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A Geospatial Assessment of the Impact of Combat Operations on Atmospheric Air Quality in Radioactively Contaminated Territories

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SUMMARY

Military operations conducted in 2022 within the radioactively contaminated territories of the Chornobyl exclusion zone and mandatory resettlement zones created an unprecedented compounded environmental threat, combining radiological legacy contamination with acute wartime emissions. Ground-based monitoring became impossible under occupation and mine-hazard conditions, necessitating exclusive reliance on satellite remote sensing for atmospheric assessment. This study assessed the impact of combat operations on the dynamics of atmospheric pollutant concentrations over Chornobyl-affected territories in the Kyiv and Zhytomyr regions across three comparable time windows: a pre-war reference period in 2021, the occupation phase in spring 2022, and the post-de-occupation period in spring 2023. Sentinel-5P satellite data processed via Google Earth Engine were used to derive surface-level mass concentrations of nitrogen dioxide, carbon monoxide, and sulfur dioxide, alongside the aerosol index. To support a consistent comparison between the analysed periods, a dynamic scale classification approach was applied and and the detection of local anomalies across all study years simultaneously was enabled. Results showed marked deterioration of air quality during active hostilities. Maximum nitrogen dioxide concentrations rose by over 60% relative to baseline; carbon monoxide levels indicative of widespread forest fires exceeded all peacetime values; sulfur dioxide increased more than fourteenfold on average. The aerosol index shifted from values characteristic of clean air toward those indicating absorbing aerosols, confirming large-scale resuspension of radioactive dust. By 2023, concentrations partially recovered but remained above pre-war levels. Although absolute gas concentrations did not exceed permissible health limits, the interaction of these pollutants with resuspended radionuclide-bearing dust particles represents a sustained long-term ecological risk.

Keywords: Sentinel-5P; TROPOMI; Atmospheric Monitoring; Chornobyl Exclusion Zone; Radioactive Contamination; Military Environmental Impact; Aerosol Index; Nitrogen Dioxide; Carbon Monoxide; Sulfur Dioxide.

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Introduction

Combat and military operations in areas contaminated by radiation as a result of the Chernobyl disaster in 2022 caused a critical man-made environmental impact that, like the Chernobyl disaster itself in 1986, is unprecedented in modern history. All zones of radioactively contaminated territories – exclusion zones, zones of unconditional (mandatory) resettlement, and zones of guaranteed voluntary resettlement – have been subjected to renewed negative environmental pressure and impact as a result of Russia's large-scale invasion of Ukraine on February 24, 2022. This impact was both directly anthropogenic in nature (emissions from heavy machinery engines, ammunition detonations, and the combustion of propellant gases) and indirect – through the provocation of large-scale forest fires caused by shelling and the inability to extinguish them due to landmines and active combat operations (Sakal et al., 2025). In other words, combat and military operations here were not merely a separate environmental factor, but a trigger that catastrophically intensified natural destructive processes (in particular, fires).

Under conditions of occupation and the threat of landmines, traditional ground-based monitoring of the natural environment proved impossible. This highlighted the importance of using remote sensing (RS) methods as the sole tool for retrospective analysis and monitoring of the natural environment, including atmospheric air. An analysis of the publications (Balashevska et al., 2023; Savenets et al., 2020; Savenets, 2021) demonstrates the relevance of satellite monitoring methods for assessing the state of the atmosphere over zones of armed conflict and detecting secondary radioactive air contamination.

The aim of our study is to assess the impact of combat and military operations on the dynamics of pollutant concentrations in the atmospheric air above areas affected by radioactive contamination resulting from the Chernobyl disaster, specifically the exclusion zone and the mandatory resettlement zones in the Kyiv and Zhytomyr regions, for the years 2020–2026.

