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ECOLOGICAL CONSEQUENCES OF MISSILE STRIKES ON FOREST ECOSYSTEMS: A CASE STUDY FROM THE BUDA-BABYNETSKA AREA, KYIV REGION, UKRAINE

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Abstract

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War and armed conflicts have tragic and devastating consequences for people, biodiversity and the environment. Among all the numerous impacts, one of the most destructive and long-lasting is the explosion of munitions, especially missiles. Despite the large territories affected by explosions, research about their comprehensive impact on ecosystems is fragmentary and insufficient. This study aims to conduct a complex assessment of the consequences of a ballistic missile explosion on the geological environment, soils and vegetation using the case study of a crater near the village of Buda-Babynetska (Kyiv region, Ukraine). The explosion caused the mixing of soil and rocks, resulting in significant changes in geological diversity, soil structure and its physicochemical properties. Despite the high potential for the restoration of native pine-oak forest in the affected area, several issues that may hinder this have been discussed, including the reduction of soil organic matter, the shift towards sand-dominated substrates and the introduction of alien species. Continued long-term monitoring will be essential to determine the direction of ecosystem development.

Key words: explosion, vegetation, landscape transformation, bombturbation, restoration.

Introduction

Russia's military aggression against Ukraine has provoked devastating harm to human lives, destroyed ecosystems and caused widespread environmental destruction (Hryhorczuk et al., 2024; Karamushka et al., 2025; Khrushch et al., 2023; Pereira et al., 2022). Among all the consequences caused by military action in Ukraine, the shelling by artillery and missiles of different calibres has caused the most serious and long-term consequences for biodiversity, geological environment and ecosystems, as well as human well-being (Bausinger et al., 2005, 2007).

In the first seconds after the missile explosion, a large amount of air pollutants is released, including gases such as ammonia, carbon monoxide, sulphur dioxide, nitrous oxides, methane, carbon dioxide and chlorofluorocarbons, as well as particles such as dust, dirt, soot and smoke (Boychenko et al., 2025; Leal Filho et al., 2024). However, air pollution is usually dynamic and short term. Still, over time, the substances eventually settle onto the soil and dissolve in water, leading to soil toxicity and contamination of both surface and groundwater.

Among the many consequences of missile explosions, the most harmful and persistent are those that destroy biodiversity, landscapes, the geological environment and soils. The blast wave destroys all vegetation within its impact radius and can also kill other forms of wildlife (Karamushka et al., 2025; Leal Filho et al., 2024; Solokha et al., 2023). It destroys landscapes and geodiversity. The explosion mixes rock layers, compacts soil, reduces water infiltration, depletes nutrients and minerals, diminishes microbial activity and bioavailability, increases toxicity and accelerates erosion and degradation (Baliuk et al., 2024; Leal Filho et al., 2024; Petrushka et al., 2024; Solokha et al., 2023). Another serious issue is pollution by heavy metals, whose concentrations can exceed the maximum permissible limits, sometimes several times higher for elements such as Ti, Zn, Cu and Ni (Krainiuk et al., 2025; Leal Filho et al., 2024; Petrushka et al., 2024). Increased levels of these elements can reduce plant growth by approximately 5–10% and significantly challenge ecosystem restoration processes (Petrushka et al., 2024).

Due to several reasons, primarily related to limited access to the affected areas and security concerns, the impacts of military actions are generally assessed using remote methods (Baliuk et al., 2024; Matsala et al., 2024). However, detailed and comprehensive evaluations of the environmental and biodiversity effects of missile explosions are extremely rare and fragmented. At the

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same time, understanding the complex impacts of the explosion on the living and non-living components of the ecosystem is necessary for making informed decisions regarding restoration and the potential future use of damaged areas.

This study aims to assess the impacts of missile explosions on the geological environment, soils and vegetation with a set of integrated methods, using a case study of a ballistic missile crater and the associated damage to a forest ecosystem near the village of Buda-Babynetska in the Kyiv Region (Ukraine).

Methods

Study area

The study area was located near the village of Buda-Babynetska in the Kyiv Region (Ukraine), where one of the Russian missiles detonated in a forested area during the attack on February 15, 2024 (N 50.61528°, E030.07225°) (Fig. 1). The type of missile is unknown, but the trajectory of the fall and the result of the explosion indicate that it was a ballistic missile. According to satellite imagery, the trees of the research area had been cut down less than two decades ago, but since then, the area has experienced substantial natural regeneration, with tree heights reaching up to 15 m. The explosion created a crater approximately 15 m in diameter and 6 m deep, partially filled with groundwater. No remediation efforts have been implemented during the first years after the explosion. However, precipitation and wind activity have gradually transformed the crater.

By May 2024, fallen trees, primarily *Pinus sylvestris*, *Quercus robur* and *Betula pendula*, were observed within a 32- to 35-m radius of the blast site. While most trees were charred and dead, early indicators of ecosystem regeneration were observed. From the geological and geomorphological structure perspective, the territory of the study area belongs to the Polissia Lowland. It is represented by a denudation-accumulative type of relief. The relief was formed in the Middle Pleistocene. Subsequent long-term exogenous processes significantly reworked its surface. The location contains traces of the cumulative work of the glacier. The corresponding relief forms are determined here: eskers, moraine hills, small dunes and others (Tectonic map of Ukraine, 2007). The elevation above sea level is 162–168 m.

Environmental survey

To study the geological environment, including soils, along the slope of the northern-facing crater, nine sedimentary rock samples were taken at 1-m intervals from the water surface of the crater bottom upwards in July 2025 (Fig. 2). Samples were collected from the surface, vertical and horizontal exploratory pits, 20–60 cm deep. During field work, soil/sand samples were taken to study the hardness and pH of soils. The analysis was performed using indicator strips. A total of nine samples from one profile were analysed (Table 1). The study of the ecological state of the soil from the surface was carried out by two pits to a depth of 70 cm in the explosion impact zone (at a distance of 10 m from the edge of the crater) and in a pristine area of pine forest (20 m from the fire zone).

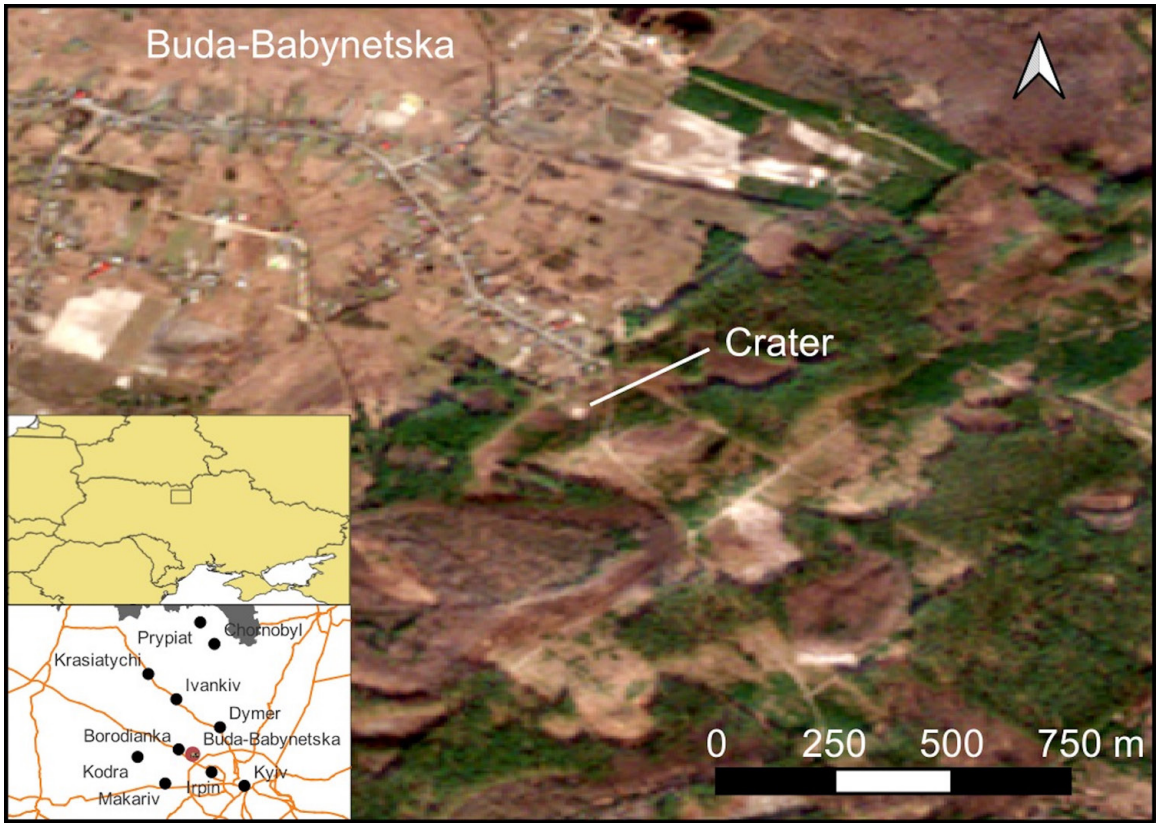


Fig. 1. Location of the study area on the outskirts of Buda-Babynetska, Kyiv Region, Ukraine.

