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The impact of combat actions on forest ecosystems: Challenges for environmental, national security and state resilience

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Abstract. This study aimed to analyse the impact of active military actions on biodiversity and forest resources. The research employed the following methods: analysis of satellite data from open sources and media reports, as well as methods of generalisation and systematisation. It was established that the accumulation of dry biomass following fires has contributed to the spread

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of wildfires. The formation of crater-like depressions due to explosions altered the composition of forest stands and the water balance, affecting the region's water supply and leading to either waterlogging or desiccation. The study's findings indicated that in 2024, following shelling in a forested area near the village of Buda-Babynetska in the Kyiv Region, the forest cover within a 25-metre radius was destroyed. This included plant species such as Scots pine (*Pinus sylvestris*), pedunculate oak (*Quercus robur*), and silver birch (*Betula pendula*). The analysis of information from open sources and media reports demonstrated that ruderal species, such as common ragweed (*Ambrosia artemisiifolia* L.) and black locust (*Robinia pseudoacacia* L.), had colonised damaged areas. This indicated active vegetation establishment by species capable of rapid recovery following disturbances. In explosion crater zones, revegetation processes progressed slowly. For instance, in one of the craters within Hetmanskyi National Natural Park in Sumy Region, only a few specimens of ragweed and black locust were recorded, while another crater remained devoid of any vegetation. To facilitate forest restoration in Ukraine following the cessation of active hostilities, the application of mycorrhizal fungi, the use of container-grown seedlings, and hydroseeding were recommended. The findings on the condition of forested areas may contribute to the development of strategies for the conservation and restoration of fire-damaged forest ecosystems

Keywords: fires; craters; invasions; ruderal plant species; biodiversity; vegetation cover

Introduction

One of the primary ecological challenges facing Ukraine has been the destruction of forests through fires. Forest ecosystems in Ukraine play a vital role in climate regulation and biodiversity conservation. The destruction of forests by fires has degraded soil and water resources, posing a threat to the existence of many species. The relevance of this research stems from the fact that one of the key ecological and economic problems is the environmental pollution of Ukraine due to the military actions of the Russian occupying forces. The loss of forest areas through fires, particularly those caused by shelling and the use of military equipment, has had catastrophic consequences for environmental quality. The disruption of carbon absorption, water cycle maintenance, and the destruction of habitats for many flora and fauna species through fires have led to soil degradation, reduced water resource quality, and threats to biodiversity, resulting in long-term impacts on ecosystems (Fedoniuk *et al.*, 2024).

The concentration of various pollution sources in occupied settlements is very high. Without comprehensive research into the effects of forest fires, risks to ecosystems and society may arise, as the degradation of forest ecosystems directly affects climate regulation, biodiversity, and the quality of life for the population. Specifically, without proper attention to forest restoration, ecosystems will be unable to perform their natural climate and water resource regulation functions, leading to further environmental degradation and increased negative impacts on public health. Therefore, the importance of this research lies not only in nature conservation but also in ensuring the long-term stability of ecosystems and preserving life-supporting functions for society.

The research problem focused on the fact that the impact of the Russian-Ukrainian war has contributed to an increase in the area of forests affected by fire. According to an investigation by journalists from NGL.media, "To cut it all",

during the full-scale Russian invasion of Ukraine (February 2022 to April 2024), over 60,000 hectares of forest in temporarily occupied Ukrainian territories were permanently destroyed (Verbovska & Tuziak, 2024). The existence of this problem was confirmed by the fact that the introduction of toxic substances into the soil due to bombardments and the use of chemical agents for military purposes resulted in significant ecosystem pollution. The excessive concentration of heavy metals has deteriorated the physicochemical properties of the soil, reduced its fertility and hindered normal plant growth.

The issue of forest stand damage due to post-combat fires was particularly acute in the Luhansk Region, where 16,500 hectares of forests were damaged between February 2022 and April 2022. The issue was investigated by O.V. Kratko & S.V. Kratko (2023). Their research demonstrated that explosions and bombardments, as well as forest and steppe fires in the Luhansk, Zhytomyr, Kyiv, Kherson, Chernihiv, and Poltava regions, led to a reduction in biodiversity within protected natural areas and disrupted forest ecosystems.

A pressing problem was the necessity to conduct statistical analysis and forecast the condition of forest resources in Ukrainian regions, particularly in the Lviv and Kharkiv regions. Research in this area was undertaken by E. Korotetska *et al.* (2022). The findings of these scientists revealed a significant difference in the state of forests between the two regions. Specifically, the forest stands in the Kharkiv Region were found to be in a worse condition compared to the forests of the Lviv Region, which is attributed to the high number of fires.

Concurrently, the study of ecological aspects of forest restoration in anthropogenically degraded areas has been an important topic for contemporary ecologists. In their research, V.B. Levchenko & T.S. Ganzhaliuk (2022) proposed an innovative technology for growing

forest seedlings with a closed root system, which significantly increased their survival rate after forest fires. This research demonstrated the importance of improving reforestation methods to prevent further ecosystem degradation.

Particular attention was drawn to the increased risk of forest fires due to combat actions and mine laying, as investigated by Y.M. Senchikhin (2022). The author showed that the highest number of fires in Ukraine (2,381 cases) was recorded in March 2022, resulting in damage to 748,116 hectares of forests, with the Kherson and Kharkiv regions and the Chornobyl zone being the most affected. The study of these data highlighted the importance of developing new approaches to the prevention and control of forest fires in conflict conditions.

The issue of mechanical and fire damage to forest lands in the Zhytomyr Region has become particularly acute due to the ongoing military actions since February 2022. According to research by I. Patsev *et al.* (2023), approximately 120,000 hectares of forest were destroyed in the region, which negatively impacted the ecological state of forest ecosystems. The significant environmental damage inflicted on the forests of the Zhytomyr Region by combat actions underscores the urgent need for forest ecosystem restoration and the implementation of new forest management methods in wartime conditions.

The study of the problem of pine mistletoe infestation on the growth of pine trees has been relevant in current conditions. O.E. Sakici *et al.* (2023) recommended developing strategies aimed at reducing infection levels, such as the timely removal of infected trees and the implementation of preventive measures to reduce the spread of mistletoe in the future. The recommended approaches are important directions for preserving the health of forest ecosystems and enhancing their resistance to diseases and pests.

The issue of forest fire management remains relevant in the context of climate change

and increasing human activity, as demonstrated in the research of A.P. Singh (2024). Given climate change and intensified human activities, the development of effective national and regional strategies for the prevention, suppression, and restoration of forest ecosystems is crucial for preserving the natural environment.

In 2024, insufficient attention has been paid to a comprehensive approach to studying the long-term effects of combat actions, deforestation, fires, and pollution on forest ecosystems, their restoration, and their resilience to further changes. This research aimed to analyse the negative factors during combat actions that cause damage to forest ecosystems, as well as to identify the main strategies for mitigating the consequences and measures for post-war restoration. The study's objectives included analysing the impact of military actions on forest ecosystems, identifying the main factors of forest damage resulting from combat actions, and developing recommendations for forest restoration in Ukraine after the end of active hostilities.

Materials and Methods

The study employed methods to assess the ecological state of forest ecosystems and analyse degradation processes resulting from military actions, as established by legislative acts: the State Standard of Ukraine No. ISO 14001:2015 "Environmental management systems. Requirements and guidelines for use" (2015), the Convention on Biological Diversity (1992), and the Forest Code of Ukraine (1994).

The study utilised the method of analysing satellite data from open sources and media to identify the main ecological consequences of military actions on forest ecosystems, collect and systematise facts about soil and water resource pollution, and analyse the impact of explosives and fires on vegetation and biodiversity. The method of generalisation and systematisation was used to form a comprehensive

assessment of ecological changes in forests caused by combat actions, to structure information on negative impact factors and their consequences, and to develop conclusions about long-term ecological risks and possible pathways for forest ecosystem restoration.

Satellite data was obtained from open sources, such as official satellite imagery platforms and scientific publications, as well as from the commercial satellite company Planet Labs, which provided access to high spatial and spectral resolution satellite imagery (3 m/pixel) captured by the PlanetScope satellite system. These images are designed for detailed monitoring of localised damage, including crater formation and vegetation cover degradation.

