the dynamic of air pollution in the conditions of war. A full–scale war in Ukraine caused the suspension of many enterprises that were the main sources of gas emissions into the atmosphere, especially in the eastern and southern parts of Ukraine. Therefore, in recent months, the content of pollutants in the atmosphere over these regions is mainly tent to background values and as a result of hostilities. However, massive shelling, the use of military heavy equipment, and fires caused additional emissions of a number of pollutants into the atmosphere. It should be noted that in certain regions and certain months during the active phase of hostilities, these emissions were exceeded by several times compared to the average for the period 2019–2021.

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Introduction

The consequences of Russia's military invasion of the territory of Ukraine are the death of the Ukrainian population (*genocide*, the intentional destruction of a people in whole or in part (UN: Office on Genocide, 2023)), the destruction of energy and other infrastructure (*urbicide*, violence against the city and infrastructure (Al–Shoubaki, 2022; Berman, 1996)) and the predatory actions of the invaders to natural resources (*ecocide*, the severe destruction of the natural environment, the home of humanity (Broswimmer, 2002; de Pompignan, 2007).

Military actions in Ukraine cause extensive direct and indirect impacts and effects for the environment, including (Averin, D., et al., 2022; de Klerk L. et al., 2023; Hrynevych, et al., 2023; IPCC, 2013; Kemme, et al., 2001; Mezentsev, 2023, Morelli et al., 2016; Seinfeld and Pandis, 2016; Terebukh, et al., 2023):

- meteorological effects (changes in the optical characteristics of the atmosphere, atmospheric pollution as a result of the emission of products of detonation of missiles and shells),
- weather effects (increase in cloud cover and the amount of atmospheric precipitation, intensification of thunderstorms, acidification of atmospheric precipitation and “black rains”),
- climatic effects (emission of greenhouse gases and gas–aerosol impurities),
- impact on the soil cover (disruption of the soil cover, intensification of erosion, deflation and dehumidification, soil pollution with heavy metals, soil acidification, waterlogging),
- natural and agro–ecosystems disturbances (fires and damage to landscapes and protected areas),
- impact on water ecosystems (pollution and acidification of natural water bodies),
- intensification of a few geophysical and geological processes (landslides and land subsidence).

The invasion of Ukraine has caused significant disruptions and challenges for the population. The forced displacement of people from their homes and the country has resulted in the loss of familiar surroundings, separation from family and society, and the need to adapt to new conditions and circumstances. Additionally, the conflict and its consequences have disrupted critical infrastructure and communications, including the internet. This has profound implications for access to information, education, scientific research, and economic activities. For a certain period since the beginning of the Russia aggression in Ukraine, education in many Ukrainian universities has been suspended due to security reasons. However, distance education was restored as early as May 2022. The war affected not only the forms of education, but also the content: military issues are increasingly reflected in educational courses and research projects. This applies directly to the bachelor's and master's training programs in the field of Ecology at the National University of Kyiv–Mohyla Academy. The form of education was both distance and partly hybrid. Distance and hybrid learning can provide flexibility in terms of when and where learning takes place (Marcinkowski, 2009; Jensen, and Schnack, 2006). Flexibility in education accommodates diverse schedules and personal circumstances, enabling learners to effectively balance their education with other commitments. This adaptability is particularly beneficial for individuals who have various responsibilities, such as work, family, or personal obligations, making it easier to manage their time effectively and eliminating the need for physical attendance at a specific location. The pandemic

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and war in the country did result in experiences and insights into the opportunities, benefits and strengths of approaches in hybrid teaching similar to (Rodríguez, et al., 2022; Goodyear, 2020). Interaction and collaboration take place through video conference tools, discussion boards, or messaging platforms. The distance learning heavily relies on technology, including reliable internet access, computers or devices, and software platforms. In some regions or for certain students, limited access to technology or reliable internet connections can pose challenges and hinder effective participation in online activities.

Discussions among colleagues focused on the specifics of working in groups using digital technologies. We have a small number of students at the Department from 10 to 15. However, we have begun to apply this technique with great success. Note, group work promotes deeper understanding of the subject matter through collective brainstorming, constructive feedback, and the synthesis of ideas. It also enhances communication, teamwork, and leadership abilities, which are valuable skills in educational and professional settings (de Prada, et al., 2022).

The purpose of this paper was to combine research and educational process in order to understand and outline the range of processes that have or may have in future a significant impact on the environment of Ukraine as a result of the military actions and to involve teachers and students of the Environmental Studies Department in this process, using modern approaches in education and research projects. Geographical area of the research included territories effected by hostilities in eastern and south–eastern regions of Ukraine.

Materials and Methods

The following methods were employed in conducting the research: data collection methods, analysis and comparison methods, as well as the systematization of information from literary sources and internet resources. The objective of the literature review was to evaluate the challenges and opportunities concerning education for climate change and ecological studies in Ukraine. Satellite data and cloud tools for processing satellite data were used for this purpose. Satellite observations of atmospheric concentrations of formaldehyde, Absorbing aerosol index, carbon monoxide, nitrogen oxide and sulfur dioxide from Sentinel–5P satellite were analyzed using the Google Earth Engine platform openly available for use in education process (Earth Engine Data Catalog, 2023). Daily satellite observation data (Table 1) were monthly and yearly averaged within the boundaries of rayons (second–level administrative units of Ukraine) for the period 2019–2022. Maps of produced from ESA remote sensing data using (Gorelick, et al., 2017).

Table 1. Information about the resources used.

Gases	Period	Source
Nitrogen dioxide (NO_2)	2019–2022	https://developers.google.com/earth–engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_NO2
Sulphur dioxide (SO_2)	2019–2021 (February–November), 2022 (February–October)	https://developers.google.com/earth–engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_SO2
Carbon monoxide (CO)	2019–2022	https://developers.google.com/earth–engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_CO
Formaldehyde (HCHO)	2019–2022	https://developers.google.com/earth–engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_HCHO
Absorbing aerosol index (AAI)	2019–2022	https://developers.google.com/earth–engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_AER_AI

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1. Integrating research in educational process.