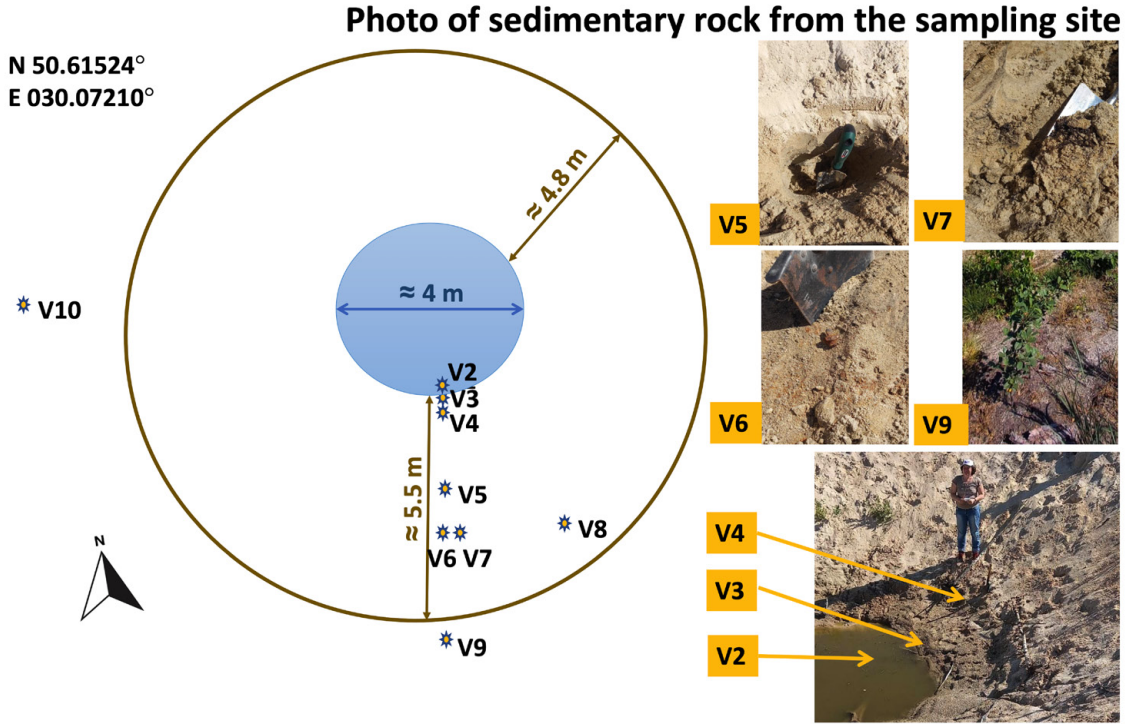


Fig. 2. Scheme of sedimentary rock samples collected at 1-m intervals from the water surface of the crater bottom upwards to the crater edges (Photos by K. Derevska).

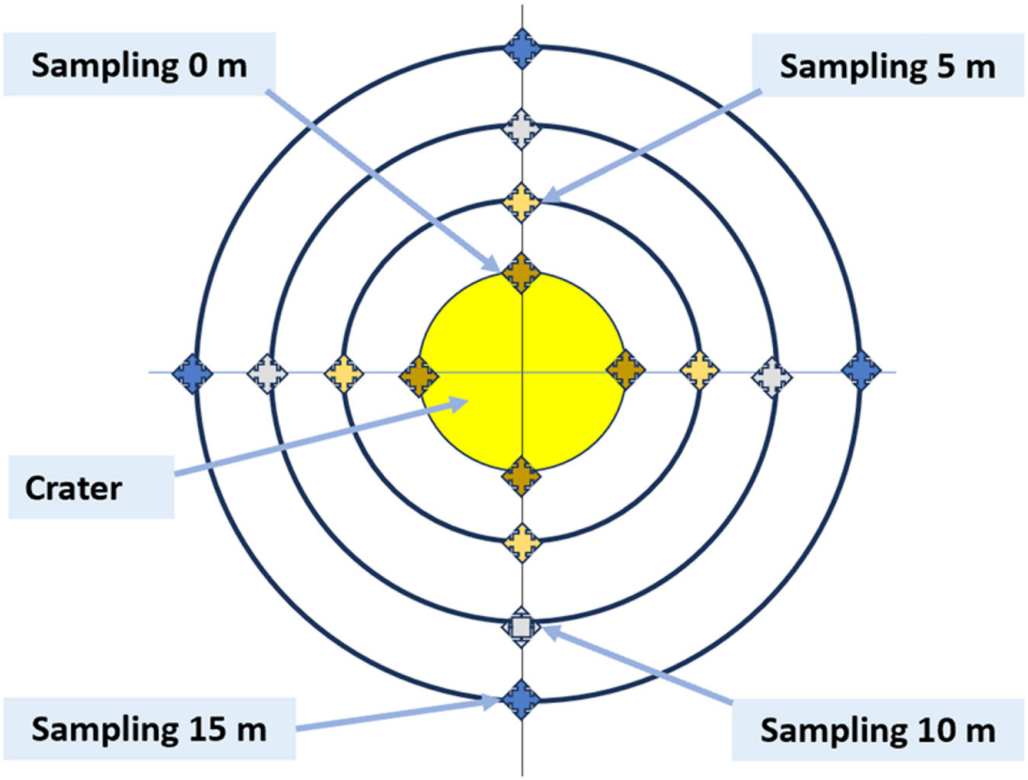


Fig. 3. Scheme of soil sampling at the crater of the missile's explosion: 0 m – four samples were taken at the edge of the crater; 5, 10, 15 m – four samples were taken, respectively, at a distance of 5, 10, and 15 m from the edge of the crater.

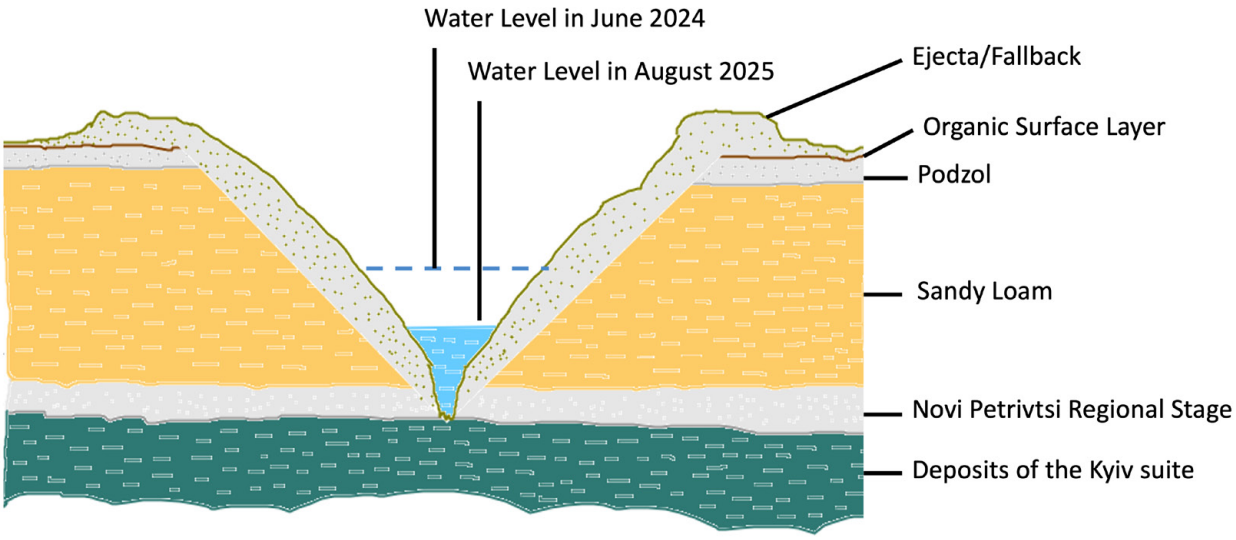


Fig. 4. Schematic cross section profile showing the morphology of the explosion crater near Buda-Babynetska village.

Soil samples of the impact area around the crater were collected from the surface layer to a depth of 10 cm in accordance with DSTU GOST 17.4.3.01:2019 in June 2025. The sampling scheme is shown in Fig. 3. Four samples taken at the crater edge (0 m) were placed into plastic containers weighing 500 ml each. Before conducting the chemical analysis, soil from these samples was combined and thoroughly mixed. The same procedure was performed for groups of samples taken at distances of 5, 10 and 15 m from the crater edge. As a control, a soil sample was taken at a distance of approximately 80 m from the crater.