Research on the effects of explosions and fires was conducted throughout 2024 in the Hetmanskyi National Natural Park in the Sumy Region and the forested area near the village of Buda-Babynetska in the Kyiv Region. The study of the impact of military actions on forest massifs was carried out in four areas located in the Sumy, Kyiv, Chernihiv, and Luhansk regions of Ukraine, as these territories were the most severely affected by military actions. A separate survey was conducted in the Zalissia National Natural Park (Hoholivski Hai tract), located on the border of the Kyiv and Chernihiv regions. Studies were conducted in damaged pine forest areas, assessing ruderal and adventive vegetation cover, analysing the herbaceous layer, and assessing the degree of forest stand damage after combat actions. These territories recorded instances of forest fires, explosions, mechanical destruction of forests by military equipment, and toxic substance contamination.

All sites were examined for mechanical damage and soil contamination. Soil samples were collected from horizons 0-10 cm, 10-30 cm, and 30-50 cm to assess changes in different layers. In each study area, 3-5 replicated test plots measuring 10 × 10 m were established.

From each plot, 5-point samples were collected and then mixed to obtain an average sample weighing 500 g. These methods were used because collecting soil samples at different depths allowed for the assessment of the contamination level and its vertical migration.

Archival data that could allow for the assessment of changes in forest conditions before and after military actions are limited, so the comparison of forest conditions was based on the analysis of open sources, field observations, and expert assessments (Almost 19 thousand..., 2024; As a result..., 2024; Examination of a..., 2024; Marchan, 2025).

Cartographic work was also conducted to determine the boundaries of damaged areas and estimate the extent of forest cover changes. The condition of the vegetation cover was assessed using descriptive and quantitative methods. It was determined which plant species had recovered after explosions, fires, and other damage. Changes in vegetation composition were monitored using square quadrats, which allowed for the determination of the percentage coverage of the area by herbaceous and shrub vegetation. The spread of ruderal species, such as common ragweed (*Ambrosia artemisiifolia*) and black locust (*Robinia pseudoacacia*), in explosion sites was assessed.

Results

The war has had a profoundly negative impact on forest ecosystems. Forests have been used as natural cover for military equipment and personnel and have been subjected to armed shelling, resulting in extensive damage. Shelling from various types of weapons has led to the destruction of trees, soil degradation, chemical contamination, and loss of biodiversity. Furthermore, explosions and fires have disrupted the ecological balance, altering the composition of forest stands and causing long-term environmental consequences. Specifically,

there has been a mass die-off of trees, which in turn has led to the replacement of native species with less resilient ones. Explosion craters have formed, and mechanical destruction of soil has occurred due to the digging of trenches and fortifications by military equipment. Soils and groundwater have been contaminated with ammunition residues, fuels and lubricants (petrol, liquefied natural gas, and motor oils), heavy metals, and toxic chemicals. Explosions, fires, and mechanical damage have resulted in the death of animals and plants, leading to forced fauna migration.

When trees are damaged or completely destroyed, and dry biomass accumulates, forest fires spread more easily. Explosions create crater-like depressions in the ground and disrupt vegetation cover, altering the water balance of forests and leading to either water-logging or drying out of forest areas. This reduces the water supply to the forest, as natural vegetation layers that help retain moisture in the soil are lost. Such changes result in faster soil drying and an increased risk of erosion. The accumulation of dry biomass after fires further promotes the spread of fire, which also has consequences for the water balance. After such fires, the ground surface loses its ability to retain moisture as organic residue layers are burned, and elevated temperatures dry out the soil. If these processes create craters or significant damage to vegetation cover, it encourages water accumulation in lower parts of the terrain, creating conditions for rising groundwater levels.

According to the Northern Forestry Office, 25 fires occurred in the Chernihiv Region in 2024, caused by artillery shelling, shell explosions, and the fall of rocket and drone fragments (Marchan, 2025). These fires affected 93.71 hectares of forest areas in the Chernihiv Region. In total, 151 fires occurred in the Sumy and Chernihiv regions due to military

actions in 2024, resulting in damage to more than 427 hectares of forest. According to reports from the Rubizhne City Military Administration website and materials provided by the Sievierodonetsk City Environmental Association Green World and the human rights organisation “Environment. People. Law”, as of 2022 (no new data is available due to the occupation of the region by Russian troops), 28,000 hectares of forests, predominantly coniferous, were damaged during combat actions in the Luhansk Region. According to the press service of the Kyiv City State Administration, it is known that since the beginning of the full-scale military actions in 2022-2024, over 1,300 trees have been damaged in the Sviatoshyn Forest Park Enterprise and 0.5 hectares of forest areas in the Darnytsia Forest Park Enterprise (As a result..., 2024).

According to materials provided by the Ukrainian National News Agency Ukrinform, as of 2024, 18,500 hectares of forests in the Sumy and Chernihiv regions remain mined (Almost 19 thousand..., 2024). Following de-occupation, 16,600 hectares of forests were cleared of mines in 8 branches of the state enterprise “Forests of Ukraine”, 5 of which are in the Sumy Region and 3 in the Chernihiv Region, while another 18,500 hectares require demining. The largest area of demined forests was in the Chernihiv branch of state enterprise “Forests of Ukraine” with 9,500 hectares. The territory under the jurisdiction of the Konotop branch of state enterprise “Forests of Ukraine,” covering more than 6,700 hectares, remains the most potentially contaminated with explosive ordnance. L. Shumilo *et al.* (2023) reported that in the temporarily occupied territories of the Luhansk Region, approximately 8,600 hectares of forest were lost due to illegal logging and other actions by the occupiers between 2014 and 2020 (no new data is available due to the occupation of the region

by Russian troops). According to information provided by experts from the society organisation Ecoaction, as of 2023, 126,000 hectares of forests in the Kyiv Region were damaged by combat actions, fires, and explosions of ammunition (As a result..., 2024). It is worth noting that a complete assessment of biodiversity losses, including the decline of certain animal populations, requires further research and monitoring, as many areas remain dangerous or inaccessible for detailed surveys.

The products of combustion and explosions (nitrogen oxides (NO₂), carbon monoxide (CO), heavy metals – lead (Pb), cadmium (Cd), mercury (Hg), uranium (U)) persist in the environment for extended periods, causing deterioration in air quality and plant health. Nitrogen oxides accumulate in plants, where they are converted into nitrates. Elevated concentrations of nitrate compounds (NO₃⁻), particularly sodium, calcium, and ammonium nitrates, have a toxic effect on plant stands, disrupting normal metabolism. Nitrogen oxides negatively impact plant chlorophyll, reducing the efficiency of photosynthesis, which leads to decreased energy production and slowed plant growth. The release of nitrogen oxides generates free radicals that damage plant cells, including cell membranes, proteins, and DNA. The increased soil acidity caused by acid rain makes heavy metals in soil layers more soluble and capable of penetrating deeper soil layers and aquifers. This can lead to groundwater contamination with heavy metals. Specifically, excessive lead concentrations in water can be toxic to humans who consume the water; high cadmium content can impair kidney function and cause other serious health problems; and copper and zinc in high concentrations can cause intoxication and water quality degradation. Table 1 presents data on heavy metal contamination of soils under forest stands at various depths in damaged forest areas.

