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Vitalii ZATSERKOVNYI[1], DSc (Techn.), Prof.
ORCID ID: 0009-0003-5187-6125
e-mail: vitalii.zatserkovnyi@knu.ua

Irina TSIUPA[1], PhD (Geol.)
ORCID ID: 0000-0002-8350-6685
e-mail: irynatsiupa@knu.ua

Mauro DE DONATIS[2], PhD (Geol.), Assoc. Prof.
ORCID ID: 0000-0002-9721-1095
e-mail: mauro.dedonatis@uniurb.it

Igor NIKOLIUK[1], PhD Student
ORCID ID: 0009-0006-0750-2603
e-mail: Histerias@ukr.net

Valentin KRAVCHENIA[1], PhD Student
ORCID ID: 0009-0002-4160-361X
e-mail: valentyn.kravchenia@knu.ua

Oleksandr TSVYK[1], DSc (Geogr.), PhD Student
ORCID ID: 0009-0006-5464-2078
e-mail: oleksandr.tsvyk@knu.ua

Tetiana MIRONCHUK[1], PhD (Philol.), Assoc. Prof.
ORCID ID: 0000-0002-5923-1028
e-mail: t.mironchuk@knu.ua

[1]Taras Shevchenko National University of Kyiv, Kyiv, Ukraine
[2]University of Urbino Carlo Bo, Urbino, Italy

# METHODS TO DETECT EXPLOSIVE HAZARDS IN AGRICULTURAL AREAS

*(Представлено членом редакційної колегії д-ром геол. наук, ст. дослідником О.І. Меньшовим)*

**Background.** ***Contamination of agricultural land with explosive ordnance (EO) following the war unleashed by the Russian Federation poses a significant threat to the life and health of farmers and hinders the restoration of agricultural activities. Detection and neutralization of EO is a complex and dangerous process that requires a comprehensive approach.***

***This article examines the main types of landmines found in Ukraine, outlines the main revealing factors of explosive ordnance, analyzes existing methods and technologies for detecting EO on agricultural land, and evaluates their advantages and disadvantages.***

**Results.** ***The application of UAVs in humanitarian demining demonstrates significant potential for risk reduction and accelerated clearance of affected territories from explosive ordnance. Specifically, aerial photography and thermal imaging scanning via UAVs prove effective for the initial inspection of extensive areas and the identification of potentially hazardous zones. The application of metal detectors and geophysical methods allows for the optimization of further efforts.***

***The integration of geographic information systems (GIS) with artificial intelligence (AI) offers a promising auxiliary approach. By leveraging satellite imagery and machine learning, AI can analyze extensive datasets to detect and classify changes in land resources resulting from military actions. Besides, it plays a crucial role in rapid and accurate monitoring of affected territories.***

***Based on the test plots in the Kyiv and Kharkiv regions, this study demonstrates the practical application of Earth remote sensing data, GIS spatial analysis, and machine learning for EO detection on agricultural lands.***

**Conclusions.** ***Traditional methods of mine detection and disposal are labour-intensive, dangerous, and often ineffective. Applying a combination of diverse EO detection methods (metal detectors, mechanical methods, geophysical methods, biophysical methods, UAVs with aerial photography and thermal imaging scanning, and other sensors) and integrating modern technologies (remote sensing tools and artificial intelligence) allows for achieving maximum survey efficiency and increasing safety. Each method has its advantages and limitations, and combining them promotes compensating for the shortcomings of individual methods.***

**Keywords:** ***danger explosives, Russo-Ukrainian War, mine contamination, agricultural territories.***

## Background

Mine contamination of territories is one of the most serious problems following armed conflicts. Mines and other explosive ordnance (EO) pose a significant threat to the civilian population, hinder economic development, and complicate humanitarian operations.

Due to the Russo-Ukrainian war, which actually began in 2014 and subsequently developed into a full-scale aggression in February 2022, Ukraine has become the most mined country in the world. The number of landmines and other explosive ordnance contaminating new territories has significantly increased including agricultural regions in the north, east, and south of the country. In August 2022 alone during the period of intense hostilities, the Russian army fired between 40,000 and 60,000 shells at Ukraine almost daily. Fortunately, some of them did not explode and remained in the ground carrying an invisible but deadly legacy and an extremely high threat to the lives of the population. According to various estimates, up to 20 % of the fired ammunition failed and continues to fail to detonate (Miroshnychenko, 2023). Furthermore, while occupying territories for some time, Russian aggressors deliberately mined forests and agricultural fields.