Method and Theory

Issues related to environmental monitoring and the analysis of atmospheric air quality over the territory of Ukraine based on remote sensing data are described in publications, notably (Balashevska et al., 2023; Savenets et al., 2020; Savenets, 2021). Methodological aspects of using spectrometric data for forecasting and analyzing the spread of pollutants are discussed in detail in (Balashevska et al., 2023), where the focus is on a multimodal approach and the use of intelligent data processing systems. At the same time, publications (Savenets et al., 2020) and (Savenets, 2021) analyze the state of atmospheric pollution in Ukraine, which allowed the authors to establish background levels of impurity content in the pre-war period and identify the main anthropogenic emission sources.

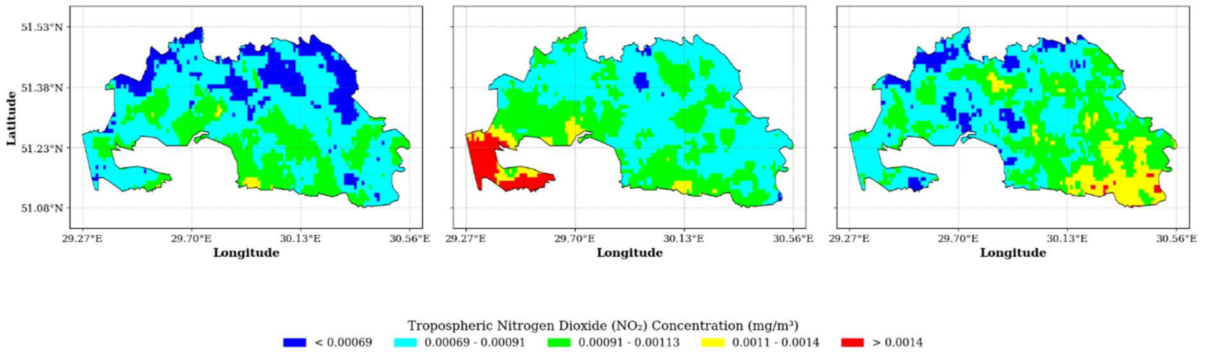
The development of public policy regarding the monitoring and control of ambient air quality in Ukraine, particularly in areas subject to a special legal regime, is based on a comprehensive approach that combines general environmental standards with specific health and hygiene requirements. According to Article 21 of the Law of Ukraine "On the Legal Regime of the Territory Affected by Radioactive Contamination as a Result of the Chernobyl Disaster" (Verkhovna Rada of Ukraine, 1991), radiation monitoring of the level of radioactive contamination of ambient air in populated areas is conducted by the central executive authority responsible for implementing state policy in the field of environmental protection. For territories contaminated by radioactive fallout as a result of the Chernobyl disaster, this entails integrated monitoring, where the results of environmental monitoring must be verified in accordance with established standards and requirements.

The study involves a comprehensive analysis of Sentinel-5P satellite data with a spatial resolution of 5.5×3.5 km (L3 level), processed using the Google Earth Engine platform. Raw data in the form of tropospheric gas column density ($mol \cdot m^{-2}$) were converted to surface-level mass concentrations ($mg \cdot m^{-3}$) according to an environmental model with a planetary boundary layer height of 1,000 meters. As a result, graphs of nitrogen dioxide (NO_2), carbon monoxide (CO), and sulfur dioxide

(SO_2) concentrations were generated. To achieve this goal, three time periods were analyzed: April 27-June 1, 2021 (reference peacetime period), February 24-April 27, 2022 (occupation), and February 24-April 27, 2023 (de-occupation). To support a consistent comparison between the analysed periods, a dynamic scale classification approach was applied. The classification range was defined using the minimum and maximum pixel values across all study years (2021, 2022, and 2023), after which the range was divided into five equal classes. This allowed local spatial anomalies to be identified more clearly than when using independent static scales for each year.