Table 1. Heavy metal contamination of soils under forest stands at various depths in damaged forest areas

| Forest area | Depth, cm | Pb, mg/kg | Cd, mg/kg | Hg, mg/kg | U, mg/kg | Soil pH | Forest stand composition |
|--|-----------|-----------|-----------|-----------|----------|---------|--|
| Buda-Babynetska | 0-10 | 85 | 1.2 | 0.15 | 2.3 | 5.2 | Scots pine (<i>Pinus sylvestris</i>), pedunculate oak (<i>Quercus robur</i>) |
| | 10-30 | 54 | 0.8 | 0.09 | 1.7 | 5.5 | |
| | 30-50 | 22 | 0.4 | 0.05 | 1.1 | 5.8 | |
| Hetmanskyi National Natural Park, Crater No. 1 | 0-10 | 97 | 1.5 | 0.18 | 2.7 | 5.1 | Pedunculate oak (<i>Quercus robur</i>), silver birch (<i>Betula pendula</i>) |
| | 10-30 | 63 | 0.9 | 0.12 | 1.9 | 5.4 | |
| | 30-50 | 27 | 0.5 | 0.06 | 1.3 | 5.7 | |

Source: created by the authors

The analysis of the obtained data on heavy metal contamination in damaged forest soils revealed the following patterns: in all studied forest areas, the concentrations of Pb, Cd, Hg, and U were higher in the upper (0-10 cm) soil layer and gradually decreased with depth. These data are consistent with the processes of migration and accumulation of pollutants in surface layers due to atmospheric precipitation, biological absorption, and the limited mobility of heavy metals in the soil. The highest levels of contamination were recorded in Crater No. 1 of the Hetmanskyi National Natural Park, which could indicate more intense anthropogenic pressure or specific soil characteristics. In the Buda-Babynetska forest area, slightly lower levels of Pb, Cd, Hg, and U were observed, but they still indicate significant contamination. In the upper soil layer, the pH was lower (5.1-5.2), which could contribute to greater heavy metal mobility. With increasing depth, the pH increased (up to 5.8), which could reduce heavy metal availability due to the formation of less soluble compounds. Areas covered with pedunculate oak, silver birch, and Scots pine may have varying degrees of influence on heavy metal migration due to differences in root systems and litter properties. For example, oak might promote greater heavy metal accumulation in the litter layer, while pine might result in less leaching of metals into deeper layers.

High levels of carbon monoxide have altered the concentration of chlorophyll in plants, reducing their ability to transport oxygen and limiting oxygen access to plant tissues, thereby impairing respiration and reducing photosynthetic efficiency. The decrease in photosynthetic efficiency and the increase in gas exchange disturbances in plants has led to a loss of soil fertility and a reduction in agricultural crop productivity, which in turn has affected yields. Although CO itself is not highly aggressive to plant tissues, it can interact with other air pollutants, such as ozone or sulphur dioxide, to form toxic compounds that damage plant cells and the tissues of roots, stems, and leaves.

Lead accumulates in the roots, stems, and leaves of plants, disrupting normal water and nutrient absorption and causing a reduction in plant growth and development. Lead can inhibit the activity of essential enzymes, such as catalase, peroxidase, and other antioxidant enzymes, causing disruptions in metabolic processes, including water balance and photosynthetic functions. This toxic metal disrupts the transport of vital ions (calcium, magnesium, and potassium) across cell membranes, affecting the plant's electrolyte balance and its ability to maintain normal water pressure levels within cells. Lead can also hinder seed germination and root growth, limiting the plant's ability to develop and adapt normally in

contaminated environments. Additionally, by affecting the DNA structure of plants, it can lead to mutations and disruptions in replication and transcription mechanisms, ultimately impacting plant reproduction and survival.

Cadmium readily penetrates plants, accumulating in tissues and causing toxic effects such as the disruption of cellular metabolism of essential minerals like calcium, magnesium, and potassium, and a reduction in protein synthesis, leading to impaired enzyme system function. This results in decreased growth, plant vitality, and a reduction in their vitamin content. Cadmium reduces chlorophyll activity, disrupting photosynthesis processes through damage to chloroplasts and decreased energy production for metabolic processes. It induces oxidative stress, leading to the formation of free radicals that can damage lipid cell membranes, disrupting their integrity and function. Cadmium can replace essential elements, such as calcium (Ca), magnesium (Mg), and potassium (K), in plant cells, leading to disruptions in various biochemical processes and even halting growth.

Mercury, which settles in the stem and root parts of plants, reduces their photosynthetic capacity and induces oxidative stress. Mercury can be toxic to cells, damaging membranes and DNA, which leads to disruptions in plant growth and development. Gradually, mercury can accumulate in soil and water, potentially contaminating water resources and food chains, and negatively affecting animals and humans.

Mercury can inhibit the activity of enzymes involved in photosynthetic processes, such as ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO). This results in a decrease in photosynthetic activity, reducing the amount of organic matter produced and lowering plant productivity. An important function of RuBisCO is carboxylation. RuBisCO adds a molecule of carbon dioxide (CO_2) to ribulose-1,5-bisphosphate, a

five-carbon sugar, resulting in the formation of two molecules of 3-phosphoglycerate. This step is the first stage in carbon fixation and organic compound synthesis. RuBisCO also performs oxygenation. RuBisCO can bind oxygen (O_2) instead of CO_2 , leading to a process called photorespiration. Photorespiration is less efficient than photosynthesis because it reduces plant productivity by consuming energy for processes that do not result in the synthesis of organic compounds.

As uranium is a toxic element for the root system, it causes changes in its structure and function, which disrupts water and nutrient absorption and slows down overall plant growth. High concentrations of uranium can lead to the oxidation of cellular components, impairing their function and reducing photosynthetic efficiency, which in turn decreases the production of organic compounds. Uranium is a radioactive element, so its accumulation in plants leads to radiation exposure of cells. This causes mutations at the genetic level, affecting the reproductive capacity of plants and reducing their resistance to stress factors. This heavy metal affects soil acidity, altering its chemical composition and the availability of micronutrients to plants. This leads to a deficiency of essential growth elements such as calcium, magnesium, and phosphorus. The toxic metal can alter soil microbial activity, which in turn reduces the availability of nutrients for plants and their ability to resist diseases and stress. The disruption of water-regulating, soil-protecting, climate-regulating, and sanitary-hygienic functions of forests has negatively impacted local and global climates.

The long-term impact of heavy metal contamination on ecosystems, particularly groundwater, can have serious consequences, including for human health. Heavy metals, such as cadmium, mercury, lead, copper, and others, can penetrate soil and groundwater as a result

of industrial emissions, agricultural practices (e.g., the use of pesticides and fertilisers), or the aftermath of forest fires, which contribute to the release of pollutants from soils. Once in the soil, heavy metals can accumulate in various soil horizons, including aquifers, and gradually migrate into groundwater. As groundwater is often used for drinking water supplies, heavy metal contamination can lead to a deterioration in water quality, posing serious risks to public health. The toxicity of mercury, cadmium, and lead can lead to chronic diseases, including kidney and nervous system disorders, as well as an increased risk of cancer.

Analysis of information from open sources has identified the following key factors that have impacted forest ecosystems during combat actions: damaged and destroyed trees due to explosions, fires, and the passage of military equipment; accumulated heavy metals,

explosive residues, fuel, and other toxic substances; detonation of munitions and ignition of military vehicles; the spread of pests and tree diseases; restricted access to forest areas due to mines and unexploded ordnance; and unburied remains of deceased humans and animals.

The impact of aerial vehicles, such as planes, helicopters, rockets, and drones, carrying ammunition, explosives, and fuel, has caused significant damage to forest ecosystems. The blast wave, shrapnel, and other fragments have broken tree trunks, branches, and roots, resulting in mechanical damage to plants and triggering forest fires. Powerful explosions have formed craters, leading to tree falls, damage to root systems, and disruption of the soil layer. A similar rocket explosion occurred in February 2024 in a forested area near the village of Buda-Babynetska, Kyiv Region. Figure 1 shows the crater formed by the rocket explosion.



Figure 1. Crater formed by a rocket impact southeast of the village of Buda-Babynetska, Kyiv Region, in 2024

Source: Examination of a rocket crater in the Kyiv region (2024)

Employees of the human rights organisation “Environment. People. Law” recorded the presence of a water-filled crater, and upon inspection of the area, the destruction of forest cover within a radius of approximately 25 meters was discovered. The formation of a

water-filled crater indicated the destruction of the soil cover, which led to changes in the hydrological regime of the area and complicated the natural restoration of the ecosystem. The destruction of mixed forest cover near the village of Buda-Babynetska within a

25-metre radius indicated the loss of tree species (Scots pine (*Pinus sylvestris*), pedunculate oak (*Quercus robur*), silver birch (*Betula pendula*)) and shrub vegetation (common hazel (*Corylus avellana*), alder buckthorn (*Frangula alnus*), elder (*Sambucus nigra*)), which negatively impacted biodiversity, microclimate, and ecosystem functions, particularly air quality due to reduced photosynthetic activity. Additionally, soil and water contamination occurred due to explosive residues and heavy metals, causing long-term consequences for vegetation and fauna. The introduction of chemical substances into the soil altered the hydrological state of the area. Furthermore, explosions generated toxic inorganic and organic compounds, such as carbon monoxide, nitrogen dioxide, nitrogen oxides, and formaldehyde, which negatively affected the environment (Resolution of the..., 2021).