A subsample was taken from the combined mixtures for chemical analysis. Soil samples were prepared according to EPA Method 3050 B (U.S. EPA, 1996) for the determination of chemical elements in soil. The determination of chemical components of the soil samples was conducted according to the methodologies specified in the Supplementary file 2. The measurement results are presented based on air-dried matter.

The water sample from the crater was collected in November 2024 (Supplementary file 1).

Vegetation survey

Surveys and monitoring were conducted from May to November 2024 and from June to September 2025. During this period, the following data were recorded: date, geographic coordinates, a detailed description of the site's condition, site photographs, morphological parameters of the seedlings, the condition and species composition of the vegetation cover and other supplementary information.

The morphological parameters of the seedlings were assessed in five randomly selected 1-m^2 plots located within a 5-m radius of the crater's edge. The number of specimens was counted within each plot, and individual seedling parameters, such as height and number of stem branches, were measured.

Analysis of the plant species composition included the collection of herbarium specimens, photographic documentation and processing of the collected data. The plant species names are provided following the accepted nomenclature from the open-access database Plants of the World Online (POWO, 2025). Following the recommendation (Chytrý et al., 2025), taxon names are presented without author citations. The habitat classification was followed by EUNIS (2025; version 2012).

Vegetation indices calculation

Satellite data were obtained, processed and analysed using the Google Earth Engine web platform and Microsoft Excel. The analysis was based on imagery from the Sentinel-2 MSI (Multispectral Instrument, Level-1C, TOA Harmonized) satellite (Earth Engine Data Catalog, 2025). Images were selected based on a cloud cover threshold that does not exceed 30%, using cloud masking with the Cloud Score+ algorithm at a threshold value of 0.5 (Pasquarella et al., 2023). Vegetation indices were calculated within a 30-m radius circle centred at the impact epicentre. To assess the presence of fires caused by missile impacts or other factors, the Normalized Burn Ratio (NBR) was used (Roy et al., 2006). This index was calculated based on reflectance values in the near-infrared (NIR, Band 8) and short-wave infrared (SWIR, Band 11) spectral bands. To assess changes in vegetation cover, the Enhanced Vegetation Index (EVI; Liu, Huete, 1995), Leaf Area Index (LAI; Watson, 1947) and Soil-Adjusted Vegetation Index (SAVI; Huete, 1988) were used. These indices were calculated using Sentinel-2 spectral bands: blue (Band 2), red (Band 4) and near-infrared (NIR, Band 8). Due to the limitations of NDVI, particularly its sensitivity to soil background, atmospheric conditions and variations in vegetation types (Martinez, Labib, 2023), EVI was used as a more reliable alternative.

Results

Environmental consequences

The vertical cross section of the geological environment of the crater, which was formed by the rocket explosion, is presented

by unconsolidated sedimentary formations ranging in age from the Miocene to the Holocene (Fig. 4). According to Zosymovych (2021), the geological structure of the upper sedimentary layer of this territory is mainly composed of sandy rock complexes of the Novi Petrivtsi Regional Stage of the Miocene (with a thickness of up to 0.3 m) and layers of variegated Neogene clays, as well as Quaternary deposits with a thickness of 5–6 m. The Neogene sands are snow-white, light grey, and grey, occasionally light-yellow in color. They consist of fine-grained, stratified quartz sands containing kaolin and locally include interbeds or lenses of sandy kaolinitic clays, as well as occasional interbeds of quartz pelitic sands. This section is the most widespread and lithologically consistent in the given area. The thickness near the villages of Babyntsi and Buda-Babynetska is about 0.3 m (Tectonic map of Ukraine, 2007).



Fig. 5. Fragment of rocket debris discovered within the slope of the explosion crater, 20–30 cm below the surface, near the Buda-Babynetska village (Photos by K. Derevska).

Quartz sands usually contain grains of ilmenite, zircon and rutile, and in some places, there is a significant concentration of sillimanite, kyanite and staurolite. Mica flakes, small carbonaceous particles and abundant kaolinite are also present. The Miocene (Novi Petrivtsi Regional Stage) is represented by three components: lower layer – polymictic, variably stratified sands and sandstones, with interbeds of carbonaceous clays and brown coal; middle layer – sorted, fine-grained quartz sands of varying degrees of kaolinite content; upper layer – variably stratified sands with interbeds of clay-iron sandstones and kaolinitic siltstone sandstones cemented in the upper part of the section. The Miocene deposits are overlain by a sequence of variegated clays and glaciofluvial Quaternary formations (Fig. 4). The missile likely reached an aquiclude consisting of clayey fine-grained sand of a greenish-grey colour (at the contact of the Neogene strata with the Kyiv Suite of the Upper Paleogene). This is indicated by the long-term presence of water at the bottom of the crater (more than 1.5 years, with a depth of more than 20 cm). Immediately after the explosion exposed the surface, the water body reached a depth of about 3 m. The possible water level is also suggested by vegetation growing on a ledge along the slope of the crater (Fig. 6). Within the slope of the crater, within vertical trenches 20–40 cm deep, remains of the missile and its components were found in summer of 2025 (Fig. 5).



Fig. 6. The crater was almost filled with water in May 2024 (A). By August 2025 (B), the water level has decreased, but vegetation indicates the previous water level (Photos by O. Kozak, K. Derevska).

As it is well known, sod-podzolic soils are typical for coniferous forests of the Kyiv Polissya region (Kupchik et al., 2010). Our research has shown that their distinctive feature is a sharply differentiated profile, consisting of a humus-eluviation horizon (2–3 cm), a dark grey podzolic horizon (5–7 cm) and a yellow illuvial horizon, which are distinguished by their colour (Fig. 4). Based on natural bioindicators, it can be determined that the soil is acidic or slightly acidic, poor in nutrients and dry. Soil pH measurements taken at a distance from the explosion zone confirm these assumptions (pH = 6; Table 1).

As a result of the detonation, an explosion crater about 6.0 m deep was formed on the surface (data by May 2024). The volume of mixed and ejected material brought to the surface is about 60 m^3. On the surface around the crater, a rim (ejecta) up to 1 m high was formed, composed of mixed unconsolidated sedimentary deposits. In addition, within a radius of up to 10 m, the forest litter was covered with sand. After the destruction of the forest by the missile explosion, the forest litter appeared as a layer of ash and charred remains of needles, branches, bark, etc., 3–5 cm thick, which indicates the destruction of the organic soil layer within the fire zone (about 20 m in radius).

Therefore, the surface layer, which now acts as newly formed soil around the crater at a distance of 10 m, consists of a mixed composition of sands of different ages, sod-podzolic forest soil and dark brown ash with charred plant remains in varying proportions. The pH of such a mixture was 6–7.5, while the pH of the water in the centre of the crater (based on observations in July 2025) reached a value of 8. It should be noted that in the autumn of 2024 (according to laboratory analyses), the pH of the crater water did not exceed 6.9. Hence, we observe that as a result of the explosion and the influence of high temperature (from 2500 °C and above), neutralization of soil acidity occurs on the surface, since neutral and alkaline elements remain in the soil, causing it to become neutral or slightly alkaline (Table 1). The alkalization of soils caused by missile impacts and detonations can be explained, on the one hand, by the mechanical mixing of geological layers. In the mixed forest zone of Kyiv Polissya, the lower strata commonly contain micaceous marl composed of approximately 30–50% limestone. These components have an alkaline reaction, which neutralizes the natural acidity of the upper soil layer and Quaternary deposits. Additionally, the high temperatures generated during explosions lead to the rapid combustion of humus, which may further alter the local chemical equilibrium of the soil (Khomiak et al., 2025).

Physicochemical analysis of soils at different distances from the crater edge confirmed soil neutralization, with pH values increasing from 3.4 in the control (unaffected) area to 4.2 at the crater edge (Fig. 7A). The pattern of organic matter (humus) content

Table 1. Characteristics of rock composition samples collected from the crater profile near Buda-Babynetska village in July 2025.

