IOP Conf. Series: Earth and Environmental Science **1474** (2025) 012016 doi:10.1088/1755-1315/1474/1/012016

Destruction of the Natural Environment Caused by the War in Ukraine: Impact on Atmosphere, Land, Water and Ecosystems

Victor Karamushka[1*], Svitlana Boychenko[1], Olena Kozak[1] and Mykhailo Khoriev[1]

[1]Department of Environmental Studies, National University of Kyiv-Mohyla Academy, Kyiv, Ukraine

*E-mail: karamushka@ukma.edu.ua

Abstract. The purpose of this study is to determine the specific impacts of military operations on the air, land surface, water bodies, and vegetation of the affected territories. This paper describes results of the examination of affected areas after explosions of the missiles in forest zone (Moshchun and Buda-Babynetska case study) and deterioration of oil depots (Kalynivka case study). Air pollution and land clogging were observed in all cases. Polluting substances were products formed as a result of ammunition explosions and burning of target materials. Monitoring the consequences of this case showed pollution of the soil and underground water by oil derivatives. The concentration of pollutants in affected land areas sufficiently exceeded background concentrations. The migration of polluted underground water ended up loading into surface water bodies. This pollution had a detrimental effect on the riparian and aquatic vegetation of the surrounding area. In this case, air pollution was temporary and dynamic, while soil and water pollution, particularly from oil products, had long-term consequences. Physical destruction of natural and anthropogenic landscapes was registered near Buda-Babynetska and Moshchun Villages, Kyiv Region. Explosion of missiles, bombs, shells in forest and agricultural areas caused the formation of deep craters, destruction of the soil cover, flora and fauna species with long-term recovery. In addition to this impact, fires in forest ecosystems caused emissions of significant amounts of combustion products into the atmosphere and complete or partial destruction of biotopes. Paper describes the case studies of the incidents, demonstrates specifics of the assessment of different forms of environmental damage.

1. Introductions

The Russian military aggression against Ukraine began in Eastern Ukraine in 2014, and the hostilities using modern weapons have had enormous consequences for the population, economy, and environment of the eastern region. However, Russia's full-scale invasion of Ukraine on February 24, 2022, covered all of Ukraine, causing and continuing to have a devastating impact on the well-being of Ukrainians, the economy, and the natural environment of the entire country. The impact of this war, which is modestly referred to in scientific publications as a conflict [1, 2], extends far beyond the country's borders, but the greatest damage has been caused to Ukraine itself [3-5]. These damages have only been partially assessed, as the war continues, and its duration is unknown. However, the assessment of damage, in particular to the natural environment, began almost from the first months of the war. To this end, the Government of

Ukraine created a special Operational Headquarters at the State Environmental Inspectorate of Ukraine to register incidents that caused environmental destruction and to assess environmental damage. International organizations and projects joined the assessment of the environmental impact of military operations, and the first reports and assessments were published in the second half of 2022 [3, 4]. These reports were mostly general in nature and did not describe the details. The recorded incidents became the object of statistics. However, each of these incidents showed not only general trends in environmental impact, but also certain features, which were key in assessing the state and damage to the affected environment.

The purpose of this paper is to show, using the cases of specific incidents that we investigated, how military actions affect the natural environment and how natural systems recover after the impact of military factors.

2. Materials and Methods

The research and monitoring in this study concentrated on hotspots — areas and sites of military incidents that led to the destruction of industrial facilities and natural ecosystems in the Kyiv region. Such hotspots are: the site of a missile attack in the forest near the village of Buda-Babynetska (N 50.61528, E030.07225), the consequences of hostilities in the forest of the village of Moshchun (N 50.61308, E030.30132), the oil depot of Ltd "AC-Investment" and its surroundings (the coordinates of oil depot in the Kalynivka village – N 50.23284, 30.23537). The coordinates were identified using Google Earth and GPS-tracker Garmin etrex Legend HCx.

Surveys and monitoring were carried out between September 2022 and September 2024 at the oil depot in the village of Kalynivka, and from May to November 2024 at hotspots in the villages of Moshchun and Buda-Babynetska.

During the survey, the following information was documented: date, area's size, coordinates, a detailed description of its condition, photographs of the site, locations and methods for water and soil sampling, as well as the condition and species composition of the vegetation cover. At the hotspots in Kalynivka, monitoring plots were established. Analysis of the plant species composition was conducted with the collection of herbarium specimens, photography, and processing of the collected data. The nomenclature, taxa of the plant families, geographical origin (native range) and status of invasiveness were determined according to GBIF [6]. The habitat classification was followed by EUNIS (version 2012) [7].