Mechanical damage was inflicted on trees and shrubs by ammunition fragments and small arms fire. Weakened plants were more susceptible to diseases and pests, as their immune and defence mechanisms were compromised. Moreover, non-viable plants were more prone to ignition, as their tissues were dry and easily combustible. Broken plant fragments served as ground fuel and leaf litter, increasing the risk of forest fire spread.

Forest fauna has been negatively impacted by various factors, including ecosystem changes, pollution, disruption of natural conditions due to human activity, forest fires, invasive species, and climate change. One consequence of these changes has been the transformation of vegetation cover, which is particularly noticeable in wartime conditions. In partially damaged or completely destroyed areas, synanthropisation processes have intensified, leading to the active spread of ruderal species. L. Zaviailova *et al.* (2022) analysed the role of ruderal plants in the restoration of vegetation cover in

transformed areas. Their research showed that the process of vegetation regrowth in cleared forest areas with destroyed upper tree canopy occurred relatively quickly. However, the regrowth in craters formed by artillery shell explosions was extremely slow, with almost no vegetation observed in the first year after the impact of military actions. Researchers noted the appearance of only a few common ragweed (*Ambrosia artemisiifolia* L.) and black locust (*Robinia pseudoacacia* L.) plants in one crater at the site of burned military equipment (Fig. 2), while no plants appeared in another crater (Fig. 3).



Figure 2. A crater area after shelling in 2022 with damaged military equipment, overgrown with *Ambrosia artemisiifolia* L. and *Robinia pseudoacacia* L.

Source: L. Zaviailova *et al.* (2022)

Due to its high resistance to adverse environmental conditions, particularly drought, common ragweed is capable of rapidly colonising damaged or burned lands. Additionally, this species has a high capacity for seed reproduction, allowing it to quickly occupy new territories and dominate them. The black locust actively spreads after ecosystem disturbances, thanks to its ability to grow rapidly and adapt to various conditions, including those created

after the burning of military equipment. The consequences of ragweed and black locust proliferation in these areas are significant. Ragweed, in particular, has a substantial impact on local flora, displacing native species and reducing biodiversity. Its aggressive reproduction disrupts natural food chains, as it is not always a primary food source for local animal species. Furthermore, ragweed is a potent allergen, significantly increasing the allergenic burden on the population, and causing seasonal allergies and other illnesses in people sensitive to its pollen. This leads to negative socio-economic consequences, including an increase in illnesses among the population, a decrease in labour productivity, and an increase in health-care costs. Figure 2 depicts a post-shelling crater overgrown with adventive plants *Ambrosia artemisiifolia* L. and *Robinia pseudoacacia* L., also showing a localised area with partially destroyed military equipment. In 2022, in the Hetmanskyi National Natural Park, within the Neskuchanske forestry in the Sumy Region, where combat actions occurred, craters 0.5 and 1 meter deep showed no signs of herbaceous cover or regrowth of annual plants. This is attributed to the high degree of damage to the soil and vegetation cover due to the thermal impact of the explosion and the absence of a seed bank of adventive plant species in the soil. Figure 3 presents a photograph of a crater area after shelling, with a completely destroyed herbaceous cover due to a fire that occurred in 2022.

Figure 3 demonstrates a crater area after shelling in 2022, where the herbaceous cover was completely destroyed by fire, indicating the severe ecological consequences of combat actions, particularly soil cover degradation and vegetation loss. The presence of damaged areas poses a threat of outbreaks of alien species such as curlycup gumweed (*Grindelia squarrosa*), common ragweed (*Ambrosia artemisiifolia* L.), spiny burr grass (*Cenchrus longispinus* (Hack.

Fernald), oleaster (*Elaeagnus angustifolia* L.), and black locust (*Robinia pseudoacacia* L.), and has caused changes in soil structure, reduced soil fertility, and slowed down natural ecosystem recovery processes. Also, the fire resulted in the displacement of local plant species such as timothy-grass (*Phleum pratense* L.), red fescue (*Festuca rubra* L.), red clover (*Trifolium pratense* L.), and common bentgrass (*Agrostis tenuis* Sibth.). The loss of these plants has led to a decrease in biodiversity and disruption of vegetation cover structure, complicating the self-restoration processes of meadow ecosystems. Moreover, the physicochemical properties of the affected soil areas have significantly changed, including increased acidity and decreased humus content, which negatively impact further vegetation succession. In such conditions, the advantage was with adventive species resistant to stress factors, which could alter the ecological balance and cause secondary degradation of biogeocoenoses. Table 2 presents data on the spread of ruderal and adventive species in damaged forest areas and the reduction of forest cover.



Figure 3. A crater area after shelling in 2022 with completely destroyed herbaceous cover due to fire

Source: L. Zavalova *et al.* (2022)

Table 2. Spread of ruderal and adventive species in damaged forest areas and reduction of forest cover

| Forest area | Percentage of forest stand damage, % | Herbaceous layer cover, % | Common ragweed (<i>Ambrosia artemisiifolia</i>), % | Black locust (<i>Robinia pseudoacacia</i>), % | Reduction of forest cover, % | Comment on tree species |
|--|--------------------------------------|---------------------------|--|---|------------------------------|---------------------------------|
| Crater near Buda-Babynetska Village | 70 | 20 | 15 | 3 | 25 | Destroyed young pine and oak |
| Hetmanskyi National Natural Park, Crater No. 2 | 90 | 10 | 8 | 0 | 30 | Death of <i>Quercus robur</i> |
| Hoholivski Hai tract | 50 | 35 | 5 | 4 | 15 | Damaged <i>Pinus sylvestris</i> |

Source: created by the authors

Table 2 shows that a significant spread of ruderal (*Ambrosia artemisiifolia*) and adventive (*Robinia pseudoacacia*) species was observed in damaged forest areas, which correlated with the degree of forest stand damage and the reduction in forest cover. The greatest losses of forest cover were observed in the Hetmanskyi National Natural Park (30%), where forest stand damage reached 90% and the death of pedunculate oak (*Quercus robur*) was noted. In the crater near the village of Buda-Babynetska, forest cover decreased by 25% due to the destruction of young pine and oak trees, with 70% forest stand damage. In the Hoholivski Hai tract, with 50% forest stand damage, forest cover decreased by only 15%, indicating a comparatively higher resilience of this community.

The lowest herbaceous cover (10%) was observed in the Hetmanskyi National Natural Park, which may indicate high soil degradation or slow vegetation recovery. The highest herbaceous cover (35%) was recorded in the Hoholivski Hai tract, which could be a result of active vegetation regrowth in damaged areas. The highest level of common ragweed (15%) was found in the crater near the village of Buda-Babynetska, indicating the aggressive spread of this allergenic species in degraded areas. Black locust (4%) was more prevalent in the

Hoholivski Hai tract, which may indicate active succession towards false acacia. The territory of the Zalissia National Natural Park (Hoholivski Hai tract), located in the forest area of the Brovary District of the Kyiv Region and the Chernihiv District of the Chernihiv Region, showed ruderalisation of the herbaceous layer (Fig. 4).



Figure 4. Damage to Scots pine trees (*Pinus sylvestris* L.) as a result of shelling in 2022

Source: L. Zavalova et al. (2022)

In the upper tier of coniferous forests, the presence of weed species from the *Chenopodium* L. s.l. a genus of the *Amaranthaceae* family

led to a change in the composition and structure of the forest biocenosis, a reduction in biodiversity, and competition for resources between native and invasive species, indicating significant anthropogenic pressure or natural changes. Damage to the upper tree canopy and soil cover due to military actions created conditions for the introduction and establishment of adventive alien plant species. In 2014, during

research in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve of the National Academy of Sciences of Ukraine, which was affected by combat actions and the movement of military equipment from the Rostov Region of Russia (Fedenko, 2023), the appearance of a new species of adventive plant, *Sporobolus cryptandrus* (Torr.) A. Gray, a perennial bunchgrass, was recorded for the first time (Fig. 5).