Sample ID	Type of sample, location	Properties/rock composition	pH of water and soil	Hardness	Remarks
V2	Silt from the bottom of the crater.	Fine-grained sand.	5.5	Soft	Depth 0.40 m
V3	Wet sand from the water‘s edge.	Fine-grained sand of yellowish colour. Light grey sand.	7	Soft	-
V4	Wet sand at a distance of 50 cm from the water‘s edge.	Contaminated sand with small burn residues along the crater edges. The sand is light grey with clumps.	7	Soft	-
V5	Light, dry sand at a distance of 3 m from the edge of the crater downwards.	Medium-grained sand, light grey to white.	6	Soft	From a vertical pit 20 cm. With a small fragment of rocket debris
V6	The sand is light grey to brown with darker, harder layers on the slope of the crater, 2 m from the crater edge downwards.	Compacted, dark grey, medium-grained sand with organic inclusions. A sintering crust formed by the explosion is present.	7.5	Soft	A solid layer up to 15 cm thick. Contains charred plant particles, roots and tree branches. With a small fragment of rocket debris.
V7	The sand is light grey to brown with darker, harder layers on the slope of the crater, 2 m from the crater edge downwards.	Compacted, dark grey, medium-grained sand with organic inclusions. A sintering crust formed by the explosion is present.	7	Soft	With a small fragment of rocket debris
V8	Brown fine sand from the crater‘s slope, 1 m from the edge downwards.	Loose, friable sand forming a lens on the slope.	7.5	Soft	No vegetation
V9	Ash from the surface at a distance of 9 m from the edge of the crater to the north.	Dark grey to black, fine-grained ash mixed with sand.	6.5	Soft	No vegetation
V10	Podzolic soil outside the explosion zone.	Dark grey, fine-grained sand.	6	Soft	No vegetation

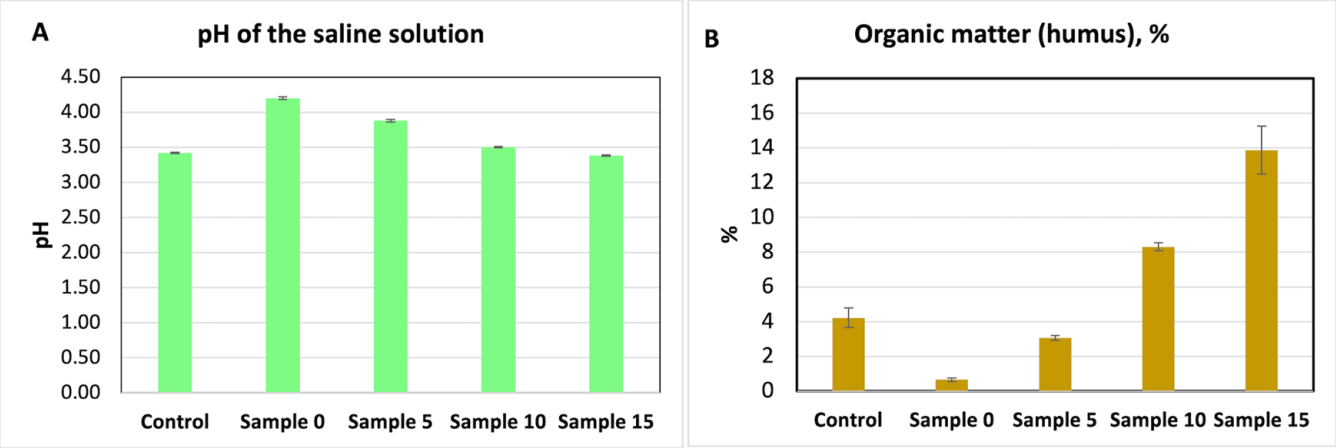


Fig. 7. Physicochemical parameters of the soil from the studied area: A – pH of the saline solution; B – organic matter content, %.

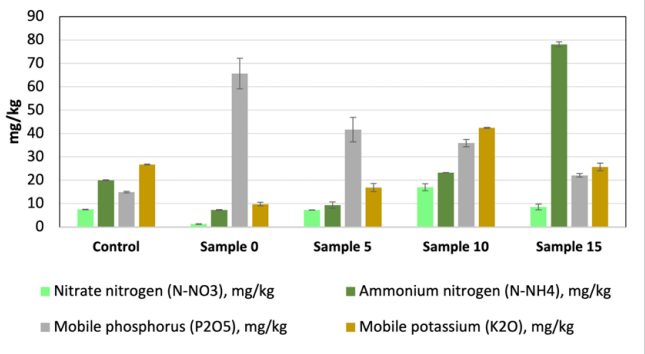


Fig. 8. Content of nitrate nitrogen, ammonium nitrogen, mobile phosphorus and mobile potassium in soil in the studied area (mg/kg).

also reflects soil and rock mixing: the smallest portion of organic matter was found in soil samples taken at the crater edges (less than 1%), but with increasing distance from the crater, the organic matter content increases (Fig. 7B). The maximum value of this indicator was found in samples taken at a distance of 15 m from the edge of the crater (13.9%). The control contains 4.22% of organic matter, which is considered high even for agricultural lands and characterizes it as soil with a high humus content (Baliuk et al., 2012). The explosion causes a gradual increase in organic matter content in the surface soil layer: close to the blast point, high temperatures destroyed organic soil components, while at greater distances, the amount of organic material could be increased due to the accumulation of plant matter that died from the fire.

The concentration of nitrate and ammonium nitrogen, as well as mobile phosphorus and potassium, changed with distance from the crater in a non-uniform manner (Fig. 8). Nitrate nitrogen ($N\text{-}NO_3$) content was minimum in the 0-m sample (1.24±0.08 mg/kg), maximum in the 10-m sample (16.98±1.45 mg/kg), and in the 5- and 15-m samples, it was approximately the same as in the control (7.29–8.55 mg/kg). The same situation with mobile potassium (K_2O): the minimum concentration is detected in the 0-m sample (9.78±0.76 mg/kg), while the maximum is in the 10-m sample (42.47±0.19 mg/kg). In a 15-m sample, the mobile K_2O concentration is the same as in the control (25.67–26.74 mg/kg). Ammonium nitrogen ($N\text{-}NH_4$) content monotonically increased with distance from the crater from 7.28±0.24 mg/kg in the 0-m sample to 78.11±1.02 mg/kg in the 15-m sample, with 19.98±0.25 mg/kg in the control. The ammonium nitrogen ($N\text{-}NH_4$) content in the 15-m sample may be considered as a high level, while in the 0- and 5-m samples, it is very low (Chorny, 2018). At the same time, mobile phosphorus (P_2O_5) content, conversely, was maximal in the 0-m sample (65.68±6.55 mg/kg), decreased with distance from the crater, and in the 15-m sample amounted to 22.07±0.77 mg/kg. The P_2O_5 content in all samples exceeded the control sample (14.91±0.36 mg/kg). The P_2O_5 content of more than 45 mg/kg is considered high and very high (Chorny, 2018).

The total calcium content increases in the samples from 229.28±32.37 mg/kg in the 0-m sample to 824.75±96.05 mg/kg at 15 m, while in the control sample, calcium content is 497.75±62.54 mg/kg (Fig. 9). The same situation is with the content of total sodium concentration: the lowest content is detected in the 0-m sample (32.2 mg/kg) and maximum in the 15-m sample (44.1 mg/kg). An ambiguous pattern was observed for the total magnesium and total potassium concentrations. Total magnesium concentrations increased in the following order: control (lowest, 114.5 mg/kg), 5-m sample (131.5 mg/kg), 0 m (144.7 mg/kg), 10 m (151.2 mg/kg) and 15 m (168.4 mg/kg). The total potassium concentrations varied with the same trends but in the range 122.1–209.7 mg/kg. This irregular trend is most likely due to the mixing of soils from different layers.

The concentration of total iron increased from control to 15-m samples, in particular, from 601.3 to 1427.13 mg/kg (Fig. 10A). Compared with the other elements, aluminium content is relatively high in the samples (Fig. 10B). Its content in the control is noticeably lower than in all other samples, and its highest values are recorded in the 0-m sample (1960 mg/kg). Aluminium content decreases in the 5-m and 10-m samples but slightly increases in the 15-m sample.

Analysis of the concentrations of other elements (zinc, manganese, copper, barium, lead, chromium) reveals similar trends: their levels increase from 0 m to 15 m, while average values are observed in the control sample (Fig. 11).