The impact of military actions on the environment, particularly the atmosphere is presently a significant focus of ecological education in Ukraine. The practice of integrating new methodological approaches, reorienting teaching, and adapting the educational process within the Ecology program to the conditions of war has become increasingly common. Therefore, the practice of integrating new methodological approaches into educational courses related to the assessment of the impact of hostilities on the natural environment and climate change, the assessment of ecological damage, and the restoration of disturbed natural systems has become widespread (Marcinkowski, 2009, Jensen and Schnack, 2006; Averin, et al., 2022; Anderson, 2012; Berkhout, et al., 2006, Boychenko, et al., 2023; Karamushka, et al., 2023, Sauve, 2005).

These initiatives are aimed at addressing the specific challenges posed by war and its impact on the environment and climate. The knowledge acquired through attending specialized courses such as " Meteorology and Climatology", "Applied Climatology", "Adaptation to Climate Change", "Geoinformation Systems", "Environmental Monitoring", "Environmental Planning" and "Environmental Management" holds great relevance in this specific context (see Figure 1).

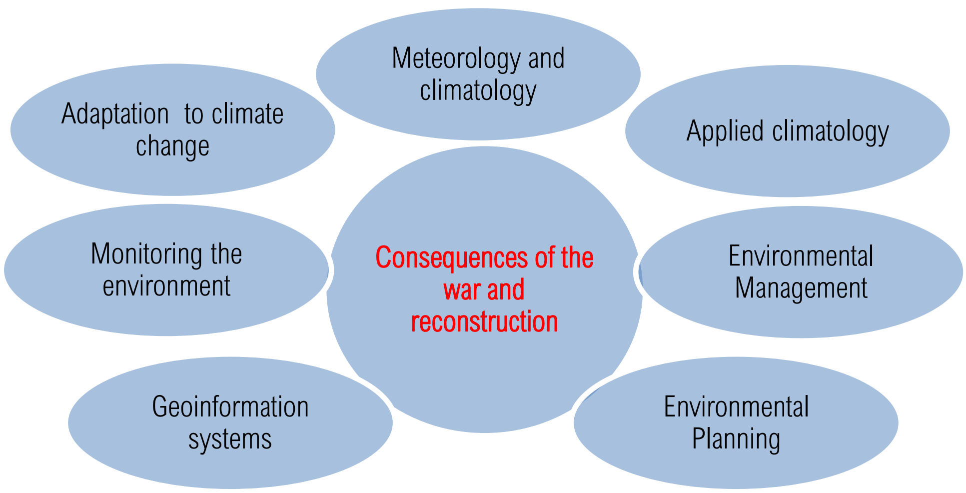

Figure 1. The circle of disciplines that are taught at the Department of Environmental Studies that are used in the direction of research on the consequences of the war and reconstruction.

The block of disciplines "Meteorology and Climatology", "Applied Climatology", "Adaptation to Climate Change". climate change competence refers to the knowledge, skills, and abilities needed to understand the impacts of climate change and implement effective adaptation strategies (Bush, et al., 2019; UNESCO, 2010). It involves understanding the changing climate patterns, assessing vulnerabilities, monitoring, education, and developing and implementing measures to minimize risks and enhance resilience in various sectors and communities (Anderson, 2012; Fuertes, et al., 2020). For example, the utilization of semi–empirical modeling techniques developed for the restoration of hydrometeorological parameter fields (Boychenko and Maidanovych, 2023), as part of the “Applied Climatology” course, is highly relevant in such circumstances.

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The *discipline "Adaptation to Climate Change"* provides consideration of approaches, environmental aspects and management of various systems and objects taking into account environmental requirements and priorities. Education in the field of climate change and adaptation requires a focus on a type of learning that promotes critical and creative thinking, as well as the development of potential that enables students to interact with information, acquire knowledge, ask critical questions, and take appropriate actions in response to climate change and its consequences. Climate education should not be limited to traditional curricula but should rely on new hybrid spaces that offer alternative learning opportunities, including international and national programs, educational, research, and innovative projects.

In particular, in situations where the environmental monitoring system is disrupted or destroyed, satellite information becomes a valuable means of monitoring the state of the environment (Kim, et al., 2020; Park, et al., 2023; Veefkind, et al., 2012). This aspect is addressed within t*he block of disciplines «Monitoring the Environment" and "Geoinformation Systems".* By studying these disciplines, students are exposed to the potential applications of geo-information technologies in environmental research. They gain knowledge of fundamental concepts such as *spatial analysis, modeling, and the utilization of contemporary methods to acquire up-to-date environmental information through earth observation*. Additionally, they develop a comprehensive understanding of the general principles behind GIS functionality, as well as the ability to process geodata and present it in cartographic or 'storytelling' form. This holistic approach cultivates systemic *spatial thinking* and equips students with skills applicable to various professional domains including natural resource management, cartography, energy conservation, urban planning, big data processing, and more. Based on the air pollution case study, students learned to analyze large-scale big data on direct and indirect war impacts, namely due to changes in the optical characteristics of the atmosphere, atmospheric pollution as a result of the emission of products of detonation of missiles and shells and increasing emission of greenhouse gases and gas–aerosol impurities over Ukraine. Satellite data (Earth Engine Data Catalog, 2023) and GIS software (QGIS) were used for this purpose.

The block of disciplines "Environmental Planning" and "Environmental Management". The formation of students' skills in making informed decisions when preventing the occurrence or when solving environmental problems is an important element of the process of training specialists in the field of ecology (Jensen and Schnack, 2006; Karamushka, et al., 2023; Marcinkowski, 2009). Such decisions can only be made after a detailed analysis of the situation. In the case of a disturbed or destroyed environment, an assessment of the state of land, water bodies, biological diversity and ecosystems as a whole is an important and necessary initial step. Such assessments are also necessary when developing infrastructural and other production projects. Based on the results of such assessments, students identify and analyze alternative approaches to decision–making. The choice of the optimal solution makes it possible to carry out the next step – to develop a program for restoring the disturbed environment or a program of measures that minimize the negative impact on the environment of the planned activity. The cases used for these exercises are real and reflect the destructive impact of military operations on natural territories and objects. The teaching of such disciplines as "Environmental Planning" and "Environmental Management" is built on this foundation.