Figure 5. The emergence of the adventive plant sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray) on sands in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve in 2014
Source: G.V. Gouz & V.V. Timoshenkova (2017)

The invasive species *Sporobolus cryptandrus* (Torr.) A. Gray, found on sparsely vegetated sandy areas, has led to the displacement of local species such as feather grass (*Stipa* spp.), narrow-leaved bluegrass (*Poa angustifolia*), spring sedge (*Carex praecox*), fringed pink (*Dianthus pseudosquarrosus*), and spurge (*Euphorbia* spp.). Shelling of forests has resulted in the death and injury of animals, forcing them to migrate and move into open areas in search of safety. Additionally, loud noises and stressful conditions have negatively affected the reproductive capacity of domestic and wild animals, reducing their populations. Research by D.A. Buyval & A.M. Pasternak (2024) has shown that elevated levels of the metabolite Bhydroxybutyrate in the milk of cattle indicate reproductive

impairment, leading to a decrease in overall herd productivity and a reduction in the animals' ability to reproduce. Military actions have significantly impacted trophic chains in forest biocenoses through the destruction or substantial reduction of populations of certain species, leading to a disruption of the ecological balance. The death of predatory animals (wolves, foxes, lynxes, and birds of prey) has resulted in uncontrolled growth of their prey populations (small mammals such as hares, voles, various rodent species, and birds), while the reduction in herbivore populations, including deer, elk, roe deer, and wild boar, has affected vegetation regeneration. Research on the ecological consequences of military actions on the environment has revealed that in the long term, such

changes can lead to a depletion of biodiversity, alteration of ecosystem structure, and even its degradation. Furthermore, soil damage, contamination with toxic substances, and disruption of natural self-purification mechanisms complicate ecosystem recovery for decades.

The occurrence and spread of fires in natural ecosystems were influenced by favourable weather conditions, forest site types, and species composition, all of which increased the risk of natural fire hazards. During wartime, the causes of fires included the use of incendiary munitions, the deliberate burning of dry herbaceous cover and forest vegetation for tactical purposes – to create barriers, obstacles or to alter the direction of forest fires – and to control fire spread or reduce fire hazards. Significant damage was inflicted on biocenoses following forest fires. The destruction of plants, animals, and microorganisms led to ecosystem collapse and biodiversity loss. Combustion products, including smoke and toxic substances, were released into the atmosphere and spread over long distances, polluting the air and causing global environmental problems.

During combat actions, when firefighting was not conducted, fires spread over large areas. Z. Cheng *et al.* (2023) noted that after forest fires, insect pests (pine mistletoe (*Viscum*, family *Viscaceae*), bark beetles (*Scolytinae* Latreille, family *Curculionidae*), tortrix moths (*Tortricidae* or *Olethreutidae*, family *Lymantriidae*), termites (*Isoptera*, family *Termitidae*)) proliferated, and fungal diseases spread, including ringless honey mushroom (*Armillaria tabescens*, genus *Armillaria*) and root rot (*Heterobasidion annosum*, genus *Heterobasidion*), wood-decay fungi (genera *Phellinus* and *Trametes*), white rot (genera *Ganoderma* and *Fomes*), and arbuscular mycorrhizal fungi of the genera *Glomus*, *Ambispora*, *Paraglomus*, and *Acaulospora*. Tree diseases such as pine rust, fusarium wilt, and pine pitch canker also spread, leading to vegetation

damage and deterioration of forest ecosystem conditions. As forests lost important functions such as soil protection, water resource regulation, sanitary-hygienic, and ecological roles, landscape degradation, soil erosion, and water resource quality deterioration occurred. As a preventive measure against pine rust, fusarium wilt, and pine pitch canker, as well as pests, the treatment of seedlings and young pine trees with the bioorganic composition Mehanit Nirbator is recommended. This composition is based on biochemical fractions of basidiomycetes and is recommended for use by the Department of Physiology, Plant Biochemistry and Bioenergetics of the National University of Life and Environmental Sciences of Ukraine.

The research findings of O. Golan *et al.* (2022) demonstrated that the use of trap trees and treatment with the natural insecticide bifenthrin reduced the number of dead trees in stands, indicating the effectiveness of such measures in preventing the spread of bark beetles. K. Youssef (2023) found in his research that latent infections of Scots pine tree roots in areas with a low risk of root rot disease (*Heterobasidion annosum* s. l.) were quite common. Moreover, these infections were more frequent in areas with a higher site index, suggesting a greater likelihood of tree infection in more fertile soils. N. Erbilgin *et al.* (2021) reported that pines subjected to bark beetle attacks and drought exhibited a significant decrease in carbohydrate reserves, which limited their ability to synthesise protective diterpenes and increased the likelihood of tree death due to physiological depletion and mechanical damage to vascular tissue by beetles. In a study by C.J. Fettig *et al.* (2020), it was found that low doses of the chemical agent verbenone SPLAT® Verb (7 grams per tree) were effectively used to protect pine trees from a type of bark beetle, the mountain pine beetle (*Dendroctonus ponderosae* Hopkins),

providing long-term protection of trees from pests. J. Kuang *et al.* (2024) found that the use of multi-temporal satellite data significantly improved the accuracy of monitoring forest stands affected by pine wilt disease compared

to using single-time satellite images. Forests in active combat zones, affected by fires, cover 19.5% of Ukraine's territory (Fig. 6). This area spans a width of about 20 km on both sides of the front line.

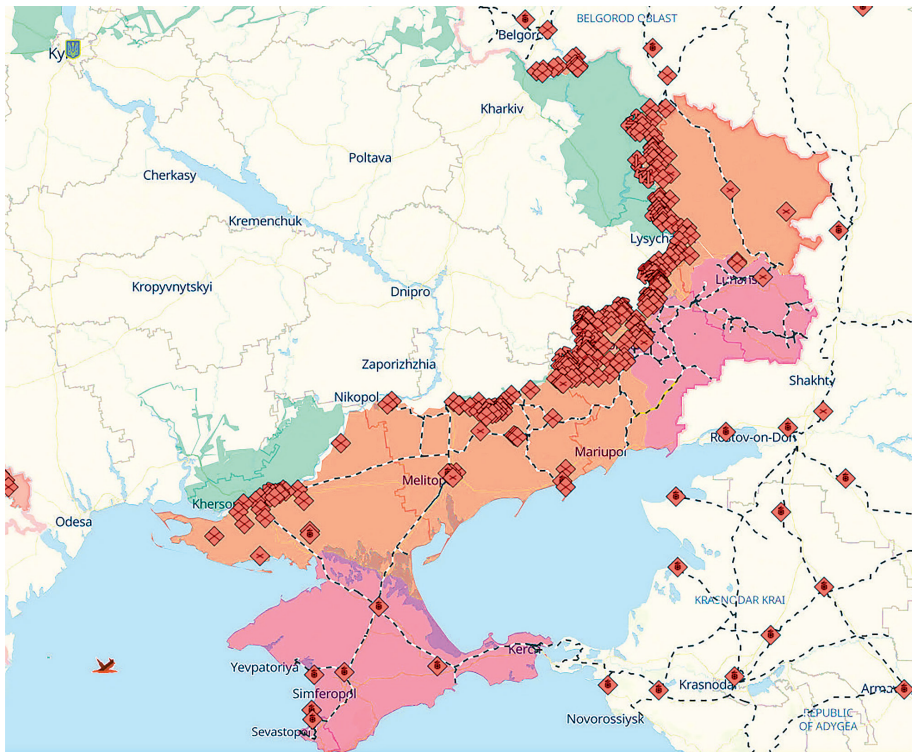


Figure 6. Map of combat actions in Ukraine as of 2nd March 2025

Source: DeepState (n.d.)

The map illustrates the situation on the front line in Ukraine as of 2nd March 2025. It includes data on active combat zones (dark red or brown), temporarily occupied territories (red), and territories liberated between late March 2023 and early April 2024 (blue). Combat actions in the conflict zone have negatively impacted forests, increasing the risk of large-scale fires.