Ukraine suffers from contamination by mines and explosive objects. In terms of the area of mined land, the UN classifies Ukraine as one of the most heavily mined countries. The scale of mining surpasses countries where military conflicts used to last for decades. According to

D. Shmyhal, the Prime Minister of Ukraine, the area of mined land in Ukraine as of September 2023, according to preliminary estimates, is approximately 174,000 km² including maritime areas, which is about 30 % of the country's territory (Fig. 1).

Of these – over 67,000 km² are contaminated with explosive ordnance (EO). Approximately 5 million people live near dangerous zones. EO can cause and does cause casualties including severe injuries and death to a significant number of people, especially among civilians and children.

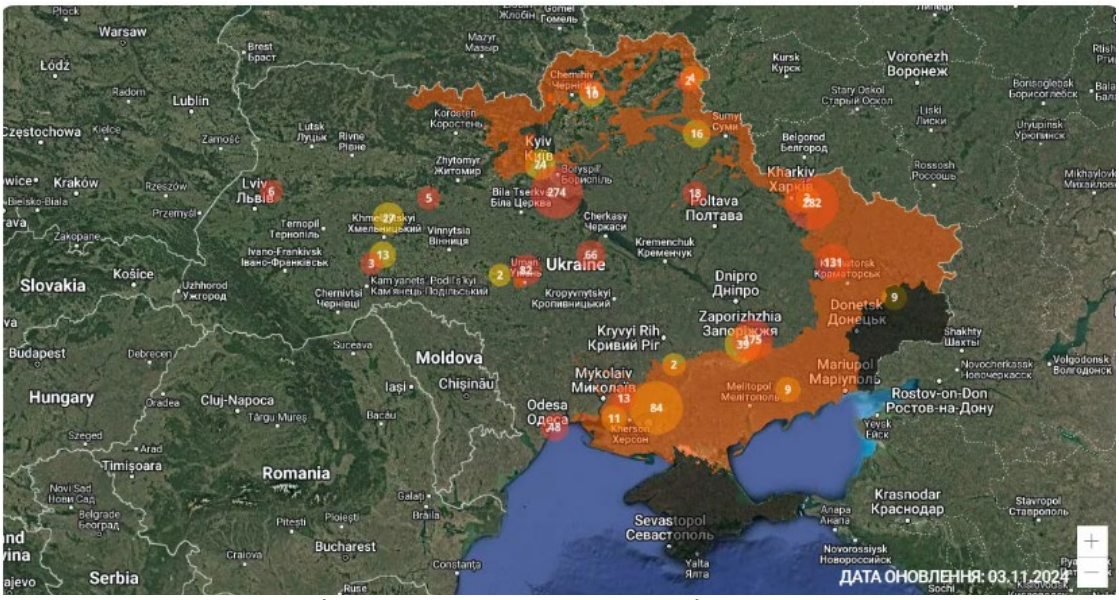



**Fig 1. Map of mine contamination in Ukraine as of November 03.11.2024**
**(The Ukrainian Association…, 2024)**

This significantly limits the possibilities for movement through such territories and their use in active farming.

The vast majority of mined territories are agricultural lands (chernozem soils). According to the Ministry of Defence, as of March 2025, 52,089 hectares of agricultural land were contaminated with mines and explosive remnants of war (Semeniuk, 2025).

***Problem Statement.*** The detection of EO in Ukraine is a very pressing issue, the resolution of which will ensure the life and safety of the population and the ability to use their territories; however, this requires the application of effective and reliable methods. Currently, about 470 hectares of agricultural land in the country are mined, which makes it completely impossible to conduct agricultural activities. According to the Ukrainian Agribusiness Club assessment, each year of downtime for these lands costs the country's economy up to 800 million USD. Additionally, 6 million hectares are under temporary occupation, which will also require inspection after liberation (Miroshnychenko, 2023).

Traditional methods of mine detection and disposal are labor-intensive, dangerous, and often ineffective. To date, none of the existing demining methods provides a 100 % guarantee of territory clearance. The focus of the Spring Innovation Contest is on the remote recognition and neutralization of the territories contaminated with explosive substances, otherwise known as remote demining operations.

The integration of modern technologies, such as remote sensing (RS) data and artificial intelligence (AI), offers new approaches to monitoring and detecting minefields, increasing the efficiency and safety of these processes.

The purpose of this study is to analyze existing methods and technologies for detecting EO on agricultural land, evaluate their advantages and disadvantages, as well as the prospects for the development of these methods and technologies.

The process of detecting, demining, and removing EO is associated with a number of problems, which are detailed in Fig. 2.