Soil and water samples were taken in accordance with national standards. Chemical analysis of samples was carried out in the Ukrainian Laboratory of Quality of Agro-Industrial Complex Products (http://quality.ua/).

The assessment of pollutant emissions into the atmosphere as a result of the fire at the oil base in Kalynivka due to a missile strike and the extent of the damage was conducted based on a methodology developed by the Ministry of Environmental Protection and Natural Resources of Ukraine on April 13, 2022, No. 175 [8].

3. Results

3.1 Environmental impact of hostilities in the village of Moshchun

In March 2022, intense fighting occurred in and around the village of Moshchun as Russian troops advanced on Kyiv and attempted to cross the Irpin River. Home to 794 residents before the war, Moshchun lies amidst forests, with its western edge reaching the Irpin River floodplain. The Battle of Moshchun, one of the fiercest in Kyiv's defense, lasted from February 27 to March 21, 2022, involving heavy artillery and air bombardment. The village was nearly destroyed, with 1,597 shell craters identified and about 2,000 of its 2,800 buildings obliterated [9].

Access to the forests around Moshchun remains partially denied, limiting surveys to a safe area northwest of the village. A May 2024 survey revealed that, despite over two years passing since the battle, the forest and trees still bear signs of severe damage. Explosion craters, visible in satellite images (Fig. 1A), are slowly being overgrown with vegetation and will gradually become shallower due to erosion (Fig. 1B). In the water-filled crater during the second year of succession, species such as *Salix* sp., *Typha* sp., and *Juncus* sp. were observed, along with numerous seedlings of other species that were difficult to identify. On the sandy part of the crater, species such as *Populus* sp., *Sorbus aucuparia* L., *Frangula alnus* Mill., *Ambrosia artemisiifolia* L., *Pteridium aquilinum* (L.) Kuhn, *Elymus repens* (L.) Gould, *Silene viscosa* (L.) Pers., *Rumex acetosella* L., *Polygonum aviculare* L., *Calamagrostis* sp., *Spergula* sp. and others were observed, along with numerous seedlings.

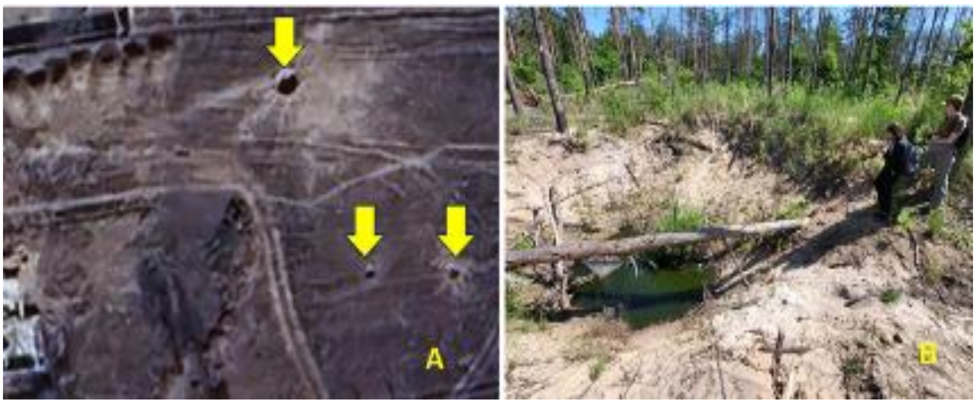

Figure 1. Craters from the explosions of aircraft bombs on a satellite image (A) (Resource: Google Earth) and during field research in the vicinity of the village of Moshchun (B) in May 2024.

The forest shows signs of fighting: many trees are damaged by shrapnel from explosive devices, some trees are either burned or bear traces of fires, the ground surface has also been significantly damaged by fire and new plants have already appeared on the burned areas. The forest is slowly restoring its structure.

3.2 Environmental impact of the missile attack near the village of Buda-Babynetska

During the Russian missile attack on February 15, 2024, one of the missiles exploded in a forest near the village of Buda-Babinetska. The affected area is located on a site where clearcutting was carried out less than 20 years ago. Before the accident, the forest had regenerated, with trees reaching heights of up to 15 meters. A rocket explosion created a crater 15 meters in diameter and about 6 meters deep, partially filled with groundwater. No remediation measures have been taken, but precipitation and wind have gradually turned the crater into a lake that is slowly filling with sand. In May 2024, fallen trees (*Pinus sylvestris* L., *Quercus robur* L., *Betula pendula* Roth,) were observed within 32–35 meters, most charred and dead, while seedlings had begun to appear on the sandy surface (Fig. 2A).