Forest fires have been a significant source of environmental pollution and greenhouse gas emissions. As of early 2024, more than

8,000 hectares of forest land in temporarily occupied territories and combat zones were affected by forest fires, resulting in CO₂ emissions of 2,300 tonnes (based on estimates that 49,600 hectares were burned in 214 days of full-scale war, resulting in 14,336,000 tonnes of CO₂ emissions) (Occupants announce area..., 2024). The destruction of forests has also affected the local climate, causing changes in precipitation patterns and increasing the risk of droughts, which negatively impact agricultural

production and, in turn, affect the country's food security. However, these impacts are not limited to the local level. Large-scale forest fires in Ukraine also contribute to global climate change, as CO₂ emissions from burned forests increase the overall concentration of greenhouse gases in the atmosphere.

Research indicates that significant losses of forest cover can lead to a reduction in precipitation due to the disruption of local and regional water cycle mechanisms. Forests play a crucial role in moisture evaporation and cloud formation, and their degradation can cause changes in atmospheric circulation, reduced air humidity, and prolonged periods of drought in the European region. Furthermore, the reduction in forest area has decreased their ability to absorb CO₂, which has amplified the greenhouse effect and contributed to overall warming. Forest ecosystem restoration is a critical task for mitigating climate change and preserving ecological balance. In addition to directly reducing CO₂ emissions, reforestation will contribute to the restoration of local water balance and reduce the risk of extreme weather events, such as droughts and abnormal temperatures.

The movement of military equipment has resulted in the breaking of trees and shrubs, the destruction of herbaceous cover, damage to plant roots, and soil compaction, which has hindered natural regeneration. Trees were felled and used to create shelters, dugouts, and camouflage structures to conceal military equipment, reducing its visibility from the air and the likelihood of detection by the enemy. It is important to note a trend towards a 5% decrease in carbon content at an average soil temperature of 15°C after forest clearing and the digging of equipment emplacements, leading to the destruction of the soil's humus horizon and a reduction in its fertility in 2024.

The construction of dugouts, defensive fighting positions, and trenches have disrupted

the fertile soil layer by mixing it with deeper, less fertile horizons, reducing its biological activity. Furthermore, soil compaction and erosion processes have led to ecosystem degradation. Military activities have altered the terrain in forest environments, creating new depressions (defensive fighting positions, trenches, and craters) and destroying hills and irregularities, which has changed the hydrological regime of the area, promoting waterlogging or, conversely, increasing the risk of erosion. The main measures for restoring damaged ecosystems after the cessation of hostilities include soil remediation, tree and herbaceous cover planting, restoration of the water regime, and gradual natural ecosystem recovery. The ecological consequences of destroying plant root systems in forest ecosystems include the destruction of soil structure, reduced soil erosion resistance, and decreased moisture retention, leading to land degradation and biodiversity loss. Alternative methods for camouflaging military equipment that would cause less environmental damage include the use of camouflage nets, natural terrain irregularities, artificial shelters made from environmentally safe materials, and digital technologies to reduce visibility in infrared and radar ranges.

Forest ecosystems play a key role in ensuring the ecological security of the state, as their primary function is to regulate water balance, maintain soil fertility, and preserve biodiversity. In addition to their ecological significance, forests are also a source of resources for forestry, hunting, and agriculture. Uncontrolled logging, driven by military needs and the use of wood as fuel, has had negative consequences for forest ecosystems, leading to reduced forest cover, habitat destruction, decreased forest capacity to absorb carbon dioxide (CO₂), hydrological imbalance, desertification, and the transformation of forests into areas unsuitable for regeneration, biodiversity loss, and soil

degradation and fertility reduction. Moreover, these negative impacts have led to changes in microclimate, increased erosion risk, and reduced access to natural resources, contributing to food crises in affected regions, particularly in the eastern and southern regions of Ukraine. It is important to note that the destruction of the Kakhovka Hydroelectric Power Plant has led to the destruction of the irrigation system in southern regions, negatively impacting agriculture and food security.

According to the Accounting Chamber of Ukraine, during the full-scale Russian invasion of Ukraine (as of the end of 2022; more current data as of 2025 is unavailable due to martial law), 3 million hectares of forest were damaged and permanently destroyed (Panchenko *et al.*, 2023). The restoration of damaged and burned forests will take 20-30 years. According to information provided by the Operational Headquarters for Recording Environmental Crimes, the regions most affected by mining and forest fires due to enemy shelling and deliberate arson were: Chernihiv Region, where nearly 400,000 hectares of forest were damaged; Sumy Region, where approximately 290,000 hectares of forest plantations were destroyed; Luhansk Region, where approximately 200,000 hectares of forest were lost; and Kyiv, Zhytomyr, and Kharkiv regions, where 120,000 to 160,000 hectares of forest land were damaged in each region.

Military actions have significantly impacted the biodiversity of the terrestrial plant layer through mechanical damage to vegetation during the movement of equipment, construction of fortifications, and explosions. This has led to the destruction of natural habitats, a reduction in species numbers, and even the complete elimination of rare flora. Plants that grow only in specific ecological conditions have been particularly affected. These include endemic species (such as those from the *Caryophyllaceae*

or *Orchidaceae* families), relict species (such as yew (*Taxus baccata*), ginkgo (*Ginkgo biloba*), sundew (*Drosera*), dwarf palmetto (*Sabal minor*), and white waterlily (*Nymphaea alba*)), as well as red-listed plants (such as edelweiss (*Leontopodium alpinum*) or pheasant's eye (*Adonis vernalis*)), which have a limited distribution range.

Unburied bodies of deceased soldiers and animals have become a source of disease transmission, including infectious diseases (such as tularemia, leptospirosis, anthrax, and rabies), which are transmitted through contact with the body or from insects that infest the corpses. Zoonoses, such as rabies and salmonellosis, are spread through contact with dead animals. Insects such as flies, ticks, and fleas, which act as vectors for infection, have also proliferated. The improper burial of bodies in forests leads to groundwater contamination, including the leaching of toxic substances like ammonia from the bodies into the soil and groundwater, the contamination of aquifers with pathogens that can cause diseases in humans and animals, and the release of various biological agents and organic residues, resulting in ecosystem imbalance and environmental resource contamination.

Territories contaminated with unexploded mines and ordnance due to military actions can be categorised into several types: areas with active mines or unexploded ordnance posing an immediate threat to humans and animals; forest massifs where reforestation is impossible due to the danger of active mines and ordnance; and areas requiring specialised treatment and clearance before they can be used for forestry or other activities. The destruction of forest ecosystems has significantly impacted the economies of regions where forestry is the primary sector. Mass forest losses have reduced timber harvesting volumes, led to job losses, and deprived local populations of income. Furthermore, the mining of forest areas due to combat actions has made their use for economic

purposes impossible in the long term, posing a threat to human life, limiting regional economic development opportunities, and requiring significant financial resources for demining and restoration. Consequently, poverty levels have risen among the population, particularly in rural areas where forests are a source of income. The loss of natural resources has forced people to migrate, contributing to demographic changes and weakening local communities.

Postconflict forest restoration is a complex process that requires a comprehensive approach, including natural regeneration mechanisms and targeted ecosystem restoration measures. One of the key natural mechanisms is the symbiosis of mycorrhizal fungi with plant root systems, which improves nutrient access, enhances resistance to drought and pathogens, and accelerates forest soil recovery. Soil microorganisms play an important role in this process, ensuring organic matter decomposition, nitrogen enrichment, and the creation of favourable conditions for tree seed germination. Additionally, forests can self-regenerate through seed regeneration and vegetative reproduction, which depends on the ability of certain tree species to form root offspring and adapt to altered environmental conditions. To accelerate natural recovery, a set of measures aimed at stabilising the ecosystem and restoring forest cover must be implemented. First and foremost, the condition of soils and ecosystems must be assessed through laboratory analysis of heavy metal, explosive residue, and toxic element contamination, as well as an evaluation of soil erosion and moisture levels. One effective measure is the introduction of mycorrhizal fungi, which helps improve soil biota and stimulate tree growth. Additionally, the use of seedlings with a closed root system is advisable, as it increases their survival rate and ensures rapid restoration of forest areas. To stabilise the soil and prevent erosion processes, hydroseeding,

which involves sowing herbaceous plants and shrubs with added fertilisers and mulch, can be used. Phytoremediation, the planting of plants capable of accumulating and neutralising heavy metals, such as poplar, willow, and sunflower, is a crucial component of the recovery process. Furthermore, the use of green manure crops, particularly lupine and clover, helps improve soil structure and facilitate its recovery. Monitoring the condition of forest ecosystems should be carried out through the observation of flora and fauna, remote sensing, and the use of bioindicators, such as lichens and mosses, to assess atmospheric pollution levels. Therefore, effective post-conflict forest restoration requires the integration of natural regeneration mechanisms with modern technologies, including mycorrhisation, planting of trees with a closed root system, hydroseeding, and the application of biological preparations, which will promote rapid ecosystem recovery, enhance their ecological resilience, and ensure biodiversity conservation.