Results

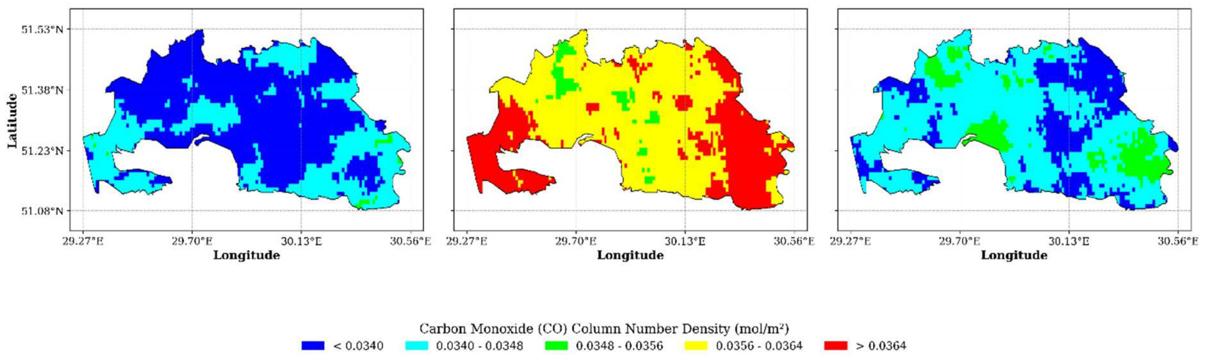
Figure 1 shows the average concentration of NO_2 over areas affected by radioactive contamination resulting from the Chernobyl disaster.



a) b) c)

Figure 1. *NO_2 concentration over the period a) from April 27 to June 1, 2021; b) from February 24 to April 27, 2022; c) from February 24 to April 27, 2023*

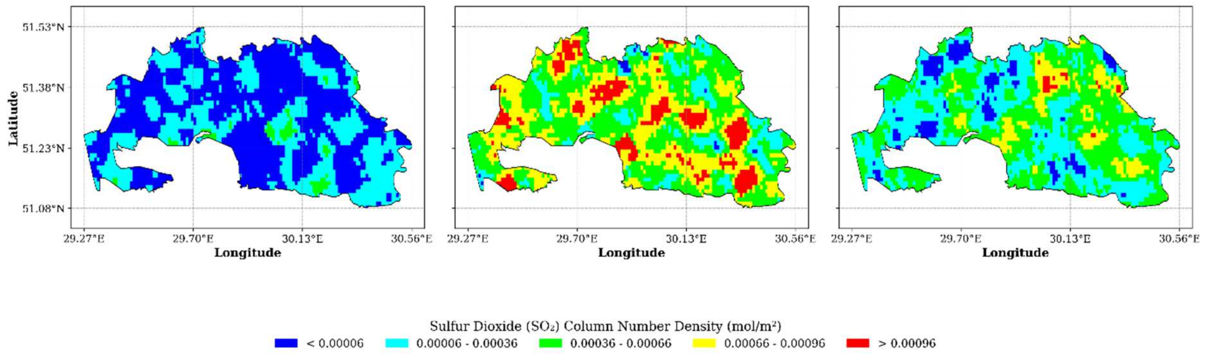
In the peaceful year of 2021, it stood at 0.00082 mg · m^{-3}; during the occupation in 2022, it rose to 0.00095 mg · m^{-3}, with maximum local readings reaching 0.00209 mg · m^{-3} – 60% higher than the reference maximum. After de-occupation in 2023, the concentration dropped to 0.00091 mg · m^{-3}, but remained higher than pre-war levels. Although peak values are less than 1% of the MPC (daily average 0.04 mg · m^{-3}), the interaction of NO_2 with radioactive dust forms nitrate aerosols – mobile carriers of radionuclides (Seinfeld et al., 2016).



a) b) c)

Figure 2. *CO concentration over the period a) from April 27 to June 1, 2021; b) from February 24 to April 27, 2022; c) from February 24 to April 27, 2023*

Figure 2 shows that the background level of carbon monoxide in 2021 was 0.95024 mg · m^{-3}. In 2022, it rose to 1.01597 mg · m^{-3}, and the minimum value during the occupation period (0.98971 mg · m^{-3}) even exceeded the peacetime maximum. This indicates widespread fires caused by combat and military operations: the burning of contaminated forest areas released Cs-137 and Sr-90 in the form of radioactive ash (Kajan et al., 2016). In 2023, the level stabilized at 0.96108 mg · m^{-3}.