The results of the physicochemical analysis of soils taken at different distances from the crater edges, 1.5 years after the ex-

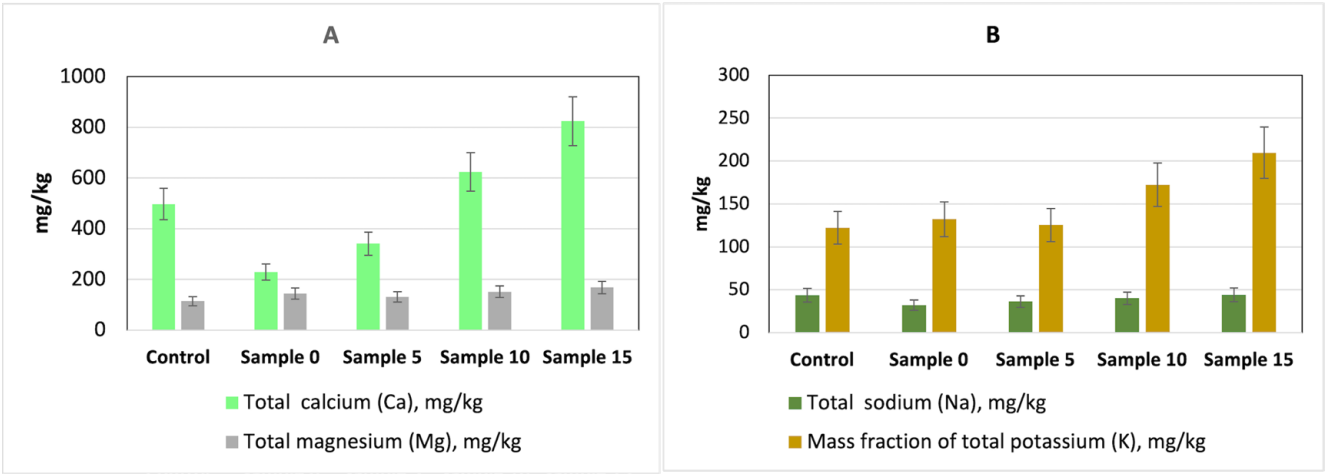


Fig. 9. Content of calcium and magnesium (A) as well as sodium and potassium (B) in soil in the studied area (mg/kg).

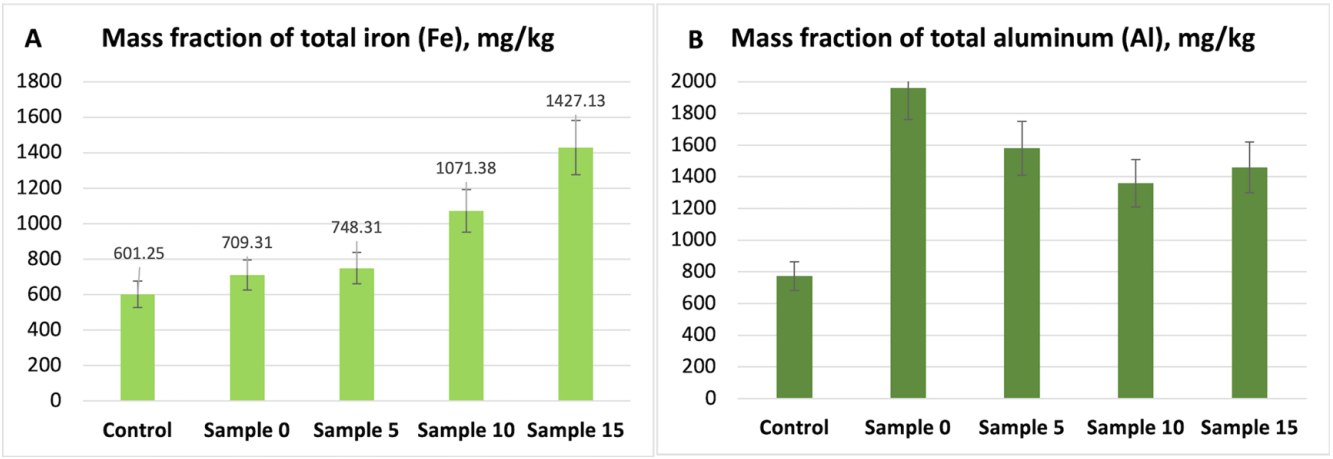


Fig. 10. Content of total iron (A) and total aluminium (B) in soil in the studied area (mg/kg).

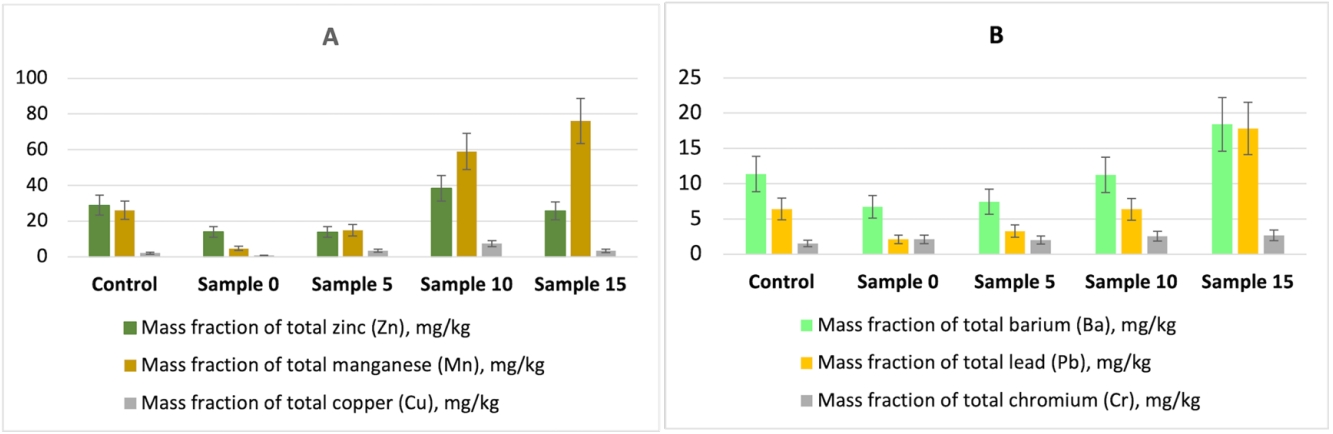


Fig. 11. Content of chemical elements in the soil from the studied area: A – total zinc, total manganese and total copper (mg/kg); B – total barium, total lead and total chromium (mg/kg).

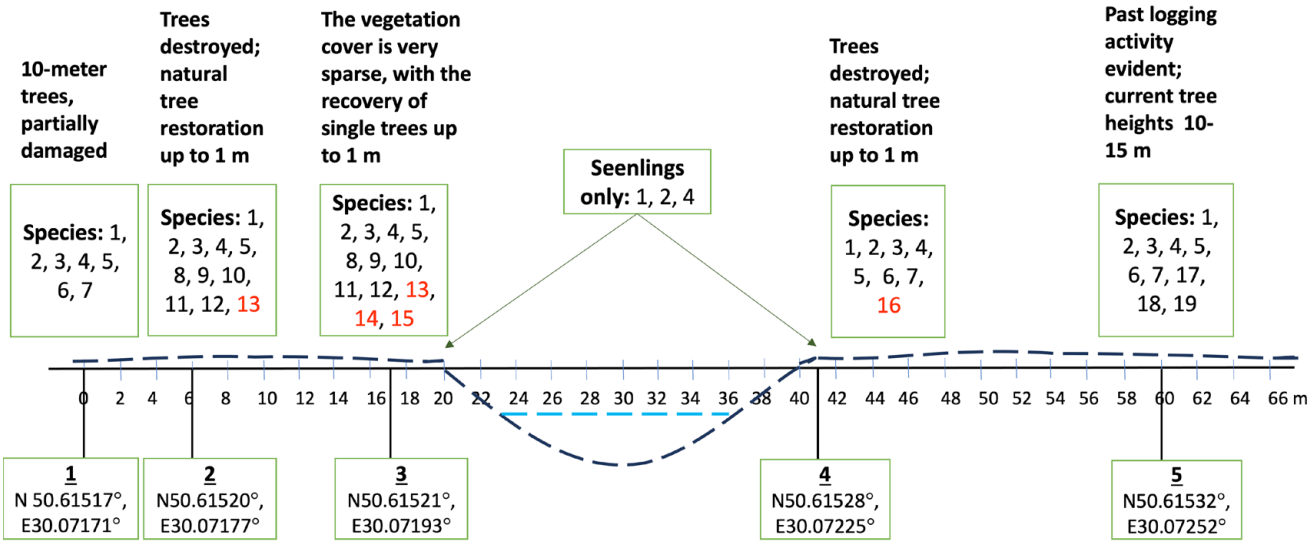


Fig. 12. Schematic representation, based on a 2024 field survey, illustrating the effects of a missile explosion on the forest ecosystem at the outskirts of Buda-Babynetska. The number corresponds to the species: 1, *Betula pendula*; 2, *Pinus sylvestris*; 3, *Quercus robur*; 4, *Frangula alnus*; 5, *Pteridium aquilinum*; 6, *Molinia caerulea*; 7, *Calamagrostis epigejos*; 8, *Rubus* sp.; 9, *Agrostis capillaris*; 10, *Digitaria* sp.; 11, *Rumex acetosella*; 12, *Setaria pumila*; 13, *Ambrosia artemisiifolia*; 14, *Erigeron canadensis*; 15, *Amaranthus* sp.; 16, *Solidago gigantea*; 17, *Calluna vulgaris*; 18, *Festuca ovina*; 19, *Pilosella officinarum*; the invasive species is marked in red.