The Project development and implementation is an instructional approach that originated in vocational education and has since that has gained international development and recognition across various educational contexts. Currently it is one of the

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teaching methods that is often used in environmental, medical and technical universities. (Knoll, 1997; Howell and Mordini, 2003). Research projects are an important technique in modern environmental and climate change education, as they enable students to engage in research activities focused on identifying mitigations and adaptation of climate change significant environmental issues and developing solutions for them. The advantages of the project method include: *active student engagement* (they become active participants in the educational process, leading to a deeper understanding of the material), *development of key skills* (working on projects promotes the development of communication, collaboration, problem–solving, critical thinking, and self–organization skills), *application of knowledge in practice* (students apply the knowledge and skills they have acquired to solve real or hypothetical problems, which helps them see the practical value of their education), *motivation and interest* (working on projects can be more motivating and interesting for students as they have the opportunity to choose topics that interest them the most). This type of student involvement facilitates the acquisition of fundamental skills in conducting individual or group research.

Additionally, it plays a crucial role in equipping individuals with practical skills to effectively manage and cope with stress (WHO, 2021; Sinatra, 2022).

However, it is important to consider that the project method requires good technical organization and support from the teachers. Clear goals, tasks, and expected outcomes of the project should be defined, and students should be provided with resources and guidance for successful project completion. Projects can vary in nature and scale, ranging from small group assignments to large interdisciplinary projects, an example of such an application is presented below.

The methodical approaches described above for teaching courses related to the field of Environmental Sciences, Policy and Management were used primarily for the training the research skills and gaining experience in the planning and conducting scientific research. The object of these research was, in particular, the impact on the atmospheric air of hostilities and missile attacks on the territory of Ukraine. Some of the results of such studies as a component of the educational process are presented and discussed below.

2. Assessment of gas aerosol atmospheric pollution over the southern and south–eastern regions of Ukraine due to military actions

Researchers and students of the Department were analyzed powerful direct and indirect effects, namely due to changes in the optical characteristics of the atmosphere, atmospheric pollution as a result of the emission of products of detonation of missiles and shells and increasing emission of greenhouse gases and gas–aerosol impurities. Note, the system of ecological, hydrometeorological and geophysical monitoring has been suspended or destroyed in more than 1/3 of the area of Ukraine.

2.1. Nitrogen dioxide (NO_2) is one of the main air pollutants (Hazardous Substances Data Bank, 2005; Lange, et al., 2023; Martin, et al., 2003; Park, et al., 2023). It is formed through the conversion of nitrogen monoxide (NO) in the presence of organic volatile compounds. The primary sources of NO emissions are vehicle traffic, industrial activities, power plants, and heating processes. Vehicle traffic is a significant contributor to NO emissions, especially in urban areas where the density of

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vehicles is high. The combustion of fossil fuels in vehicles releases nitrogen oxide gases into the atmosphere. Additionally, industrial activities, such as manufacturing processes and chemical production, as well as power plants and heating systems, contribute to NO emissions. NO_2 is an important precursor to the formation of secondary pollutants. When NO_2 reacts with other pollutants and sunlight, it can lead to the production of peroxyacyl nitrates (PANs), nitric acid (HNO_3), and ozone (O_3). These secondary pollutants contribute to the formation of smog, acid rain, and the greenhouse effect. Nitrogen dioxide and its associated pollutants can react with volatile organic compounds (VOCs) in the presence of sunlight, resulting in the formation of ground–level ozone, a major component of smog. Acid rain occurs when nitric acid (HNO_3), formed from the reaction of NO_2 with other pollutants, is deposited onto the Earth's surface through precipitation. Acid rain can have harmful effects on ecosystems, including the acidification of soil and water bodies, which can negatively impact plant, animal and human life (Morelli, et al., 2016; WHO, 2005; WHO, 2010). N_2O and other greenhouse gases contribute to the greenhouse effect, which leads to global warming and climate change (Seinfeld and Pandis, 2016).

The analyses of the imagery extracted from Sentinel–5P for the period 2019–2021, reveal that the 3–year average NO_2 column number density over the territory of Ukraine was $7.7 \pm 0.7 \times 10^5$ mol./m^2 (Figure 2) the seasonal course of the NO_2, the seasonal course of the NO_2 is also observed.

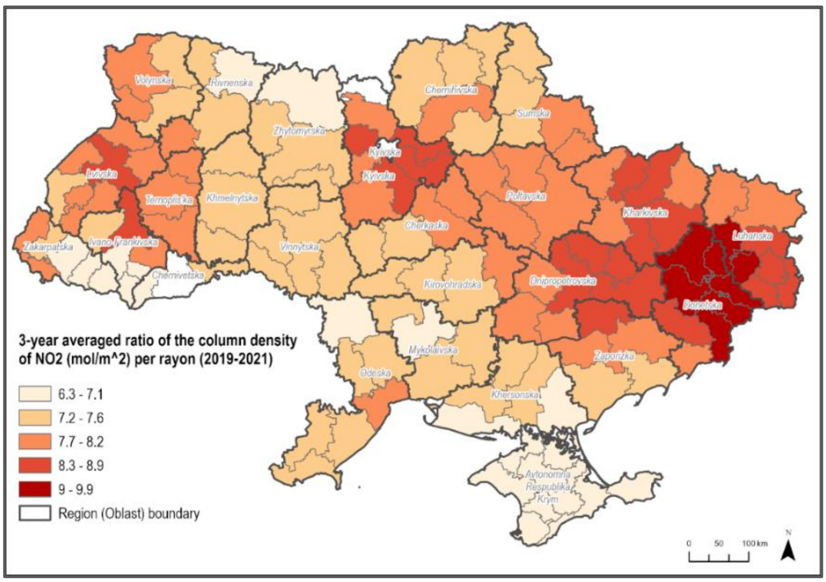

Figure 2. The 3–year averaged ratio of the column density of NO_2 over Ukraine for the period 2019–2021. Produced from ESA remote sensing data using (Gorelick, et al., 2017).