The habitat of this area can be classified according to the EUNIS system [7] as mixed *Pinus sylvestris*-acidophilous *Quercus* woodland (G4.7), featuring the presence of the following species: *Pinus sylvestris* L., *Quercus robur* L., *Betula pendula* Roth, *Frangula alnus* Mill., *Calamagrostis arundinacea* (L.) Roth, *Molinia caerulea* (L.) Moench, *Pteridium aquilinum* (L.) Kuhn, *Vaccinium myrtillus* L., *V. vitis-idaea* L., *Convallaria majalis* L., *Festuca ovina* L., *Calluna vulgaris* (L.) Hull, *Rubus* sp., and some others.

Restoration of the tree layer is occurring through the recovery of affected specimens of *Frangula alnus* and *Betula pendula*, which have regenerated, as well as through seed regeneration predominantly from *Pinus sylvestris*. The herbaceous layer is being restored mainly through the growth of native species, including *Pteridium aquilinum*, *Calamagrostis arundinacea,* and *Molinia caerulea*. However, a limited number of ruderal and invasive species were observed in the affected area, in particular, such as *Erigeron canadensis* L., *Ambrosia artemisiifolia* L., *Solidago gigantea* Aiton, *Amaranthus* sp., *Galeopsis* sp. Around the crater, we registered several dozen pine seedlings up to 10 cm tall, all of them with branched stems (Fig. 2B).

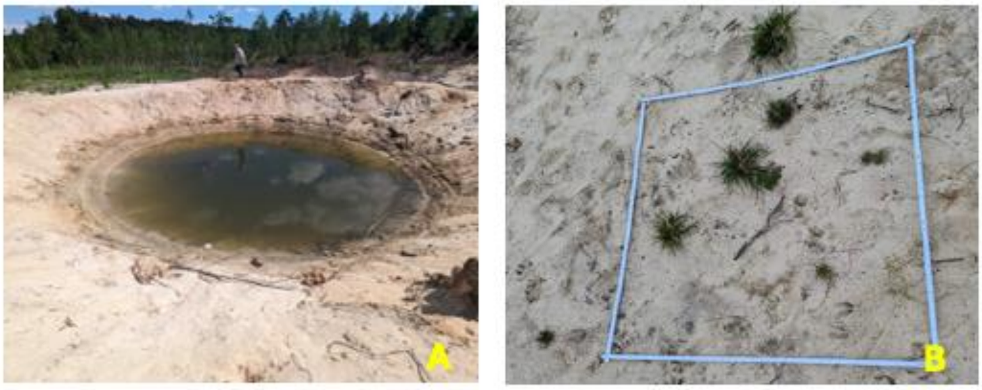

Figure 2. Crater formed after a missile explosion in the forest near the village of Buda-Babynetska (A) and Pinus sylvestris seedlings near the crater (B).

It is worth noting that most of the plants exhibited signs of stress, such as leaf curls, wilting, chlorosis, necrosis, and pigmentation (browning), with the most pronounced effects observed in *Pteridium aquilinum*. Continuing monitoring and further studies are essential to assess the long-term recovery of the ecosystem.

Sampling of water from the crater showed that most of the indicators correspond to the normative values, but there is a noticeable excess of the content of iron compounds (by 40%) and ammonium (almost twice). At the same time, the value of permanganate oxidation exceeds the normative values by more than 15 times, which indicates the presence of a significant mass of organic contaminants [10]. Their nature and origin are not yet known, but in this case, it cannot be ruled out that these contaminants can get into groundwater.

3.3. Environmental impact of missile attack on oil depots

The environmental consequences of missile attacks on industrial and energy facilities are more complex and severe, since in such cases, the factors of pollution from the destroyed industrial facilities are added to the factors of damage caused by weapons. On March 24, 2022, the AC-Investment Ltd oil depot in the village of Kalynivka, Kyiv region, was attacked. As a result of a missile attack (Fig. 3), the stored petroleum products were completely burned out.

Figure 3. Oil depot of AC-Investment Ltd. Satellite image of March 3, 2020 (A) and March 31, 2022 (B). Source: Google Earth.

This incident has already been considered previously [11], but the attention of researchers was limited mainly to the impact on the environment. Since September 2022, we have been monitoring the territories and objects affected by the missile attack on this oil depot, and we can describe the complex long-term consequences of the hazardous impact on the environment.