Fig. 13. *Pteridium aquilinum* is showing signs of stress alongside planted *Miscanthus* sp. (A) and damaged trees (B) (Photos by O. Kozak).

plosion, also show that the content of heavy metals in all samples does not exceed the maximum permissible concentrations, nor do they contain residues of explosives and their metabolites, including nitroaromatic compounds and nitroamines (see more details in Supplementary file 2). This means that after about a year in the environment, there are no toxic substances left in the soil; however, other physicochemical parameters of the soils change; in particular, there is a significant impact on the structure and content of nutrients and biogeochemical elements.

In water samples taken in November 2024 (about 9 months after the explosion) from the crater, no toxic elements were detected, and most indicators were within normative limits (Supplementary file 1). However, concentrations of iron compounds were approximately 40% above the norm, while ammonium lev-

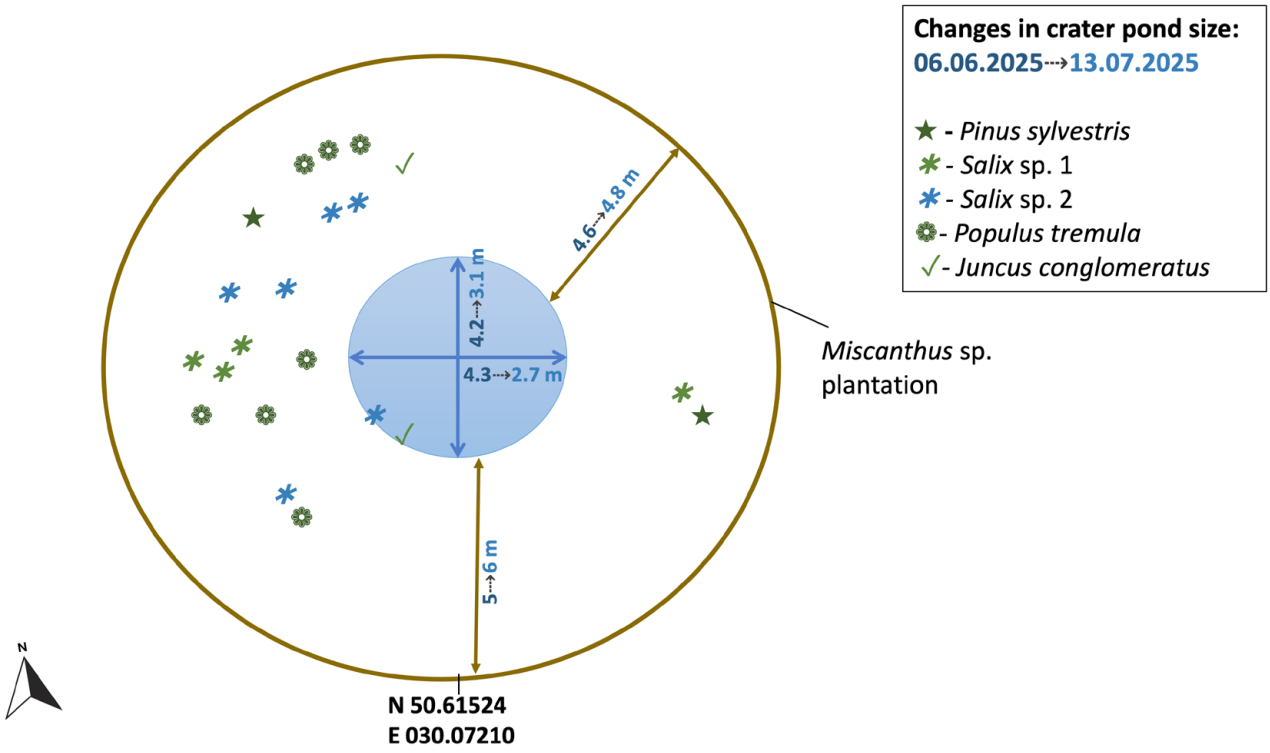


Fig. 14. Based on a 2025 field survey, the schematic representation illustrates the vegetation recovery within the crater as well as changes in crater pond size.

els were nearly double. Additionally, the permanganate oxidation value exceeded the standard by more than 15 times, indicating a substantial presence of organic pollutants (Laszakovits et al., 2022). The exact nature and origin of these contaminants remain unclear, but their potential to infiltrate groundwater cannot be ruled out. It should be noted that the water and soil sampling and further analysis were conducted only about 9 months and 1.5 years, respectively, after the explosion, meaning the pollutants could have already leached by that time.

Impact on vegetation

The habitat type of the affected area can be classified according to the EUNIS system (EUNIS, 2025) as mixed *Pinus sylvestris*–acidophilous *Quercus* woodland (G4.7), with the presence of the following species: *Pinus sylvestris*, *Quercus robur*, *Betula pendula*, *Frangula alnus*, *Calamagrostis epigejos*, *Molinia caerulea*, *Pteridium aquilinum*, *Vaccinium myrtillus*, *V. vitis-idaea*, *Convallaria majalis*, *Festuca ovina*, *Calluna vulgaris*, *Rubus polonicus* and some others.

Figure 12 illustrates the impact of missile exposure on the vegetation of the forest ecosystem in the study area. The explosion created a crater approximately 15 m in diameter, where no vegetation was present in the mid of summer 2024. All vegetation was initially destroyed along the edges of the crater, within an additional 5-m radius. However, the area is now naturally regenerated, with seedlings of *Betula pendula*, *Pinus sylvestris* and *Frangula alnus* reaching approximately 25 cm. The damaged vegetation was sparse in the zone extending 5–10 m from the crater, alongside scattered tree species, including *Betula pendula*, *Pinus sylvestris*, *Quercus robur* and *Frangula alnus*. Such species as *Pteridium aquilinum*, *Calamagrostis epigejos* and *Molinia caerulea* were the most abundant among herbaceous species. The limited number of ruderal and invasive species was also observed in the affected area, including *Erigeron canadensis*, *Ambrosia artemisiifolia*, *Solidago gigantea*, *Phytolacca acinosa, Galeopsis pubescens, Echinochloa crus-galli*, *Setaria viridis*, *Amaranthus* sp. and others. Finally, in the zone extending up to 20 m from the crater edge, the vegetation cover was less affected, although some trees were damaged. This area exhibits the highest species richness, with typical acid pine forest vegetation, including not only the previously mentioned species but also native plants such as *Calluna vulgaris*, *Festuca ovina*, *Convallaria majalis, Pilosella officinarum* and *Hylotelephium maximum*. The alien species in this zone are less abundant.

In addition to tree damage, herbaceous plants also exhibited signs of stress, such as leaf curling, wilting, chlorosis, necrosis and browning (pigmentation changes), with *Pteridium aquilinum* showing the most pronounced symptoms (Fig. 13). In addition, it is worth noting that during the initial visit in May 2024, several individuals from the *Poaceae* family were found planted in rows near the crater (Fig. 13A). The identity of those responsible for this intervention remains unknown. By autumn 2024, the planted species was identified as *Miscanthus* sp., most likely *Miscanthus sinensis* Andersson, an alien species in Ukraine. This uncontrolled intervention raises concerns, as such introductions