Since the beginning of the Russian invasion of Ukraine, the content of the NO_2 dropped sharply due to the shutdown of the industry (in February 2022), however, there is a sharp increase in its content in some regions in the active shelling and movement of military equipment in March (active phases of the war) Figure 3 (a, b). At the same time, in November and

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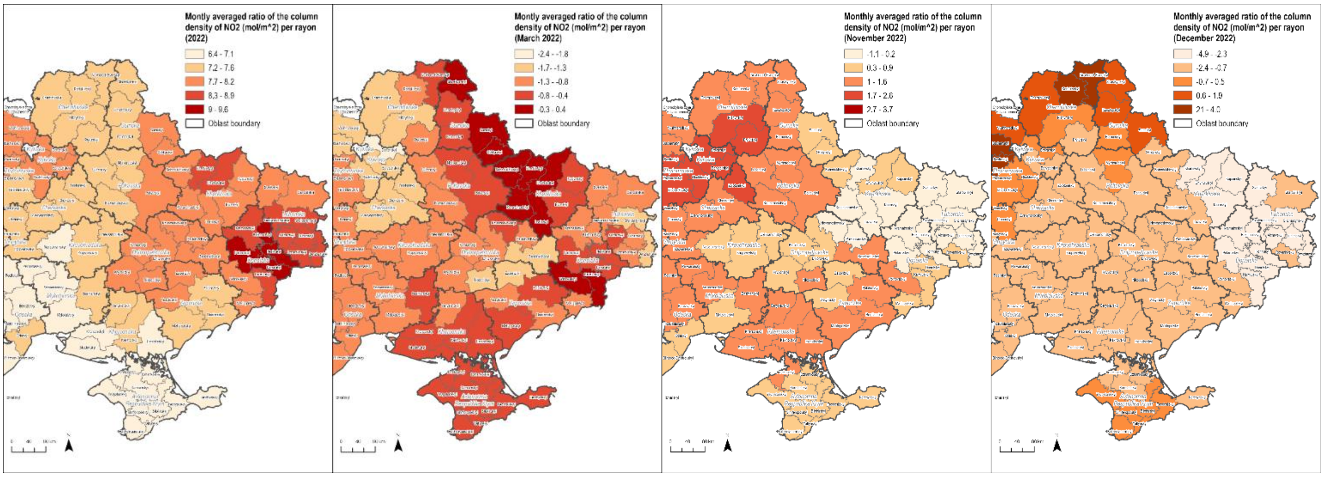
December, there is a decrease in concentration, including, as a result of a blackout Figure 3 (c, d). So, average annual value of the column density of NO_2 over the territory of Ukraine for the 2022 was $7.6 \pm 0.6 \times 10^5$ mol./m^2.



(a) (b) (c) (d)

Figure 3. Average annual value of the column density of NO_2 over Ukraine for the 2022 (a) and anomalies of the monthly average ratio of the column density of NO_2 over the territory of Ukraine in 2022 from the monthly average value for the period 2019–2021 in March (b), November (c) and December (d). Produced from ESA remote sensing data using (Gorelick, et al., 2017).

2.1. Sulphur dioxide (SO_2) is a compound that enters the Earth's atmosphere through both natural and anthropogenic processes (Hedelt, et al., 2019; Li, et al., 2021; Theys, et al., 2017). It has a significant impact on atmospheric chemistry at both local and global scales, with effects ranging from short–term pollution to long–term climate implications. Natural sources of SO_2 include volcanic eruptions, forest fires, and certain biological processes. Volcanic eruptions are a major natural source of SO_2, releasing large amounts of the gas into the atmosphere along with other volcanic gases (Fioletov, et al., 2023). Forest fires also produce SO_2 as a byproduct of the combustion of organic matter. Some biological processes, such as the metabolism of sulfur–containing compounds by certain bacteria and marine organisms, can also contribute to the release of SO_2. While approximately 30% of emitted SO_2 comes from natural sources, the majority of it is of anthropogenic origin. The largest contributors to SO_2 emissions are fossil fuel combustion activities in power plants and various industrial facilities. Power plants and industrial facilities that rely on fossil fuels for energy production are particularly significant sources of SO_2 emissions. Anthropogenic SO_2 emissions have been a significant environmental concern due to their detrimental effects on air quality and human health (WHO, 2005; WHO, 2010). Sulphur dioxide is a primary contributor to the formation of acid rain. On a global scale, SO_2 can impact climate by influencing the Earth's radiation balance. When SO_2 is released into the atmosphere, it can form sulphate aerosols through atmospheric reactions in-situ. These aerosols can scatter and absorb solar radiation, leading to a cooling effect on the climate (Seinfeld and Pandis, et al., 2016).

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The analyses of the imagery extracted from Sentinel–5P for the period 2019–2021 (February–November), reveal that 3–year average of the SO_2 column number density over Ukraine was 36.4±4.3 $\times 10^5$ mol/m^2, the seasonal course of the SO_2 is also observed. The 3–year averaged ratio of the column density of SO_2 over Ukraine for the period 2019–2021 is shown in the Figure 4.

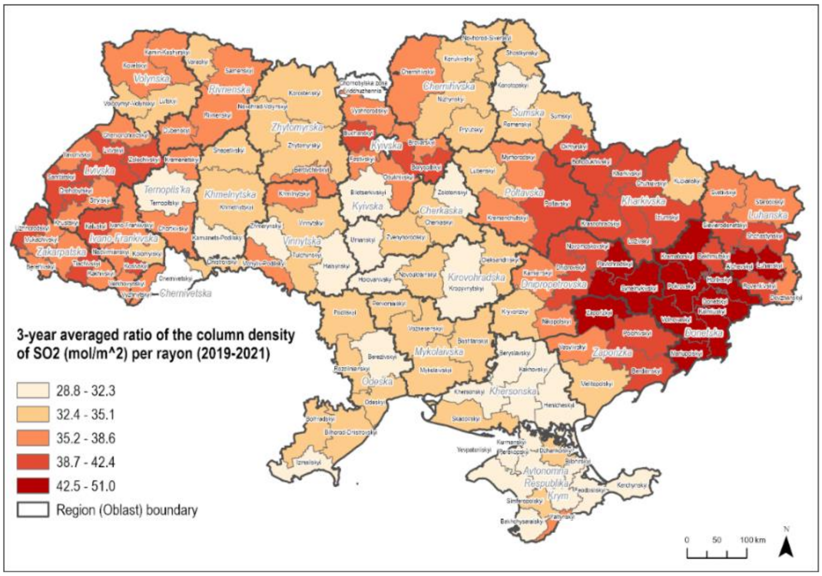

Figure 4. The 3–year ratio of the column density of averaged SO_2 over Ukraine for the period 2019–2021. Produced from ESA remote sensing data using (Gorelick, et al., 2017).