**PROBLEMS ARISING DURING THE PROCESS OF DETECTION, DEMINING, AND REMOVAL OF EO**

**Loss (absence) of maps and other information about EO locations**
The lack of information regarding EO is not always meticulously recorded. Even when maps are available, they can only serve as a guide due to inherent uncertainty. In some cases, EO is deployed chaotically via drops from aircraft and drones

**Change in EO location in the soil due to climatic factors and the influence of time**
Natural disasters (floods, earthquakes, sandstorms, etc.) can shift mines and unexploded ordnance or cover markers indicating mined areas. Soil type can also pose a problem for the detection and neutralization of landmines

**Long term persistence of explosive ordnance hazards**
The high sensitivity of EO to detonation over time presents a great danger to people

**Lack of precise information regarding the quantity and types of mines laid**
There are hundreds of types of landmines, which can have metal, plastic, wooden, and other casings

**High cost of demining**
Demining 1 km² of territory is estimated to cost $3 million

**Fig. 2. Problems in EO detection, demining, and removal**

Demining of fields does not guarantee a quick return to agricultural activities on these lands for farmers. The surface still needs to be levelled and recultivated, soil fertility to be restored, etc. (Miroshnychenko, 2023). This significantly weakens the state of food security within the country and the share of its agricultural production and sales on global markets.

Explosive Ordnance (EO) encompasses industrial-grade explosive materials, improvised explosive devices, and ammunition containing explosive substances, as well as biological and chemical substances (Mine Safety, 2025). This category comprises items such as artillery and rocket projectiles, warheads of missiles and torpedoes, cartridges for military small arms, grenades, aerial and depth bombs, anti-personnel blast mines and fragmentation mines, booby traps, engineering and naval mines, demolition charges, anti-tank guided missiles, remotely controlled anti-tank mines, cluster bombs, and submunitions. These also include electrical explosive devices and other assembled items equipped with explosive substances intended for firing from firearms or causing an explosion. Some of them are represented in Fig. 3.

**Fig. 3. Examples of EO in the territory and waters of Ukraine**

According to the Ministry of Defence of Ukraine, as a result of detonations of mines and other EO just in the period 2014–2019, 833 civilians were affected, of whom 269 died, and the rest suffered injuries of varying severity and mutilations. Every tenth victim was a child (Ministry of Defence of Ukraine, 2019). Explosive ordnance does not distinguish between soldiers and civilians or children.

Demining efforts in these territories currently involve collaboration between the military, domestic specialists and scientists, and foreign experts for explosive ordnance detection and neutralization. Ukraine closely cooperates with various international organizations – the UN, OSCE, NATO, the Geneva International Centre for Humanitarian Demining (GICHD), demining centres in Denmark, France, Croatia, Estonia, and several others. The global community has not remained indifferent to Ukraine's problems. The USA, Canada, Great Britain, Denmark, Norway, Estonia, Austria, Poland, Japan, Switzerland, Sweden, Slovakia, and other countries provide both financial assistance and vehicles, equipment to search for explosive ordnance, gear, and protective equipment. Furthermore, they are training Ukrainian military personnel in advanced technologies for demining and ordnance disposal.

The detection of explosive ordnance on agricultural lands is a complex task that requires consideration of several factors directly impacting the effectiveness of search operations. Understanding these factors is critically important for ensuring the safety and success of demining operations.

The detection of EO is influenced by:

- physical and chemical properties of the soil (Density, moisture, and composition of the soil determine the penetration of electromagnetic and other waves and signals used in detection methods);
- morphological characteristics and condition of EO (The depth of burial, size, degree of corrosion, deformation, and fragmentation of explosive ordnance affect signal strength complicating their identification.);
- meteorological conditions (Weather conditions and extreme temperatures hamper search operations and can affect equipment performance.);
- vegetation (Tall and dense vegetation cover can obstruct access to the territory; seasonal changes in vegetation conceal previously visible EO).

The inherent complexity of demining is increased by the wide variety of mines used. Currently, over 700 types of EO which have been developed, are manufactured, and are employed (Neroba, 2019; Hutsul, Tkach, & Khobzei, 2024).

Based on their intended purpose, mines are divided into anti-personnel and anti-tank (Bhuiyan, & Nath, 2006). The types of anti-tank mines are presented in Tab. 1.

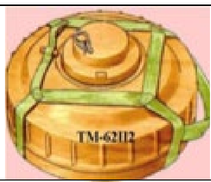
Each landmine consists of three components:

1. a casing (which can be metal, wooden, plastic, or a combination thereof);
2. an explosive charge (TNT, RDX, a mixture of RDX with TNT, Tetryl, or other explosive substances);
3. an initiator / fuse (pressure sensor, electronic, or any other type of sensor).

Landmines can be classified by their construction and intended purpose. By construction, landmines are divided into three categories: blast mines, bounding mines (like the Bouncing Betty), and fragmentation mines.