The National Council for the Recovery of Ukraine from the War has developed a draft of the Recovery Plan of Ukraine (draft) (2022), which includes materials from the Working Group "Environmental Security". In total, the Recovery Plan of Ukraine includes 76 environmental projects with a total budget of EUR 25.5 billion. The Recovery Plan of Ukraine in the field of environmental safety envisages the implementation of measures in three stages: the first stage (2022) has already been completed. It involved the development of a methodology for determining damage and losses caused by the destruction or damage of Ukraine's forest fund, forest plant species, and damage to bioresources. The second stage (2023-2025) is to include the development of an Action Plan for the implementation of the State Strategy of Forest Management in Ukraine up to 2035, the implementation of projects for the

restoration and modernisation of environmental infrastructure, and the introduction of modern technologies to reduce pollution and improve environmental quality. The third stage (2026-2032) aims to achieve sustainable development, integrate environmental standards into all sectors of the economy, and ensure environmental safety at the national level. The presence of craters formed by explosions, as well as the destruction of vegetation cover, has led to the disruption of the hydrological regime, particularly changes in the water balance of forest areas. The restoration of Ukraine's forest ecosystems after the hostilities is necessary, including the implementation of measures such as soil decontamination from toxic substances, vegetation cover restoration, and water resource monitoring.

Discussion

Analysing the obtained research results, it can be concluded that the increased intensity of wildfires due to military actions has negatively impacted natural ecosystems. In particular, one of the most critical problems was the disruption of vegetation recovery, which led to biodiversity loss and changes in the structure and functioning of forest phytocoenoses, with long-term consequences for the stability and resilience of these ecosystems.

It was established that the increased intensity of wildfires and deforestation in temporarily occupied territories and combat zones in 2024 had severe negative consequences for the ecosystem, particularly for forest soils, due to a decrease in soil organic carbon content. A similar issue was raised by F. Niccoli *et al.* (2023). The authors found that fires significantly reduced the ability of trees to photosynthesise and absorb carbon dioxide (CO₂) due to defoliation and crown damage. The results of the current study did not align with the conclusions of F. Niccoli *et al.*, as the current study investigated

the impact of soil organic carbon on forest ecosystems rather than the physiological state of trees, as in the research by the analysed authors. In the case of the conducted research, the impact of soil organic carbon may be a longer-term process, with its consequences becoming apparent over a more extended period. In the short term, even if trees have sustained significant damage, the soil may continue to change due to the burning of organic matter and the disruption of soil structures. The research by F. Niccoli *et al.* was conducted in central Italy, while the present study was carried out in Ukraine, leading to differences in conclusions. Geographical factors, such as climate, soil types, flora, and fauna, can influence the recovery of forest ecosystems after fires. The current study employed methods assessing soil organic carbon content, focusing on the chemical and physical characteristics of the soil, whereas F. Niccoli *et al.* research concerned tree physiology. The response to fires may vary depending on the type of forest ecosystem (e.g., coniferous or deciduous forests). It is important to consider that soil organic carbon in deciduous forests generally has different properties than in coniferous forests. Fires can have varying impacts on different tree types and, consequently, on soil organic carbon.

The reduction in soil organic carbon content in forest ecosystems in temporarily occupied territories and combat zones in 2024 is directly related to the impact of deforestation and the digging of emplacements for military equipment, which affected the topsoil layer (Matkivskyi & Taras, 2024). J. Adkins & J.R. Miesel (2021) have also studied this topic. Their research showed that at high soil temperatures (up to 200°C), the soil's ability to absorb carbon decreased. Similar conclusions were reached in the presented study, as the results indicate a trend towards a decrease in carbon content at an average soil temperature of 15°C

after deforestation, leading to the destruction of the soil's humus horizon and a reduction in its fertility.

According to the conclusions of the current study, soil organic carbon content decreased by 5% in 2024, which is associated with soil degradation following deforestation. E. Grieco *et al.* (2024) also studied this problem. They found that the conversion of primary forests to other land cover types significantly affected total carbon stocks, particularly aboveground biomass carbon and soil organic carbon. A 5% reduction in soil organic carbon content after deforestation is a significant indicator, as organic carbon is a crucial component of soil ecosystems and plays a key role in maintaining soil fertility and climate stability (Lozinska *et al.*, 2024). In pristine forest ecosystems, soil organic carbon content can vary, but it is generally significantly higher compared to anthropogenically altered areas (Kruglov *et al.*, 2023). For example, soil organic carbon content in natural forests can range from 20 to 80 t/ha, depending on the forest type, climatic conditions, and soil type. This correlates with data obtained by E. Grieco *et al.*, who found that the conversion of primary forests to other land cover types, such as agricultural or industrial land, reduces soil organic carbon due to a decrease in aboveground biomass. A 5% reduction in carbon content can have serious long-term consequences (Romanchuck *et al.*, 2017). If this process continues, it can lead to soil degradation, reduced soil capacity to retain moisture and nutrients, as well as decreased biodiversity and increased greenhouse gas emissions. Furthermore, long-term carbon loss can impair the ability of ecosystems to recover from anthropogenic changes. Thus, comparing the results of this study with the research of E. Grieco *et al.* confirmed that changes in soil organic carbon after deforestation are critical for ecosystem stability and

require urgent measures for the preservation and restoration of forest ecosystems.

It was noted that in January 2024, more than 8,000 hectares of forest land were affected by forest fires in temporarily occupied territories and active combat zones, resulting in CO₂ emissions of 2,300 tonnes and the accumulation of greenhouse gases in the atmosphere. A. Brito *et al.* (2022) studied a similar problem. The scientists found that increased greenhouse gas emissions and deforestation had severe consequences for the local ecosystem, including a reduction in biodiversity, forest degradation, and disruption of the water balance, as well as a decrease in groundwater levels, which negatively affected agricultural production. This assertion can be agreed with, as the degradation of forest ecosystems indeed reduces the ability of forests to absorb carbon dioxide, further increasing the concentration of greenhouse gases.

High concentrations of zinc, manganese, copper, lead, and other metals in soil after the 2022-2024 forest fires posed a danger to the environment (Biyashev *et al.*, 2024). G. Singh *et al.* (2021) raised a similar issue. The authors obtained results showing that the metal pollution index ranged between 1.84 and 6.62, and plants growing in areas S10 to S17 accumulated particularly high concentrations of metals. The assertion of G. Singh *et al.* can be agreed with, as the process of phytoextraction can negatively affect plant growth, reduce their viability, and even cause death.

It was established that soil compaction in 2022-2024 due to the movement of heavy military equipment and vehicles caused damage to its structure and degradation of the soil environment. M.R. Shaheb *et al.* (2021) have studied a similar issue. The researchers obtained results showing that soil compaction increased its bulk density and strength, decreased porosity and hydraulic properties, and slowed the root growth of forest plant species. The assertion of

M.R. Shaheb *et al.* can be agreed with, as delayed root growth indeed reduces the efficiency of nutrient and water absorption by plants.

It was found that after fires caused by military actions in 2014, a new species of adventive plant, sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray), appeared in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve, displacing local species such as feather grass (*Stipa* spp.), narrow-leaved bluegrass (*Poa angustifolia*), spring sedge (*Carex praecox*), fringed pink (*Dianthus pseudosquarrosus*), and spurge (*Euphorbia* spp.). A.K. Verma *et al.* (2024) have studied a similar issue. In their research, the authors found that invasive plant species not only increased the frequency and intensity of forest fires but also changed the structure of local ecosystems, suppressed the growth of native species, and created conditions conducive to the further spread of invasive plants. This assertion should be agreed with, as invasive species are indeed capable of accumulating large amounts of dry biomass, which becomes highly flammable material.