The SO_2 content has also dropped sharply due to the shutdown of the industry (in February 2022), however, there is a sharp increase in its content in some regions in the active shelling and movement of military equipment in March, May and October 2022. So, average annual value of the column density of SO_2 over Ukraine for the 2022 (February–October) was 36.8±4.3$\times 10^5$ mol./m^2. Average annual value of the column density of SO_2 over Ukraine for the 2022 is shown in Figure 5 (a). and anomalies of the monthly average ratios of the column density of SO_2 over Ukraine in 2022 from the monthly average value for the period 2019–2021 are shown in Figure 5 (March (b), May (c) and October (d)).

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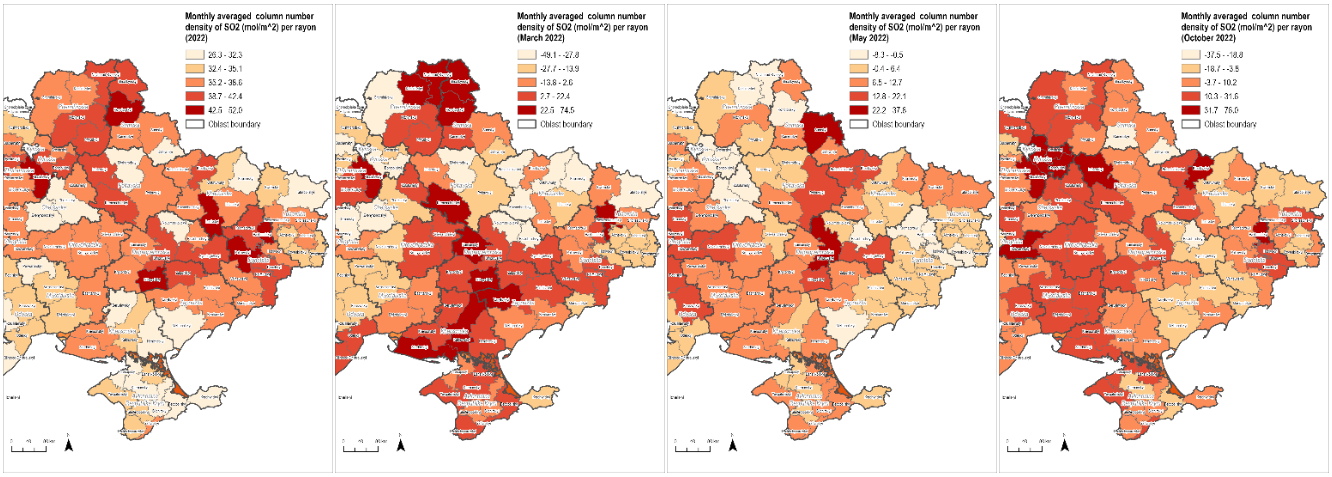

(a) (b) (c) (d)

Figure 5. Average annual value of the column density of SO_2 over Ukraine for the 2022 (a) and anomalies of the monthly average ratio of the column density of SO_2 over Ukraine in 2022 from the monthly average value for the period 2019–2021 in March (b), May (c) and October (d). Produced from ESA remote sensing data using (Gorelick, et al., 2017).

2.2. Carbon monoxide (CO) is an important atmospheric trace gas for our understanding of tropospheric chemistry. It is considered a pollutant in urban areas due to its adverse effects when present in high concentrations (Borsdorff, et al., 2023; Morelli, et al., 2016; Seinfeld and Pandis, 2016). The main sources of CO in the atmosphere include: the combustion of fossil fuels (the burning of coal, oil, and natural gas in vehicles, power plants, industrial processes, and residential heating releases carbon monoxide into the air. In urban areas, vehicle emissions are often a major contributor to elevated CO levels); biomass burning (the burning of biomass, such as forests, agricultural waste, and wood–burning stoves, can release significant amounts of carbon monoxide. This source is particularly relevant in regions where biomass burning is common, such as certain rural areas or during forest fires); atmospheric oxidation (methane and other hydrocarbons present in the atmosphere undergo atmospheric oxidation processes, leading to the formation of carbon monoxide as a byproduct. These reactions contribute to the overall CO levels in the atmosphere).

The analyses of the imagery extracted from Sentinel–5P for period 2019–2021, reveal that 3–year averaged of the content of the CO vertical column density was $3.4\pm0.1\times10^2$ mol/m^2, the seasonal course of the CO is also observed. The 3–year averaged ratio of the column density of CO over Ukraine for the period 2019–2021 is shown in the Figure 6.