*Table 1*

**Types of anti-tank mines**

| Name | Appearance | Specifications |
|---|---|---|
| ***TM-62M Anti-Tank Mine*** |  | *Material: Metal. Weight: 9.5 – 10 kg.*<br>*Explosive weight (TNT, TGA, MS): 7.5 –8 kg.*<br>*Diameter: 32 cm. Height with MVSh-62: 12.8 cm.*<br>*Height without MVSh-62: 10.2 cm.*<br>*Sensor diameter: 9 cm.*<br>*Sensitivity: 200 – 500 kg* |
| ***TM-62P Anti-Tank (Anti-Track) Mine*** |  | *Material: Plastic. Weight: 9.0 – 11 kg.*<br>*Explosive weight (TNT, TGA, MS): 7.5 – 8 kg.*<br>*Diameter: 34 cm. Height with MV-62: 12.8 cm.*<br>*Height without MVSh-62: 33.0 cm.*<br>*Sensor diameter: 12 cm.*<br>*Sensitivity: 200 – 500 kg.*<br>***Detection:** Not detectable by metal detectors. Can be detected by radio-frequency mine detectors, sniffers, or search dogs* |
| ***TM-62P2 Anti-Tank (Anti-Track) Mine*** |  | *Material: AG-4V plastic. Weight: 9.35 – 10 kg.*<br>*Explosive weight (TNT, TGA, MS): 6.5 – 7 kg.*<br>*Diameter: 32 cm. Height with MV-62: 12.8 cm.*<br>*Height without MVSh-62: 33.0 cm.*<br>*Sensor diameter: 12.5 cm.*<br>*Sensitivity: 80 – 750 kg.*<br>*Hard to detect with metal detectors* |
| ***TM-62P3 Anti-Tank (Anti-Track) Mine*** |  | *Material: Polyethylene. Weight: 7.5 – 8 kg.*<br>*Explosive weight (TNT, TGA, MS): 6.5 – 7.2 kg.*<br>*Diameter: 32 cm. Height with MV-62: 12.8 cm.*<br>*Height without MVSh-62: 33.0 cm.*<br>*Sensor diameter: 12.5 cm.*<br>*Sensitivity: 120 – 750 kg.*<br>*Hard to detect with metal detectors* |
| ***TM-62B Anti-Tank (Anti-Track) Mine*** |  | *Material: No casing. Reinforced outer layer of explosive used as body.*<br>*Weight: 8.6 kg.*<br>*Explosive weight (TNT, TGA, MS): 8 kg.*<br>*Diameter: 31.5 cm. Height with MV-62: 12.8 cm.*<br>*Height without MVSh-62: 33.0 cm.*<br>*Sensor diameter: 12.5 cm.*<br>*Sensitivity: 120 – 750 kg.*<br>*Hard to detect with metal detectors* |
| ***TM-62T Anti-Track Blast Mine*** |  | ***Material:** Capron*<br>***Weight:** 8.3 – 9 kg*<br>***Explosive charge weight (TNT, TGA, MS):** 7.0 – 7.9 kg*<br>***Diameter:** 32 cm*<br>***Height with MV-62 fuse:** 12.8 cm*<br>***Sensor diameter:** 12.5 cm*<br>***Sensitivity:** 120 – 750 kg*<br>***Detection:** Hard to detect with metal detectors* |
| ***TM-62D Anti-tank Mine*** |  | ***Body material:** Wood*<br>***Weight:** 11.3 – 12 kg*<br>***Explosive charge weight (TNT, MS):** 5.8 – 11 kg*<br>***Length:** 34 cm*<br>***Width:** 29 cm*<br>***Height with MV-62 fuse:** 12.8 cm*<br>***Sensor diameter:** 12.5 cm*<br>***Sensitivity:** 120 – 750 kg*<br>***Detection:** Hard to detect with metal detectors* |

*Blast mines* are buried close to the soil surface and are triggered by pressure (when driven over or stepped on, or when handled / damaged). For pressure-activated mines to detonate, typically 5 to 16 kg of pressure is required. The main purpose of these mines is to destroy an object in the immediate vicinity, for example, a person's foot or leg. A blast mine is designed to shatter the target object into fragments, causing secondary damage – amputation or infection (Abujarad, 2007).

*Bounding mines* are usually buried with only a small part of the initiator protruding from the ground. Upon activation, the initiator sets off a propelling charge that launches the mine approximately 1 meter into the air aiming to cause injury to a person's head and chest (Abujarad, 2007).

At present, numerous means, technologies, and devices for detecting EO are known. The application of a particular device depends on many factors, one of which may be the type of casing, the type of explosive ordnance, the depth of burial, the quantity, the presence of natural and artificial obstacles, etc. The general algorithm for the EO detection process is presented in Fig. 4.