It was demonstrated that the upper parts of plants, particularly trees, shrubs, and grasses, were most vulnerable to fires. A similar study was conducted by A. Ishak (2024). The researcher's results showed that during periods of low humidity and high temperatures, the protected and tourist zones of the national park were particularly vulnerable to forest fires. This assertion can be agreed with, as low humidity reduces the water content in plants and soil, making them more susceptible to ignition, and high temperatures promote faster drying of vegetation and increase the likelihood of outbreaks.

For the effective protection of Scots pine trees against pathogens of pine rust, fusarium wilt, and pine pitch canker, as well as against pests such as pine mistletoe (*Viscum*, family *Viscaceae*), bark beetles (*Scolytinae Latreille*, family *Curculionidae*), tortrix moths (*Tortricidae*

or *Olethreutidae*, family *Lymantriidae*), and other insect pests, the use of the innovative preparation Mehanit Nirbator is recommended. This preparation is based on biochemical fractions of basidiomycetes and is designed for the restoration of forest resources after fires. K. Zhang & J. Stenlid (2023) studied a similar issue. Their research revealed that protocols for monitoring and managing Scots pine blister rust epidemics, designed to detect the rust fungus (*Cronartium pini*), were effective and specific for identifying this fungus in Scots pine samples. Using these protocols, they were able not only to detect the presence of this pathogen in asymptomatic and symptomatic trees but also to track the emergence of Scots pine blister rust in Northern Europe. The conclusion of K. Zhang & J. Stenlid is agreeable, as the application of these developed protocols allows for the timely detection and control of the spread of Scots pine blister rust, contributing to the effective management of the phytosanitary condition of forest stands and reducing economic and ecological losses.

It was observed that at the crater site resulting from shelling in 2022 within the Hetmanskyi National Natural Park, specifically in the Neskuchanske forestry of the Sumy Region, there has been a proliferation of non-native plant species such as curlycup gumweed (*Grindelia squarrosa*), common ragweed (*Ambrosia artemisiifolia* L.), spiny burr grass (*Cenchrus longispinus* (Hack.) Fernald), oleaster (*Elaeagnus angustifolia* L.), and black locust (*Robinia pseudoacacia* L.). This has led to the displacement of native plant species, including timothy-grass (*Phleum pratense* L.), red fescue (*Festuca rubra* L.), red clover (*Trifolium pratense* L.), and common bentgrass (*Agrostis tenuis* Sibth.). A similar issue was studied by M. Harrison *et al.* (2024). Their research indicated that the burned forest not only experienced significant structural and microclimatic changes but also suffered substantial biodiversity loss, particularly in

the species diversity of trees, molluscs, and butterflies. The conclusions of M. Harrison *et al.* are valid, as the loss of habitats, changes in resource availability, and other ecological factors following a fire can significantly alter an ecosystem.

This section has reviewed studies on the ecological consequences of forest fires and military-related activities on natural ecosystems. Particular attention was paid to the impact on forest soils, specifically the reduction of soil organic carbon, which is a crucial factor in maintaining soil health and ecosystem stability. In the context of the studied ecological impacts of forest fires and military activities on natural ecosystems, especially forest soils, it is necessary to consider possible strategies for the restoration of damaged forest areas. These include implementing measures to restore biodiversity through the planting of native trees and plant species that support natural ecosystem regeneration. Habitat restoration programs for native species, such as feather grass, sedge, and other grasses, will help prevent the displacement of local species by invasive plants. This can be achieved through methods to control invasive species, such as mechanical removal or limiting their spread using chemical or biological means.

Conclusions

During the 2024 study, the following tasks were carried out: as a result of the analysis of the impact of military actions on forest ecosystems, it was found that military activities caused serious ecological consequences, including the transformation of vegetation cover, a decline in biodiversity, and disruption of trophic chains. In identifying the main factors of forest damage, it was noted that the primary causes were fires resulting from military actions, leading to the death of a portion of the flora and fauna, as well as the spread of pests and diseases among woody plants. Recommendations for forest

restoration were developed, and a set of measures was proposed for the rehabilitation of forest ecosystems, including strategies for combating invasive species, restoring soil cover, and preserving biodiversity.

Based on theoretical research using open-source information, it has been shown that in 2014, the emergence of a new species of adventive plant, sand dropseed, was first recorded in the Trokhizbenskyi Steppe branch of the Luhansk Nature Reserve of the National Academy of Sciences of Ukraine. This led to the displacement of native species such as feather grass, narrow-leaved bluegrass, spring sedge, fringed pink, and spurge. The impact of explosions and forest fires destroyed important tree and shrub species, including Scots pine, pedunculate oak, and silver birch, as well as shrubs like common hazel, alder buckthorn, and elder. Following the damage to territories and the formation of craters, there was a noticeable spread of invasive species, particularly ragweed and black locust. The loss of native plant species, such as timothy-grass, red fescue, red clover, and common bentgrass, disrupted the structure of the herbaceous cover, negatively affecting food chains in forest ecosystems. The replacement of natural species with ruderal and invasive plants altered ecosystem functions, such as carbon sequestration, soil stability, and water balance.

For the effective restoration of forest ecosystems following military actions, it is proposed to conduct a detailed analysis of soils to determine the level of contamination by heavy metals, toxic elements, and explosive residues. The introduction of mycorrhizal fungi into soils damaged during military activities is recommended, as it will contribute to faster ecosystem and forest biota recovery. For the rapid restoration of forest areas, it is advisable to use seedlings with a closed root system, which increases their survival rate in damaged soil conditions. Hydroseeding herbaceous plants and

shrubs with added fertilisers and mulch can help restore soil cover more quickly, protecting it from erosion, improving soil structure, and increasing its fertility.

The limitation during the 2024 study of areas affected by forest fires was the unavailability of data on the precise level of soil contamination with heavy metals and explosive residues in some zones. This limited the ability to accurately assess the extent of contamination and its impact on ecosystem recovery processes. The study did not account for additional factors that may affect recovery, such as changes in climatic conditions, the level of anthropogenic

pressure on forest ecosystems after military actions, and the potential impact of invasive species on biodiversity and ecosystem resilience. The prospect for further research includes conducting more detailed monitoring of ecological changes in regions damaged by military actions to develop more effective methods for restoring forest ecosystems.

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None.

Conflict of Interest

None.

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Вплив бойових дій на лісові екосистеми: виклики для довкілля, національної безпеки та стійкості держави

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Анотація. Метою дослідження був аналіз впливу активних військових дій на біорізноманіття та лісові ресурси. У дослідженні використано такі методи: аналіз супутникових даних з відкритих джерел та повідомлень ЗМІ, а також методи узагальнення та систематизації. Встановлено, що накопичення сухої біомаси після пожеж сприяло поширенню лісових пожеж. Утворення кратероподібних западин внаслідок вибухів змінило склад лісових насаджень та водний баланс, що вплинуло на водопостачання регіону та призвело до перезволоження або висушування земель. Результати дослідження свідчать, що у 2024 році після обстрілу лісового масиву поблизу села Буда-Бабинецька Київської області було знищено лісовий покрив у радіусі 25 метрів. Серед них такі види рослин, як сосна звичайна (*Pinus sylvestris*), дуб черешчатий (*Quercus robur*) та береза срібляста (*Betula pendula*). Аналіз інформації з відкритих джерел та повідомлень у засобах масової інформації показав, що рудеральні види, такі як амброзія полинолиста (*Ambrosia artemisiifolia* L.) та лобода чорна (*Robinia pseudoacacia* L.), колонізували пошкоджені ділянки. Це свідчить про активне заселення рослинності видами, здатними до швидкого відновлення після порушень. У зонах вибухових кратерів процеси відновлення рослинного покриву відбувалися повільно.

Наприклад, в одному з кратерів Гетьманського національного природного парку в Сумській області було зафіксовано лише кілька екземплярів амброзії та чорної сарани, тоді як інший кратер залишився без будь-якої рослинності. Для сприяння відновленню лісів в Україні після припинення активних бойових дій було рекомендовано застосування мікоризних грибів, використання саджанців, вирощених у контейнерах, та гідропосіву. Отримані дані про стан лісових масивів можуть сприяти розробці стратегій збереження та відновлення пошкоджених пожежами лісових екосистем

Ключові слова: пожежі; воронки; інвазії; рудеральні види рослин; біорізноманіття; рослинний покрив