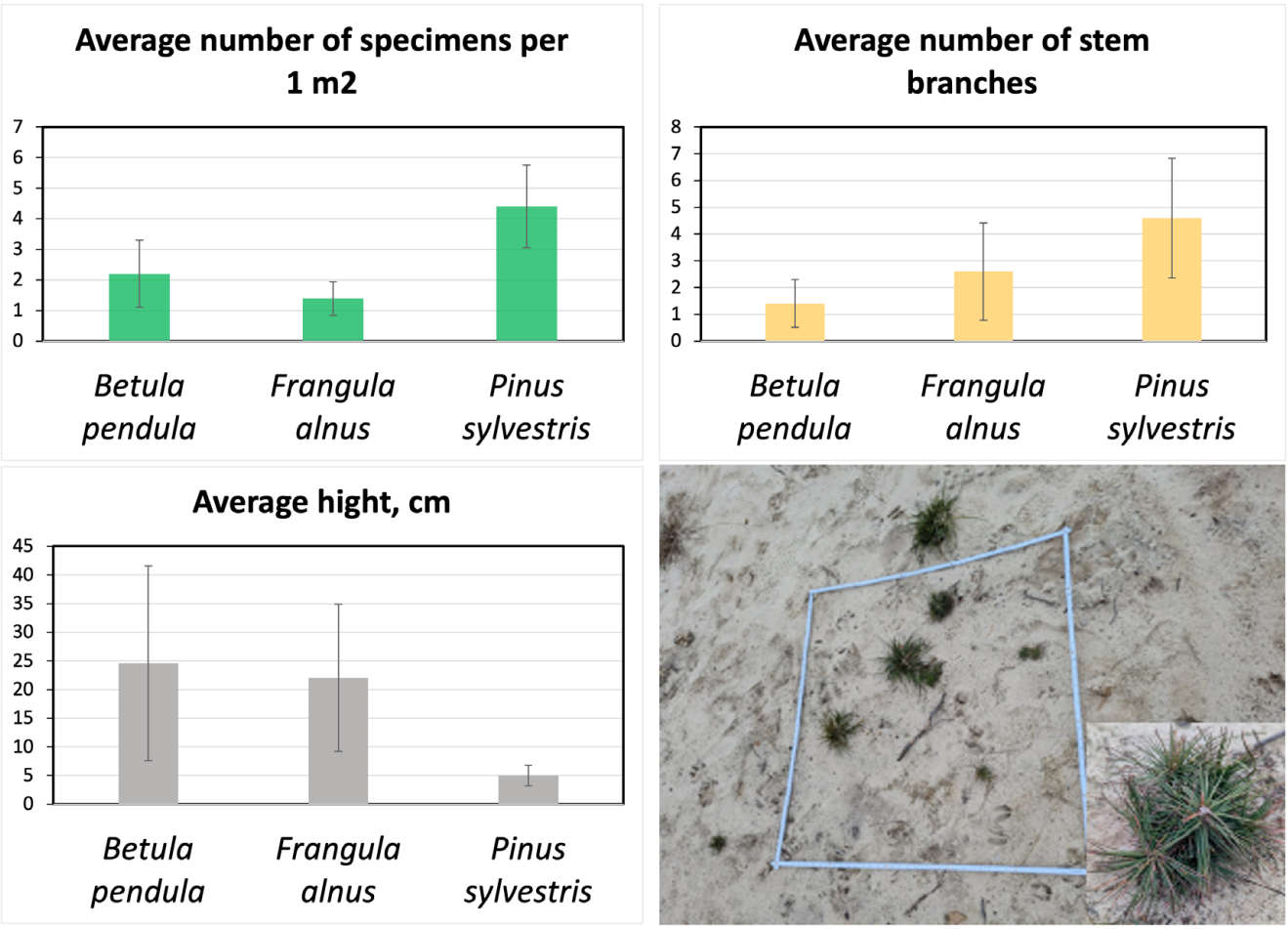


Fig. 15. Seedling parameters within a 5-m zone from the crater edge (November 2024; Photos by O. Kozak).

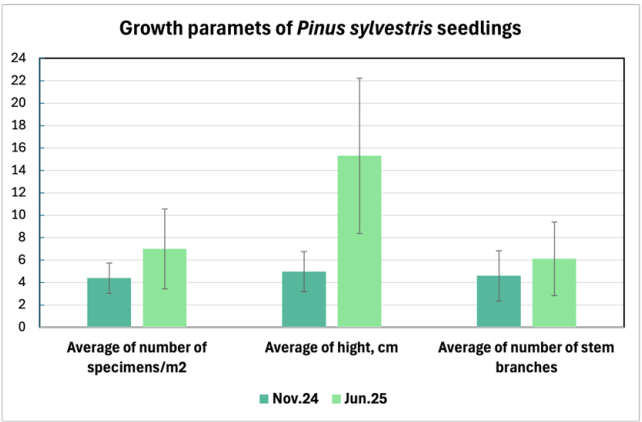


Fig. 16. Comparison of growth parameters of *Pinus sylvestris* seedlings measured in November 2024 and June 2025.

could potentially have negative impacts on the forest ecosystem recovery. During the summer of 2025, observations indicated that *Miscanthus* rhizoma density increased, ranging from 2 to 15 new rhizomas per plant (5–9 on average).

Observations conducted in June–July 2025 indicate active recovery of vegetation cover in the study area. Trees have grown taller, and in addition to last year's *Pinus sylvestris* seedlings, a significant number of new seedlings have emerged this year. The overall vegetation cover has increased, particularly due to increasing cover of grasses, such as *Calamagrostis epigejos*, *Molinia caerulea*, *Corynephorus canescens, Festuca ovina*, *Digitaria sanguinalis*, as well as various herbaceous plants, including *Pteridium aquilinum*, *Carex leporina*, *Juncus conglomeratus*, *Spergularia rubra* and *Rumex acetosella*. Notably, alien species such as *Erigeron canadensis*, *Ambrosia artemisiifolia*, *Solidago gigantea* and *Phytolacca acinose* were less abundant compared to previous observations. Additionally, several new plant species on the crater edge were observed in 2025, where no vegetation was present in 2024 (Fig. 14). It is worth noting that the size of the crater pond decreased by approximately 30% from June to July 2025. Most of the plants were likely at the water's edge. The most abundant were seedlings of *Populus tremula* and *Salix* spp., with preliminary identification suggesting *Salix caprea* and *S. pentandra* as the likely species. Occasional *Pinus sylvestris* and *Juncus conglomeratus* seedlings were also observed in this area.

Within a 5-m radius of the crater's edge, where the vegetation was destroyed, *Betula pendula*, *Pinus sylvestris* and *Frangula*

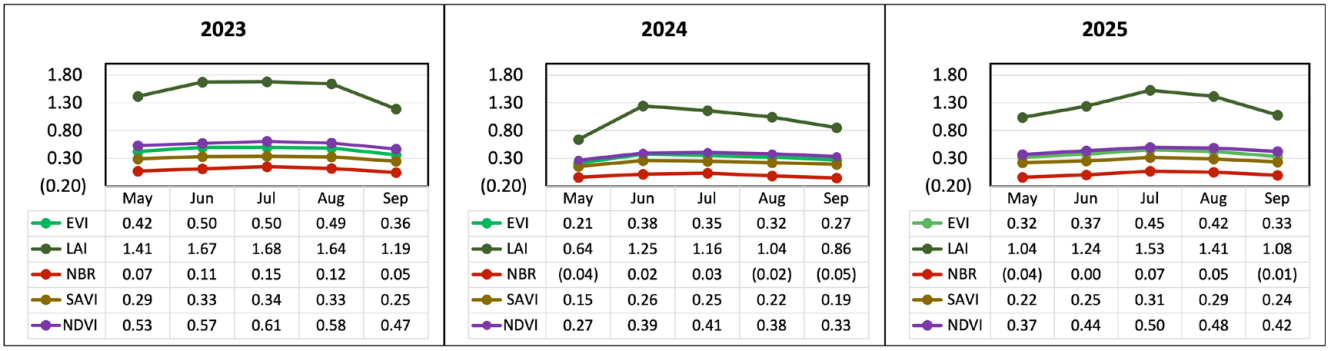


Fig. 17. Comparison of EVI, LAI, NBR, SAVI and NDVI values in the research area during May–September 2023 (before the event), 2024 (first growing season after the missile explosion) and 2025 (second growing season after the accident).

alnus seedlings have begun to appear on the sandy surface. *Pinus sylvestris* regenerates primarily from seeds, with an average density of 4–5 individuals per square meter (Fig. 15). In contrast, *Betula pendula* and *Frangula alnus* are likely re-establishing vegetatively through root shoots, showing lower densities of 1–2 individuals per square meter. The average height of *Betula* and *Frangula* seedlings ranges from 10 to 40 cm, whereas *Pinus* seedlings average around 5 cm in height.

An interesting finding was revealed in the study area: an unusual branching was observed in *Pinus sylvestris* seedlings, indicating a growth anomaly and reduced apical dominance. In particular, the number of stem branches ranged from 2 to 9 per pine seedling (Fig. 15). In contrast, no similar anomaly was observed in the two other phanerophyte species (*Betula pendula* and *Frangula alnus*), where the number of stem branches varies in the range 1–3. The anomalous growth of *Pinus* seedlings may be associated with many factors, which will be discussed later. However, to determine the exact cause, further long-term observation and a detailed physicochemical survey are necessary.

As shown in Fig. 16, all growth parameters for pine increased between November 2024 and June 2025. Notably, the average seedling density increased from 4 to 7 seedlings per m^2, while the average plant height tripled, increasing from 5 to 15 cm over 6 months. Although less pronounced, the number of stem branches also increased with plant growth, ranging from 3 to 9 in June 2025.

Vegetation indices

To assess the impact of the missile explosion on vegetation, four vegetation indices were calculated: EVI, LAI, NBR, SAVI and NDVI (Fig. 17). As shown in Fig. 17, all five indices in 2024 were about 1.3 to 2.2 times lower than in 2023, before the explosion. Notably, the affected area was covered by a relatively young forest, approximately 20 years old, which may have contributed to the more significant decline in the vegetation indices. The LAI reflects the structure of the vegetation canopy. A comparison of LAI dynamics between May and September in 2023 and 2024 reveals a strong decline following the missile explosion, followed by a gradual recovery. Specifically, the LAI in May 2023 was 1.414, compared to just 0.638 in May 2024. By September, LAI values were 1.191 in 2023 and 0.855 in 2024, indicating partial but incomplete recovery. The other vegetation indices, including EVI and SAVI, observed a similar trend. In September 2023, the NBR index median was 0.047, and the value decreased to 0.038 by May 2024, therefore indicating that no fires occurred within the study area because of the missile explosion. In 2025, a significant increase in all vegetation indices is observed, although they remain lower than before the explosion. Comparing all five indices, EVI, LAI, NBR and SAVI, it can be assumed that only LAI reflects a significant difference and is therefore best suited for analysing forest ecosystem recovery.