To clear EO from the affected territories, various demining methodologies are used worldwide, including manual demining, the use of metal detectors, trained dogs or rats, drones, robots, and specialized demining machines. The choice of methodology depends on the type and quantity of mines, the geography of the mined territory, available resources, and technologies.

The classification of EO detection methods according to data from Mentus, Jasko, and Saprykin (2024) is presented in Fig. 5.

The choice of methods depends on the demining conditions, the type of mine casing, the explosive substance, the soil where they are located, etc. The detector (sensor) can be mechanical, acoustic, optical, electromagnetic, nuclear, biological one, etc.

A characterization of mechanical methods (manual and mechanized) for the detection and neutralization of EO is presented in Tab. 2.

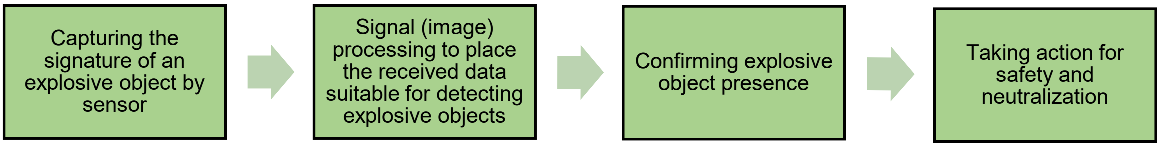



**Fig. 4. Stages of the explosives detection process**

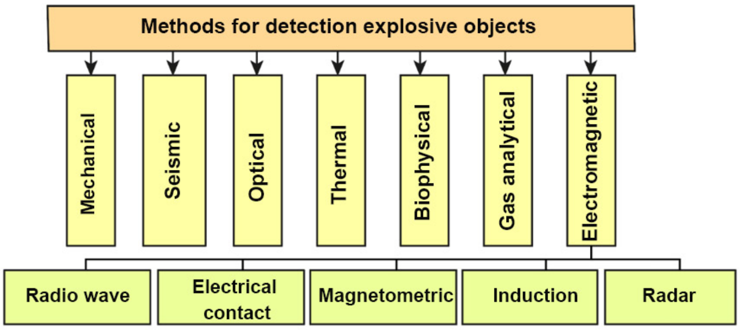
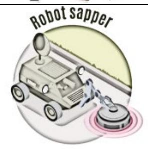
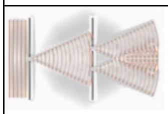
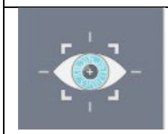



**Fig. 5. Methods for the detection and identification of potentially explosive objects**

*Table 2*

**Characteristics of EO detection and neutralization methods**

| | Method Description | Safety and Effectiveness |
|---|---|---|
|  | **Manual methods**. A person using probes (prodders) performs a search and demining. Probes are included with army mine detectors. The detectors themselves are divided into many types and differ in the method of searching for explosive devices (metal detectors, thermal imagers, chemical, radiation, acoustic mine detectors) (Velichko, 2023) | Although dangerous for humans and time-consuming, in some cases this may be the only option, especially in complex or hard-to-reach terrains |
|   | **Mechanized methods** are based on mechanical search followed by neutralization of EO that involves the use of special armoured vehicles. To improve quality, combined systems are used (e.g., cultivator and flail). Various tools, search systems, navigation, remote control, etc. are installed on multifunctional platforms. Disadvantages: high equipment cost and operational expenses, environmental consequences. Technical characteristics: weight – up to 23 tons; clearing width – 2.75 m; clearing depth – up to 350 mm; clearing speed – up to 2.3 km/h; demining productivity – up to 30,000 m²/day; fuel consumption – 40-50 L/h; remote control distance – up to 1000 m | Safe, fast, and effective for demining mines, improvised explosive devices (IEDs), cluster munitions with explosive content up to 15 kg, and over large areas. Cannot always be used, e.g. steep slopes over 35°, or the areas with numerous natural obstacles |
|  | **Seismic and acoustic methods** stem from the difference in seismo-acoustic signals reflected from the searched object in the audible and infrasound frequency ranges. These methods allow detecting inhomogeneities in the medium that arise between the material of the searched object and the surrounding environment | |
|  | **Optical and visual methods.** Optical and visual methods for detecting explosive ordnance draw on the use of light waves and images to identify objects. They include the use of special devices, such as optical instruments, lasers, or thermal imagers, which enable spotting the objects by their physical properties, contrast, or anomalies in the environment (vegetation color, soil, micro relief). Advantages: simplicity, accessibility, non-requirement of complex equipment, territorial universality and machine learning use (Popov, et al., 2022). LiDAR technology creates three-dimensional surface models permitting the identification of anomalies that may indicate the presence of dangerous objects, such as mines or improvised explosive devices | Depend on the human factor, experience, attentiveness, and qualifications of the specialist. Support the exposure of only EO found on the surface, while being indispensable for detecting threats at a distance or in visually accessible places. Methods are effective with aerial photography (recognition by geometric outline), but dangerous for humans (in case of visual search).<br>LiDAR scanning is safe; allows for scanning large areas; is capable of detecting both metal and non-metal objects, and is independent of climatic conditions or time of the day |
|  | **Thermal methods** rely on the ability of the objects to emit or absorb heat and create a temperature contrast with the surrounding environment. The main disadvantages include a significant number of interferences caused by the heterogeneity of the topsoil layer and vegetation, the presence of a large time gap during the day (up to 6-8 hours) in the absence of contrast, and a high cost of thermal imaging equipment | They facilitate scanning large areas at a safe distance minimizing risk to humans, with being effective for detecting objects in darkness. The latter depends on the material of the explosive ordnance |