During the missile strike on the oil base, the storage tanks contained 4515.5 tons of diesel fuel and 1603.2 tons of motor gasoline. Additionally, the base housed 9 trucks and trailers (models DAF FT and MAN TGA) carrying 3.2 tons of gasoline and 2.7 tons of winter diesel fuel.

Each vehicle had 10 wheels with tires weighing about 70 kg (total weight – 6.3 tons). On average, a tire consists of: natural and synthetic rubber – 40–45%; soot (carbon) – 20–30%; acidic clays and metal oxides – 10–27%; corded metal and textile threads – 2–10%; silicon dioxide – 5–15%; and various additives – 7–10% [15]. As a result of tire combustion, toxic smoke and ash are released, washing out with water and atmospheric flows, further contaminating the environment and negatively affecting human health.

The percentage of chemical substances remaining after tire burning in the ash is 3.21 tons, or 51% of the total mass [16]. Another aspect of contamination caused by the fire is the use of fluorinated foam (fluorosynthetic film-forming agent – AFFF, AFFF AR). These types of fluorinated foams typically consist of: water – 80%, fluorinated surfactants – 3%, hydrocarbon surfactants – 2%, solvents (propylene glycol) – 10%, foam-forming agents – 4%, and stabilizers – 1% [17]. At least 12–15 thousand liters of fluorinated foam were used to extinguish the fire in an area of about 1.4 hectares.

The assessment of pollutant emissions into the atmosphere [8] due to the fire at the oil base in Kalynivka assumed that 90% of the available fuel is burned in the process. According to our calculations, considering emission coefficients and fuel type, as a result of the fire, the atmosphere released: CO_2 ~14326.9 tons, H_2O ~6470.2 tons, particulate matter (PM10, PM2.5) and soot ~27.4 tons, as well as NO_x ~5.8 tons and SO_2 ~0.05 tons. The total amount of damage caused by atmospheric pollution due to the emergency caused by the actions of the aggressor country is estimated at around 184 million UAH, or 4.5 million USD (as of August 1, 2024).

The missile explosion destroyed the oil depot's concrete coating and drainage system, allowing oil products to contaminate the soil and groundwater. The spill caused a leak and fire, damaging an agricultural plot. Soil samples taken five weeks later showed oil derivatives at concentrations seven times above regulatory standards. In June 2022, two months after the attack, oil contamination was found in the Riznytsia pond, 520 meters downstream, where the coastal area up to 100 meters wide had oil-saturated soils, killing riparian and aquatic vegetation. Further analysis confirmed the oil depot as the source of pollution. Oil films were still visible on the pond's surface until June 2024, though the pollution gradually diminished.

The second impact concerns the soil and vegetation. The burning and spillage of oil products affected the land, making it unusable for agriculture. Groundwater contamination and the destruction of riparian vegetation were significant. However, vegetation began to recover after a few months. A total of 58 vascular plant species from 24 families were recorded in the studied area. Dominant species include *Polygonum persicaria* Wahlenb. ex-Nyman, *Cirsium arvense* (L.) Scop., *Erigeron canadensis* L., and, in some areas, *Alisma plantago-aquatica* L., *Oenanthe aquatica* (L.) Poir., *Juncus bufonius* L., and *Salix* sp. Nine invasive plant species were also identified. The habitat is classified by EUNIS as periodically inundated shores with pioneer and ephemeral vegetation (C3.5) and medium-tall non-graminoid waterside communities (C3.24). Dead *Typha* sp. along river margins suggests the presence of *Typha* beds (C3.23) before the disaster. The results indicate that vegetation is recovering naturally, without targeted restoration efforts. Thus, the key impacts of the accident are groundwater and surface water pollution and biodiversity loss, particularly in vegetation.

The use of explosive devices causes deep, lasting damage to natural systems. The recovery from these incidents is ongoing, and we continue to monitor these processes.

4. Conclusions

The impact of military activities, including combat operations (artillery shelling, bombing, missile attacks, etc.), heavy equipment use, and the construction of fortifications, significantly affect natural systems in a multi-faceted way. Explosive devices, in particular, cause severe and lasting damage, including the physical destruction of landscapes, air pollution, soil and water contamination, and loss of biodiversity. The damage to industrial facilities adds to another layer of pollution, as seen in the case of the Kalynivka oil depot attack, where rocket explosions, combustion products, and oil derivatives polluted air, water, soil, and groundwater, affecting local biodiversity. This environmental impact is long-term and challenging to manage, with groundwater pollution being especially difficult to remediate. Despite these challenges, we observed a notable recovery in vegetation, highlighting the natural environment's strong regenerative potential.