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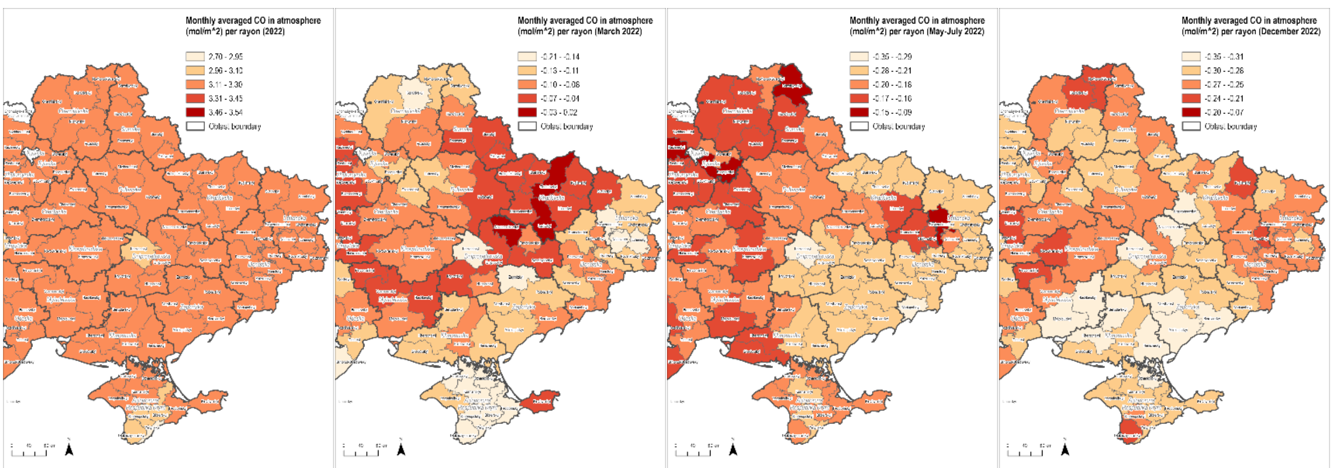
Figure 6. The 3–year ratio of the column density of averaged CO over Ukraine for the period 2019–2021. Produced from ESA remote sensing data using (Gorelick, et al., 2017).

The content of the CO has also dropped sharply due to the shutdown of the industry (in February 2022), however, there is a sharp increase in its content in the active shelling areas in March, May–July and December 2022. So, average annual value of the column density of CO over Ukraine for the 2022 was $3.1\pm0.1\times10^5$ mol./m^2. Average annual value of the column density of CO over Ukraine for the 2022 is shown in Figure 7 (a) and anomalies of the monthly average ratios of the column density of CO over Ukraine in 2022 from the monthly average value for the period 2019–2021 are shown in Figure 7 (March (b), May–July (c) and December (d)).



(a) (b) (c) (d)

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Figure 7. Average annual value of the column density of CO over Ukraine for the 2022 (a) and anomalies of the monthly average ratio of the column density of CO over Ukraine in 2022 from the monthly average value for the period 2019–2021 in March (b), May–July (c), December (d). Produced from ESA remote sensing data using (Gorelick, et al., 2017).

2.3. Formaldehyde is formed as an intermediate product in the oxidation process of NMVOCs. As NMVOCs undergo atmospheric reactions, they are oxidized, leading to the production of formaldehyde before eventually being converted to carbon dioxide (Johansson, et al., 2014; Morelli, et al., 2016; Seinfeld and Pandis, et al., 2016). This oxidation chain involving formaldehyde is a significant pathway for the removal of NMVOCs from the atmosphere. The primary source of formaldehyde in the remote atmosphere is the oxidation of methane (CH_4). Methane, a potent greenhouse gas, reacts with hydroxyl radicals (OH) in the atmosphere, producing formaldehyde as an intermediate product (Spivakovsky, et al., 2000). Over continents, the oxidation of higher NMVOCs emitted from various sources such as vegetation, fires, traffic, and industrial activities leads to significant localized enhancements of formaldehyde levels. These emissions from different anthropogenic and natural sources contribute to the overall formaldehyde levels in the atmosphere. The distribution of formaldehyde exhibits seasonal and inter–annual variations primarily influenced by temperature changes and fire events. Temperature affects the rate of atmospheric reactions, including the oxidation of NMVOCs, which in turn impacts the production and concentration of formaldehyde. Fire events can release substantial amounts of NMVOCs, leading to localized increases in formaldehyde levels.

The analyses of the imagery extracted from Sentinel–5P for the period 2019–2021, reveal that 3–year averaged of the Formaldehyde column number density was $8.6 \pm 0.6 \times 10^5$ mol./m^2, the seasonal course of the formaldehyde is also observed. The 3–year averaged ratio of the column density of Formaldehyde over Ukraine for the period 2019–2021 is shown in the Figure 8.