*Ending Tab. 2*

| | Method Description | Safety and Effectiveness |
|---|---|---|
|  | **Biophysical methods** employ technical means to analyze biophysical signals. Biophysical methods (biosensors) depend on the possibility of direct sensing of explosive compounds (Habit, 2007) and also include the help of living creatures (dogs, rodents, bees, some types of plants and bacteria) capable of sensing odours and chemical traces of explosive substances (Hutsul, Tkach, & Khobzei, 2024; Rebuilding lives through mine clearance, 2024). One of the most effective sensors for detecting landmines is dogs. They can be trained and precisely taught to find the scent of any explosive filler, casing material, or container buried in the ground up to 60 cm deep. The sensitivity of dogs to mine-related substances is estimated to be 10,000 times higher than that of artificial detectors (Sieber, 1995) | One animal can survey an area the size of a tennis court in 30 minutes. (Implied safety advantage for the operator compared to manual methods) |
|  | **Gas analytical and chemical** methods are grounded on detecting gaseous vapours from the slow decomposition or evaporation of the explosive substance (EO usually contains from several tens of grams to kilograms of explosive). Detection is carried out using chemical, mass-spectrometric, and other methods. A gas analytical detector is capable of identifying molecules characteristic of explosives in the air (e.g., searching for TNT or nitro-glycerine vapours). The chemical method involves the use of reagents or special test systems that change colour or other properties upon contact with certain hazardous explosive chemical compounds. The concentration of explosive vapours reaches $10^{-7}$–$10^{-8}$ g/L near the soil surface above the location of an anti-tank mine buried at a depth of 5 cm (at positive temperatures) | Methods are characterized by high accuracy, but may require specific equipment and conditions for their implementation |
|  | **Electromagnetic methods** operate via the use of electromagnetic waves to identify materials with different physical properties by detecting distortions of an external electric or magnetic field.<br>Electrical Resistivity Tomography (ERT) method runs on the principle of measuring the electrical properties of the medium, such as conductivity or resistance. It is used to detect small objects in the soil by creating an external electric field in the studied area and analyzing field changes caused by inhomogeneities in the material or structure of the soil.<br>Metal detectors are the most common example. They work on the principle of detecting changes in the electromagnetic field caused by the metallic components of explosive devices.<br>Induction methods employ inductive sensors to measure the electromagnetic response of objects and identify potentially dangerous ones among them.<br>Radio wave method is built around detecting differences in dielectric permittivity between the object (EO) and the soil. Ground Penetrating Radar (GPR) methods use radio waves to scan the soil and detect hidden objects. These systems allow detecting explosives through the analysis of material structure and density | Methods are quite accurate and applied both in open areas and in urban conditions. They provide effective detection even at significant depths and in any natural environments. Magnetic methods prove effective for detecting ferromagnetic objects in any natural environments, while being unable to identify plastic and wooden EO or substances with dielectric properties. Radio wave methods can detect non-metal objects, are independent of weather conditions and lighting. Searches are operative in natural environments (soil, vegetation, water, ice, etc.), and provide detection of engineering mines at depths up to 10 cm |

In practice, no single method is universal or 100 % effective; only their combination allows for increased demining efficiency.

One promising direction to search for and neutralize EO is the development of demining robots (sapper robots), which can be used in conjunction with UAVs to improve the efficiency of mine search and neutralization. Such robots can operate in complex terrain conditions, as well as over large areas.