a) b) c)

Figure 3. *SO_2 concentration over the period a) from April 27 to June 1, 2021; b) from February 24 to April 27, 2022; c) from February 24 to April 27, 2023*

The SO_2 level showed the largest relative increase: the average concentration rose from 0.00290 (2021) to 0.04165 mg · m^{-3} (2022) – more than 14 times higher (Figure 3). Peak values reached 0.11501 mg · m^{-3}, which was twice the reference maximum. The source was the widespread use of non-modernized diesel engines. In 2023, SO_2 decreased to 0.02461 mg · m^{-3}. There is no chemical hazard based on the MPC, but SO_2 is a precursor to sulfate aerosols, which exacerbate secondary soil pollution (Savenets, 2021).

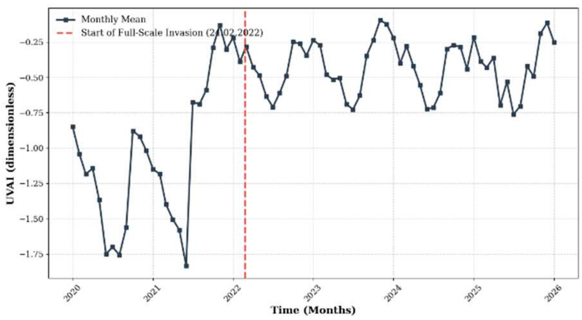


Figure 4. *Average Monthly Aerosol Index (UVAI) over the Chernobyl Exclusion Zone (2020–2026)*

The aerosol index value shown in Figure 4 had an average of -1.60 in 2021, which is indicative of clean air. During the occupation, it rose sharply to -0.34, clear evidence of the widespread presence of absorbing aerosols: smoke, soot, and radioactive dust. After de-occupation, its value was -0.49. Since the UVAI is a physical optical marker of atmospheric conditions rather than a chemical toxic substance, the classical concepts of maximum permissible concentration (MPC) or sanitary standards do not apply to it. The increase in the concentration of absorbing aerosols in 2022 directly correlates with the intensity of mechanical destruction of the radioactively contaminated topsoil.

The interaction of the gases under study (CO, NO_2, SO_2) with the aerosol index is due to the formation of soot particles and secondary sulfate compounds, which actively absorb UV radiation (Seinfeld et al., 2016). At the same time, it is aerosol dust that serves as the primary carrier of strontium, cesium, plutonium, and americium isotopes in the lower atmosphere (Talerko et al., 2025). The period of atmospheric self-cleaning from these plumes is up to three weeks (Seinfeld et al., 2016). However, the natural stabilization of disturbed soil cover and self-recovery takes 3-5 years, while the full rehabilitation of damaged forest ecosystems takes 15 to 25 years (Talerko et al., 2020). During this time, any human intervention will trigger new surges of resuspension.

Conclusions

This study assessed the impact of combat operations on atmospheric air quality in territories radioactively contaminated as a result of the Chornobyl disaster. Sentinel-5P data were used to analyse changes in NO_2, CO, SO_2 and the aerosol index during the pre-war, occupation and postoccupation periods. The results show a clear deterioration in air quality during February-April 2022. Maximum local NO_2 concentrations increased by more than 60% compared with the 2021 reference period. CO reached its highest values during the same period, which may be linked to uncontrolled forest fires. SO_2 showed the largest relative increase, with the average concentration rising more than fourteenfold. The aerosol index also changed markedly during the occupation period. This suggests an increase in absorbing aerosols, such as smoke, soot and resuspended dust. In the study area, such dust may include radionuclide-bearing particles from disturbed contaminated soils. The analysed gas concentrations did not exceed established health limits. However, their interaction with aerosol particles may create longer-term ecological risks. The study therefore shows the value of satellite-based geospatial monitoring in areas where field measurements are unsafe or unavailable.

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