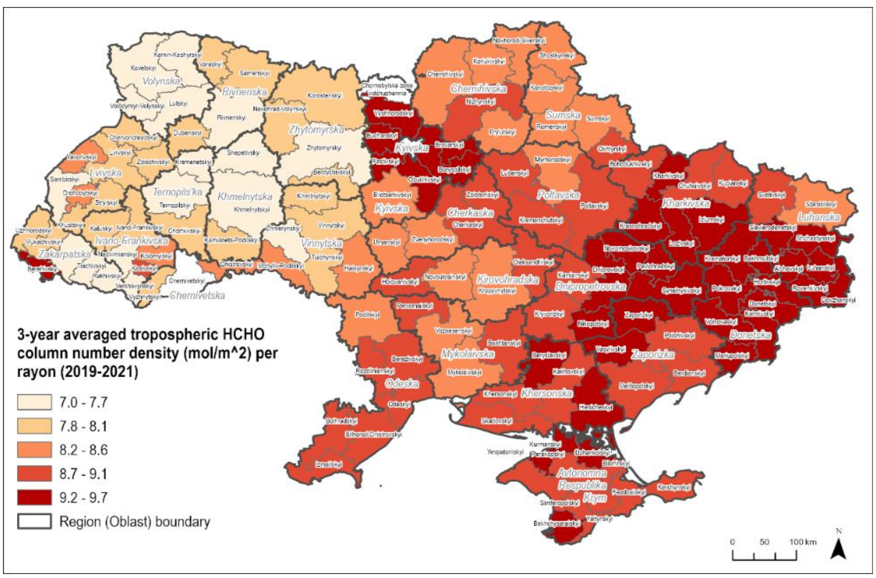

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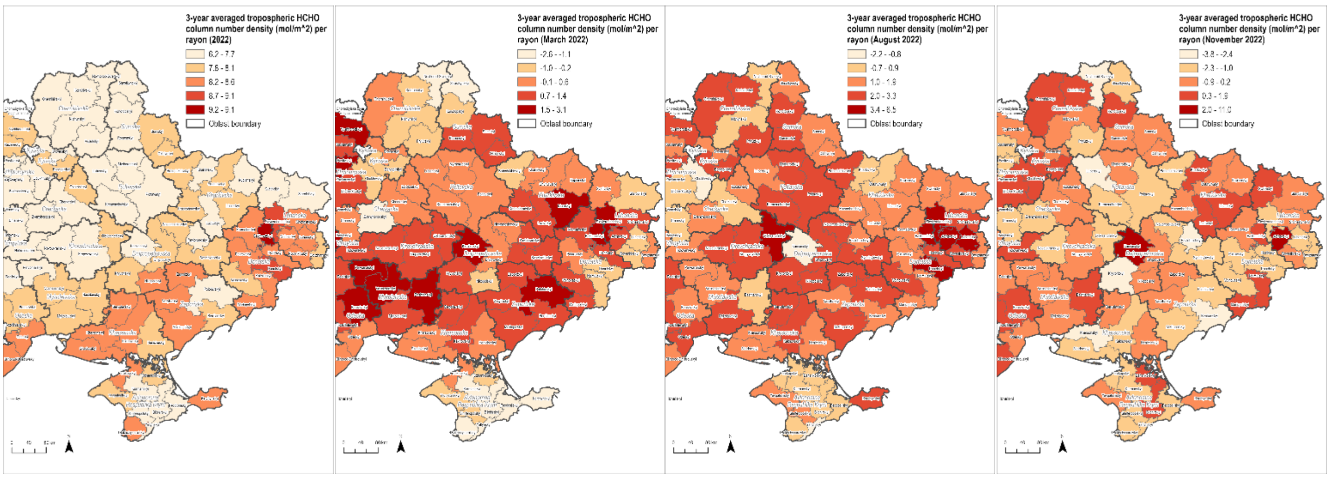
Figure 8. The 3–year ratio of the column density of averaged of the Formaldehyde over Ukraine for period 2019–2021. Produced from ESA remote sensing data using (Gorelick, et al., 2017).

Average annual value of the column density of Formaldehyde over Ukraine for the 2022 is shown in Figure 9 (a) and anomalies of the monthly average ratios of the column density of Formaldehyde over Ukraine in 2022 from the monthly average value for the period 2019–2021 are shown in Figure 9 (March (b), August (c) and December (d)).



(a) (b) (c) (d)

Figure 9. Average annual value of the column density of Formaldehyde over Ukraine for the 2022 (a) and anomalies of the monthly average ratio of the column density of Formaldehyde over Ukraine in 2022 from the monthly average value for the period 2019–2021 in March (b), August (c) and November (d). Produced from ESA remote sensing data using (Gorelick, et al., 2017).

2.5. Absorbing Aerosol Index (AAI), also known as the UV Aerosol Index (UVAI) is a measurement derived from satellite observations that provides information about the presence and intensity of UV–absorbing aerosols in the atmosphere (Bellouin, et al., 2005; Park, et al., 2023, Seinfeld and Pandis, et al., 2016). It is particularly useful for tracking the evolution of episodic aerosol plumes resulting from events such as dust outbreaks, volcanic ash emissions, and biomass burning. The AAI is based on the comparison of observed and modelled reflectance at specific wavelengths in the UV spectral range. The principle behind the index is that UV–absorbing aerosols, such as mineral dust and smoke particles, cause a reduction in UV radiation reaching the satellite sensor compared to clear–sky conditions. This reduction is due to the absorption of UV radiation by the aerosol particles. By analyzing the differences in UV reflectance at specific wavelengths, the AAI can be calculated. When the index has positive values, it indicates the presence of UV–absorbing aerosols in the atmosphere. Higher positive values generally correspond to higher aerosol loading or stronger UV absorption. Conversely, negative values indicate the absence or minimal presence of UV–absorbing aerosols. One of the advantages of the AAI is its ability to provide global coverage on a daily basis. Unlike other aerosol measurements that rely on the visible or near–infrared spectral range, the AAI utilizes UV wavelengths

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that are minimally affected by ozone absorption. Therefore, it can be calculated even in the presence of clouds, allowing for continuous monitoring of aerosol events.

The analyses of the imagery extracted from Sentinel–5P for period 2019–2021, reveal that 3–year averaged of the Absorbing aerosol index over Ukraine was –1.07±0.05, the seasonal course of the aerosol is also observed 3–year averaged of the AAI over Ukraine for period 2019–2021. The 3–year averaged ratio of the column density of Absorbing Aerosol Index over Ukraine for the period 2019–2021 is shown in the Figure 10.

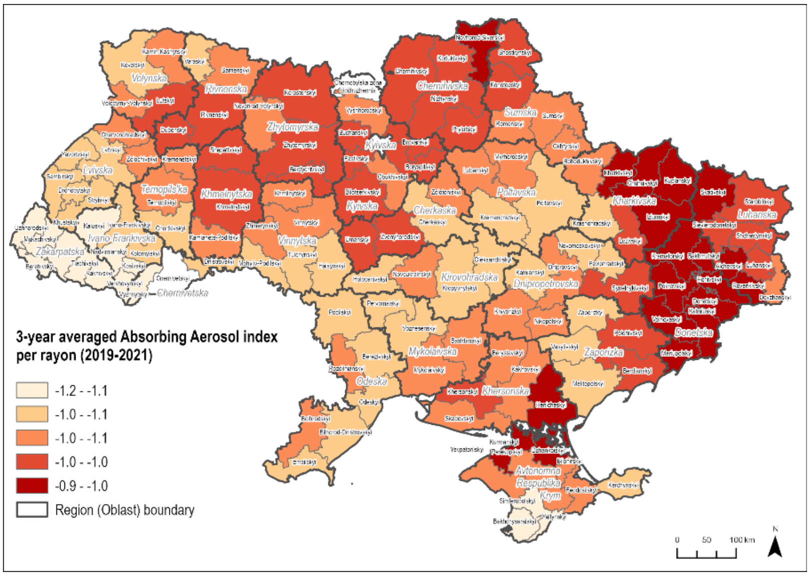

Figure 10. The 3–year averaged of Absorbing aerosol index (AAI) over Ukraine for period 2019–2021. Produced from ESA remote sensing data using (Gorelick, et al., 2017).