To detect EO, it is necessary to know their demasking features (tell-tale signs), which are determined by a number of factors:

a) presence of explosive substance;

b) discovery of a metal concentrated locally (even so-called "non-metallic" mines contain up to 0.1 g of aluminium);

c) characteristic shape of the EO (mine, shell, bomb, missile, etc.);

d) inhomogeneities in the environment (disturbance of the soil surface, road surface, building wall, changes in vegetation colour or snow cover, etc.);

e) existence of the objects unfamiliar or uncharacteristic of the area;

f) prominence of certain sounds coming from the object (ticking clock, signals at intervals) or flashing indicator on the object;

g) appearance of power sources on or near the mechanism (batteries, accumulators, etc.);

h) manifestation of tripwires or wires extending a long distance from the mechanism;

i) discovery of an object left in an unusual place for it;

j) occurrence of plastic bottles (trash) and other items.

A mine is primarily demasked by three factors:

- presence of a concentrated mass of explosives;
- characteristic mine construction (shape, casing material, etc.);
- disruption of the homogeneity of the surrounding background (vegetation colour, soil density, etc.).

**Application of Unmanned Aerial Vehicles (UAVs)**

The use of UAVs opens new possibilities for detecting EO and significantly reduces risks in dangerous situations saving human lives. The United Nations has recognized UAVs as a real tool in mine action. Currently, UAVs are the most promising technology.

To solve demining tasks, various types of sensors are installed on UAVs (Cherednychenko, et al., 2023), such as:

- hyperspectral remote sensing cameras for detecting changes in vegetation cover caused by the presence of mines;
- infrared (thermal) cameras for identifying temperature anomalies associated with EO;
- radar locators to search for EO (Ground Penetrating Radar – GPR);
- mobile metal detectors that allow remote scanning of the Earth's surface;
- magnetometers.

Improving demining methods involves integrating various technologies into a unified system. The use of artificial intelligence and geographic information technologies allows for the creation of minefield maps based on the analysis of satellite images and data from UAVs. Furthermore, the development of autonomous demining systems that can operate without direct human involvement is a promising direction.

UAVs promote a rapid and effective survey of large territories and obtaining of high-quality data that can be used for detecting and identifying EO.

UAVs equipped with high-resolution cameras are capable of performing aerial photography from various altitudes and angles. This enables obtaining orthophotos and 3D models of the terrain which can be analyzed in detail. Experienced analysts can detect visual signs of EO presence, namely:

- changes in relief caused by explosions even if partially covered by vegetation;
- atypical depressions, mounds, or other changes in landforms that may indicate the presence of buried EO;
- damage to vegetation, changes in its colour or structure, which may result from explosions or falling ordnance;
- parts of EO located on the soil surface that can be detected on aerial photographs.

UAVs equipped with thermal cameras are capable of detecting temperature anomalies on the soil surface that may be related to the presence of EO (owing to thermal conductivity different from the surrounding soil).

Combining aerial photography and thermal scanning enables obtaining a comprehensive picture of the territory characteristics significantly increasing the probability of detecting EO. The obtained data can be used to create mine hazard maps, plan demining operations, and evaluate the effectiveness of conducted measures.

*Table 3*

**Comparative analysis of EO detection methods**

| Detection Methods | Detection Effectiveness | Survey Speed | Cost and Availability | Safety of Application |
|---|---|---|---|---|
| Visual Inspection | Low (only surface objects) | High (rapid overview) | Low (minimal costs) | High (remote survey) |
| Metal Detectors | Medium (depends on soil type and depth) | Medium (depends on territory size) | Medium (includes cost of equipment and training) | Medium (requires qualified specialists) |
| Geophysical Methods (magnetic survey) | High (detection of metal objects at depth) | Medium (depends on territory size) | High (includes cost of equipment and data analysis) | Medium (requires qualified specialists) |
| GPR Survey (Ground Penetrating Radar) | High (detection of metal and non-metal objects) | Low (requires detailed scanning) | High (includes cost of equipment and data analysis) | Medium (requires qualified specialists) |
| UAV (aerial photography) | Medium (detection of visual signs) | High (rapid survey of large territories) | Medium (includes cost of equipment and data analysis) | High (remote survey) |
| UAV (thermal imaging survey) | Medium (detection of thermal anomalies) | High (rapid survey of large territories) | High (includes cost of thermal imaging equipment) | High (remote survey) |

***Application of Geographic Information Systems (GIS) and Artificial Intelligence***

Geographic Information Systems (GIS) play a significant role in researching the impact of military actions, providing tools for data analysis, visualization and modelling, event documentation, assessing the scale of infrastructure destruction consequences, environmental impact, and recovery planning. GIS technologies provide a multidimensional approach to analyzing the impact of military conflicts allowing for more informed decision-making.