References

[1] Pereira P., Bašić, F., Bogunovic I., Barcelo D., 2022. Russian-Ukrainian war impacts the total environment. *Science of The Total Environment*, 837, 155865, https://doi.org/10.1016/j.scitotenv.2022.155865.
[2] Hrynevych O., Blanco Canto M., & Jiménez García M., 2023. The war effect: a macro view of the economic and environmental situation of Ukraine. Applied Economics, 56 (39), 4685–4701. https://doi.org/10.1080/00036846.2023.2212975.
[3] Angurets O., Khazan P., Kolesnikova K., Kushch M., Černochova M., Havránek M., 2022. Environmental consequences of Russian war in Ukraine. 79 p. https://cleanair.org.ua/wp-content/uploads/2023/03/cleanair.org.ua-environmental-consequences-of-russian-war-in-ukraine-war-damages-en-version.pdf (accessed on 21 November 2024).
[4] UNEP 2022. The Environmental Impact of the Conflict in Ukraine: A Preliminary Review. https://www.unep.org/resources/report/environmental-impact-conflict-ukraine-preliminary-review (accessed on 21 November 2024).
[5] Kyiv School of Economics 2023 The total amount of direct damage to Ukraine's infrastructure caused due to the war as of June 2023 exceeded $150 billion. https://kse.ua/about-the-school/news/the-total-amount-of-direct-damage-to-ukraine-s-infrastructure-caused-due-to-the-war-as-of-june-2023-exceeded-150-billion (accessed on 21 November 2024).
[6] GBIF | Global Biodiversity Information FacilityGBIF. 2023. Available from: https://www.gbif.org (accessed on 21 November 2024).
[7] EUNIS: European Nature Information System, 2024 https://eunis.eea.europa.eu/ (accessed on 21 November 2024).
[8] MEPNR (2022). (Ministry of Environmental Protection and Natural Resources of Ukraine) Order of 13.04.2022 N.175. https://zakon.rada.gov.ua/laws/show/z0433-22#Text (accessed on 21 November 2024).
[9] Kyiv School of Economics 2022 Report on the Damage to Moshchun village. RebuildUA project. https://rebuildua.net/moshchun (accessed on 21 November 2024).
[10] Laszakovits J., Adaline Kerr A., MacKay A., 2022. Permanganate Oxidation of Organic Contaminants and Model Compounds. *Environmental Science & Technology*, 56(8) 4728-4728. https://doi.org/10.1021/acs.est.1c03621
[11] CEOBS, 2022. Ukraine conflict environmental briefing: Fossil fuel infrastructure - CEOBS https://ceobs.org/ukraine-conflict-environmental-briefing-fossil-fuel-infrastructure/ (accessed on 21 November 2024).
[12] Lemieux M., Lutes C., Santoianni D., 2004. Emissions of organic air toxics from open burning: a comprehensive review, *Progress in Energy and Combustion Science*, 30 (1), 1-32. https://doi.org/10.1016/j.pecs.2003.08.001.
[13] Hobbs J., Ferek R., and Peter V., 1996. Particle and Gas Emissions from an In Situ Burn of Crude Oil on the Ocean. Journal of the Air & Waste Management Association, 46(3), 251–259. https://doi.org/10.1080/10473289.1996.10467459
[14] Bernodusson J., 2018. Combustion of Fossil Fuels. Icelandic Transport Authority. 18 p. https://www.samgongustofa.is/media/siglingar/skyrslur/Combustion-of-fossil-fuels-2018-en-1.pdf (accessed on 21 November 2024).
[15] Klockner P., Seiwert B., Eisentraut P., Braun U., Reemtsma T., Wagner S., 2020. Characterization of tire and road wear particles from road runoff indicates highly dynamic particle properties. *Water Res.* 185:116262 https://doi.org/10.1016/j. watres.2020.116262
[16] Senin M., Shahidan S., Leman A., Hannan N., 2016. Analysis of Physical Properties and Mineralogical of Pyrolysis Tires Rubber Ash Compared Natural Sand in Concrete material. *Materials Science and Engineering* 160:012053, https://doi.org/10.1088/1757–899X/160/1/012053.
[17] Buck, R. C., Franklin J., Berger U., Conder J., Cousins I., de Voogt P., Astrup A., 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. Integrated Environmental *Assessment and Management,* 7(4):513–541. https://doi.org/10.1002/ieam.258.