The AAI dropped sharply due to the shutdown of the industry (in February 2022), however, there is a sharp increase in its content in the active shelling areas in July 2022. So, average annual value of the column density of AAI over Ukraine for the 2022 was –0.34±0.06.

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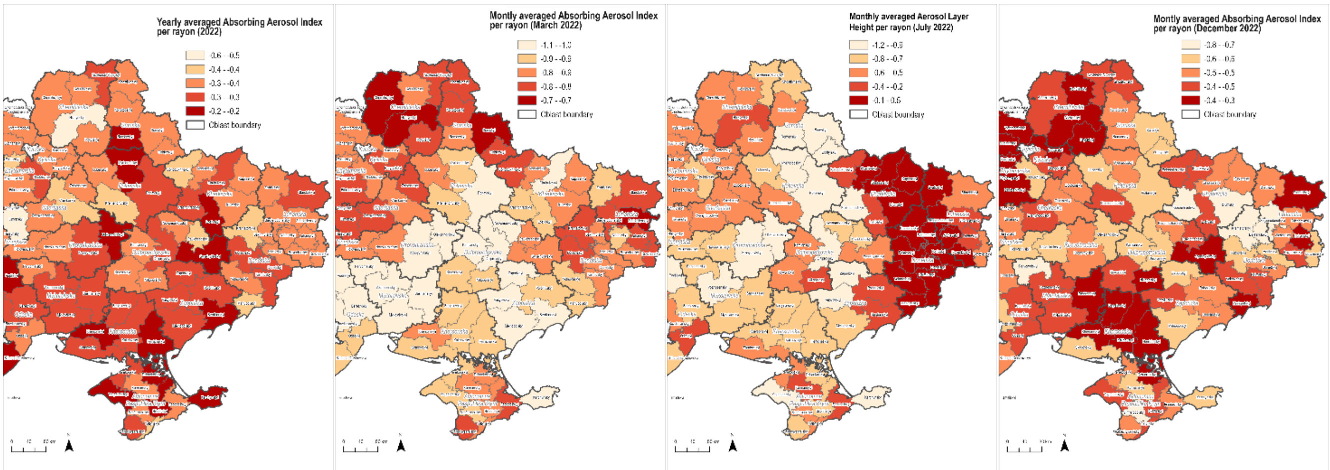

(a) (b) (c) (d)

Figure 11. Average annual value of the column density of the Absorbing aerosol index over Ukraine for the 2022 (a) and anomalies of the monthly average ratio of the column density of the Aerosol Index over Ukraine in 2022 from the monthly average value for the period 2019–2021 in March (b), July (c), December (d). Produced from ESA remote sensing data using (Gorelick, et al., 2017).

Average annual value of the column density of Absorbing aerosol index over Ukraine for the 2022 is shown in Figure 11 (a) and anomalies of the monthly average ratios of the column density of AAI over Ukraine in 2022 from the monthly average value for the period 2019–2021 are shown in Figure 11 (March (b), July (c) and December (d)).

The war in Ukraine has led to the suspension of many enterprises that were significant sources of atmospheric emissions formaldehyde, aerosol, carbon monoxide, nitrogen oxide, and sulphur dioxide, particularly in the eastern and southern parts of the country. But, during the active phase of hostilities in the northern regions in March 2022, there was a significant increase in atmospheric pollutant levels. However, by summer, there was a decrease in their concentrations yet. On the other hand, due war in the eastern and southern regions of Ukraine, there was an observed significantly increase in the concentration of these gas-aerosol contaminants during the second half of the year. This happened due to massive shelling, heavy military equipment usage, and fires.

Conclusions

Unfortunately, the impact of war on the environment is a significant focus of ecological and climate change education in Ukraine. The practice of integrating methodological approaches, reorienting teaching, and adapting the educational process the to the conditions of war has become actually. One of the key aspects of this educational focus is the assessment of ecological damage caused by the war. The direct and indirect effects of war, focusing on changes in the optical characteristics of the atmosphere resulting from the emission of pollutants during missile and shell detonations, as well as the increasing release of greenhouse gases and gas–aerosol impurities were analyzed.

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Satellite observation of atmospheric concentrations of formaldehyde, absorbing aerosol index, carbon monoxide, nitrogen oxide, and sulphur dioxide from the Sentinel–5P satellite was an important research method integrated into the educational process. The integration of satellite observations into the educational process has been a crucial research method. Additionally, the use of the Google Earth Engine platform for cloud–based geospatial analysis has proved to be an effective tool for satellite data analysis and visualization. This freely available platform has enabled students to access spatial information on environmental conditions, including long–term satellite observations, thereby supporting the development of research and data science skills.

It is worth noting that the war in Ukraine has led to the suspension of many enterprises that were significant sources of atmospheric emissions, particularly in the eastern and southern parts of the country. Consequently, in recent months, the atmospheric pollutant levels in these regions have generally returned to background values, influenced by both ground hostilities and the temporary shutdown of industrial activities. However, during the active phase of the conflict, there were instances of substantially increased emissions due to massive shelling, heavy military equipment usage, and fires. In specific regions and months, these emissions exceeded the average values recorded between 2019 and 2021 by several times.

Overall, the combination of research, education has provided valuable insights into the environmental impacts of war in Ukraine. It has equipped researchers and students with a better understanding of the processes occurring in the environment as a result of military actions and has fostered the development of essential skills for addressing and mitigating these environmental challenges.

Data availability

The results presented in this study are based on the data available in the open sources, which are described in the section Methods and Materials and are listed in the References.

Author contributions

SB, TK and VK designed the study; SB and TK analyzed the data; SB and TK visualization; SB, TK and VK discussed the results; VK reviewed and edited the manuscript; SB, TK and VK wrote the paper, and all authors provided input on the paper for revision before submission.

Competing interests

The authors declare that they have no conflict of interest.

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