Discussion and conclusion

Soil Degradation, Loss of Geological Diversity and Landscape Transformation

The Russian missile hit the forest near the village of Buda-Budinetska, influencing the evolution of the forest landscape and resulting in the formation of an element of bombturbation landscape. As is known, in modern soil science, the term 'bombturbation zone' is used to describe the area around the crater that was directly affected by the explosion of the munition (missiles, shells, mines, etc.) with signs of displacement, redeposition, compaction and mechanical deformation of the soils and rocks (Hupy, Schaetzl, 2006). Bombturbation contributes to the decrease of geological diversity. It also promotes negative geomorphological processes, including landslides, erosion and suffusion (Baliuk et al., 2024), which can cause long-term consequences for affected landscapes. Negative processes can be intensified and have a cumulative effect when the density of craters increases. In areas experiencing very active and prolonged hostilities, the average density of explosive craters is about 66 craters per 1 km^2, but can reach up to thousands (Baliuk et al., 2024). The high density of craters may directly correlate with soil degradation and landscape transformation, as well as their recovery.

Apart from the bombturbation zone around craters, the contamination zone can be defined as an area affected by remaining explosive materials and secondary pollutants (Baliuk et al., 2024; Bonchkovskyi et al., 2023). Combustion products from explosives and metallic components of the ammunition (in this case, missiles) are dispersed into the air and subsequently de-



Fig. 18. Trees with spherical morphology in the landscape reserve of national importance 'Kozinskyi' (Kyiv region): A – *Pinus sylvestris*; B – *Quercus robur* (Photos by O. Kozak).

posited onto the land surface. According to Gilles et al. (2007), most substances derived from explosions, particularly heavy fractions such as particles from incomplete combustion and heavy metals, settle out onto the ground. Consequently, heavy metals are among the primary soil pollutants in such scenarios (Solokha et al., 2023). Sod-podzolic soils have a high potential for retaining pollutants (Baliuk et al., 2024). However, our results show that 1.5 years after the explosion, heavy metal concentrations in all samples remain below maximum permissible limits, and no explosive residues or metabolites were detected. At the same time, other physicochemical soil parameters have been changed. Compared to the control, in all samples of the affected area, the pH increased and the content of mobile phosphorus P_2O_5 was elevated, as well as elements such as Fe, Al, K and Cr (Figs 7–11). While such elements as Na, Mg, Ca, Zn, Ba, Mn, Pb and Cu are characterized by a heterogeneous content in the soil, usually the lower level is closer to the crater and increases in samples 15 m compared to the control (Figs 9–11). Signs of soil and rock mixing due to the explosion are also reflected in the results regarding the content of such important nutrients as organic matter (humus), ammonium and nitrate nitrogen: the smallest portion was found in soil samples taken at the crater edges, but with increasing distance from the crater, it increases (Figs 7–8).

The missile explosion, because of high temperature and pressure, destroyed vegetation, changed the structure of the soil and its chemical composition, mixed sedimentary rocks and contaminated the natural environment with explosives and debris both at depth and on the surface. The natural recovery of such a landscape will take a long time and will require many years of monitoring.

Vegetation recovery and ecosystem restoration

The explosion caused severe damage to the forest vegetation, destroying it within a radius of approximately 20 m. At the centre of the crater, organic matter was almost eliminated (< 1%). Moving outward from the crater, the amount of organic matter gradually increased. Vegetation recovery in areas where more than 80% of the organic matter was removed can be considered an almost primary succession (Chapin et al., 2011), meaning that recovery is expected to take longer time than after typical forest fires. On the other hand, the presence of seedlings of key tree species such as *Pinus sylvestris*, as well as important pioneer species including *Populus tremula* and *Salix* spp., indicates that the native forest has great potential for recovery. The positive recovery dynamics are also shown by increasing cover of typical native grasses and herbs, such as *Molinia caerulea*, *Corynephorus canescens*, *Festuca ovina* and *Pteridium aquilinum*. However, several issues challenging forest recovery should be discussed.

The first one is possible changes in ecosystem types and further ecosystem and landscape evolution. The first indicator of such a possibility is observed unusual branching in seedlings of *Pinus sylvestris*. Many factors can cause such branching, including pollution, radiation and extreme heat from a missile explosion (Bessonova, 2024; Morgun, Yakymchuk, 2021; Nybakken et al., 2023), which could affect the *Pinus* seeds. But another reason for such branching could be the reduction in nutrients (in particular, organic matter) and changes in soil structure caused by the explosion. For example, in the floodplain areas of landscape reserve of national importance 'Kozinskyi' (Kyiv region), the trees with spherical morphology are very abundant, including *Pinus sylvestris* and *Quercus robur* (Fig. 18). This growth

form is likely driven by a combination of factors, including dry, sandy soils poor in organic matter, high light exposure and possibly frequent strong winds. Consequently, the combined effects of declining soil organic matter and the shift towards a sand-dominated soil structure may prevent the natural regeneration of native pine-oak forests in this area. Instead, scrub vegetation or even heathland may develop here. The possible biotopes according to EUNIS that may form on this area include Closed non-Mediterranean dry acid and neutral grassland (E1.7), Pteridium aquilinum fields (E5.3), Temperate thickets and scrub (F3.1), Dry heaths (F4.2), etc.

Another issue is the presence of alien species, which may prolong the recovery process and may even lead to another ecosystem type. Although highly invasive alien species such as *Erigeron canadensis*, *Ambrosia artemisiifolia* and *Solidago gigantea* have shown a decline in abundance, continued monitoring of their dynamics remains necessary. This is especially crucial for the last species, since the first two are therophytes and may disappear in the process of succession. Another issue is that the introduction of *Miscanthus* in spring 2024 potentially represents a serious threat that could further challenge forest regeneration. *Miscanthus* demonstrates a high multiplication ratio ranging from 10 to 30 (Xue et al., 2015). In 2025, *Miscanthus* rhizoma density in the study area increased, with each original rhizoma producing between 2 and 15 new plants. As a result, the acidophilic pine forest may not recover there, since *Miscanthus* may form a dense structure of tall stems through which local forest species will not germinate. *Miscanthus* can spread vegetatively and form a stable monodominant plantation, the area of which may gradually expand. Due to challenging control and active reproduction from rhizomas and seed (Quinn et al., 2010), *Miscanthus sinensis* Andersson is recognized as an invasive species in 21 countries (GBIF, 2025). Recent studies show that *Miscanthus* species have a very strong potential for uncontrolled spreading and invasion in Eastern Europe (Bylak et al., 2025). *Miscanthus* plantations can also reduce the richness and diversity of vegetation cover, depleting the soil seed bank (Hager et al., 2015), which is a key issue for healthy natural ecosystems and essential to their recovery and restoration. Apart from this, the *Miscanthus* plantation can negatively affect the bird community (Kaczmarek et al., 2019), changing other important forest species interactions and ecosystem function. Finally, the accumulated biomass of *Miscanthus* can potentially be a fuel and may cause a forest fire. Therefore, *Miscanthus* plantation is a serious threat to the recovery of this forest area and should not be recognized as a remediation and restoration intervention for forest ecosystems.

In our case, the remote sensing data analysis has a limited application. Nevertheless, it was useful to establish the absence of secondary fire after the explosion, which could affect the process of vegetation recovery and soil chemical characteristics. In the forest ecosystem, Leaf Area Index (LAI) proved its ability in detecting changes in vegetation cover after shelling, which could be further useful for the automated detection of damaged areas.

In summary, the studied site, disturbed by a missile explosion, shows favourable conditions for the regeneration of native pine-oak forest. Nevertheless, several factors may influence successional pathways, including the changes in geomorphological parameters, the shift towards sand-dominated substrates and the introduction of alien species. The absence of detectable toxic substances, more likely due to the occurrence of only one explosion, suggests that chemical contamination is not a major obstacle to the restoration of this site. Continued long-term monitoring will be essential to determine the direction of ecosystem development. By contrast, locations exposed to higher shelling intensity may experience more severe degradation, with a significantly reduced probability of native ecosystem recovery.

Supplementary materials

All supplementary files are available via the link https://doi.org/10.5281/zenodo.18374951.

Data Availability

All data supporting the findings of this essay are available within the text and its Supplementary files.

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