There is a growing number of trials combining GIS methods with geostatistical methods for modelling mine risks to supplement data on demining activities (Alegria, et al., 2017). GIS are used to create risk maps that delineate high-danger zones requiring priority demining (Hutsul, Tkach, & Khobzei, 2024). The use of information management can enhance the safety and effectiveness of mine action. Mine action involves collecting large amounts of data from various sources and data required for different processing steps. High spatial resolution satellite images (up to 1 m) are useful for working in minefields as they do not require interpretation. Images with spatial resolution up to 10–30 m are useful as regional maps for team planning.

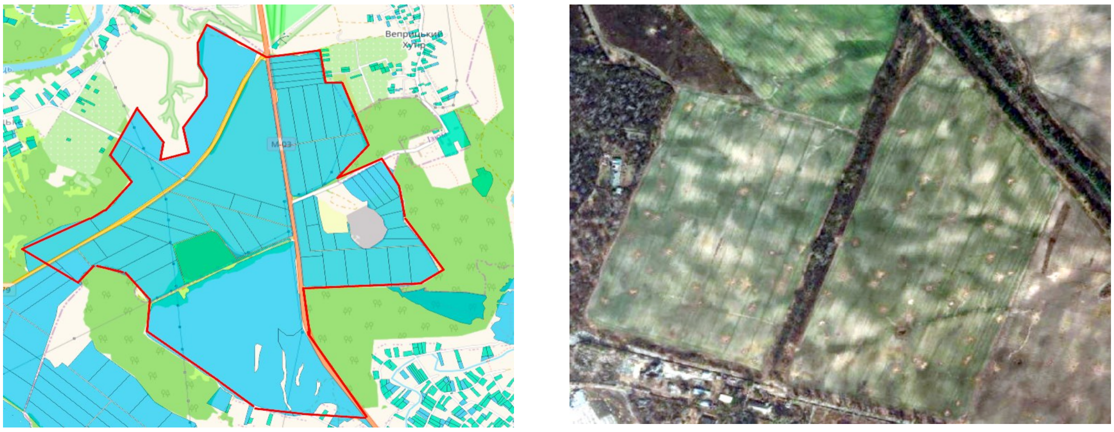
Using high spatial resolution satellite imagery data and computer vision algorithms, it is possible to automatically identify and analyze damage to land plots, infrastructure, forests, agricultural lands, and even residential areas. Such algorithms can learn to recognize specific signs of combat impact: explosion craters, destroyed buildings, lost or damaged vegetation cover, and other traces of destructive influence.

A growing trend today is the combination of GIS and machine learning, which involves training algorithms based on input data and optimizing their performance over time. Neural networks are effective for detecting landmines due to their ability to process large volumes of data, recognize complex patterns, and adapt to diverse environmental conditions. Due to neural networks, the process of landmine detection has undergone significant changes as they provide effective tools for pattern recognition and classification.

***Practical aspects of detecting EO on agricultural lands***

The presence of EO on agricultural lands poses a serious threat to the life and health of farmers working in these areas. A sudden explosion can lead to numerous injuries including traumas and fatalities. Furthermore, the mine hazard complicates agricultural work negatively affecting the region's economy.

*Study Object № 1.* For the study, agricultural lands located in the vicinity of the city of Izium (Fig. 6a), Kharkiv Oblast, were selected. This territory suffered significant destruction during the Russian occupation, which lasted from April 2022 until September 10, 2022. The city of Izium, being a strategically important point, was at the epicenter of active hostilities involving artillery, aviation, mining, and other types of weapon, which led to a large-scale contamination of the territory with EO. Despite the city's liberation, the threat of mine danger remains extremely high, especially on agricultural lands (Fig. 6b), where areas are mined with anti-personnel and anti-tank mines. Besides, there is a likelihood of remnants of unexploded artillery shells, cluster munitions, mines, aerial bombs, improvised explosive devices, etc.



a) b)

**Fig. 6. Study objects of agricultural lands:**
a) Plot 1: territory of agricultural lands of Izium city; b) Plot 2: agricultural lands of the Hostomel community territory

The city of Izium is located on the banks of the Siverskyi Donets River. The M03 and P79 highways and a railway pass through the city. The city is surrounded by very dense forests interspersed with numerous hills and steppe ploughed plots. The territory's relief is varied, from flat areas to hills and ravines, which complicates demining operations. Absolute elevation marks range from 57 m to 183 m.

***Surveying the selected territory***

*Preparatory stage.* To begin operation, it is necessary to familiarize oneself with the geological conditions of the study area, create a plan with images of the search zone, and plot the movement trajectory. Zones can be divided into squares with corresponding values by applying a grid to the map. An example of zoning for surveying the territory is shown in Fig. 7.

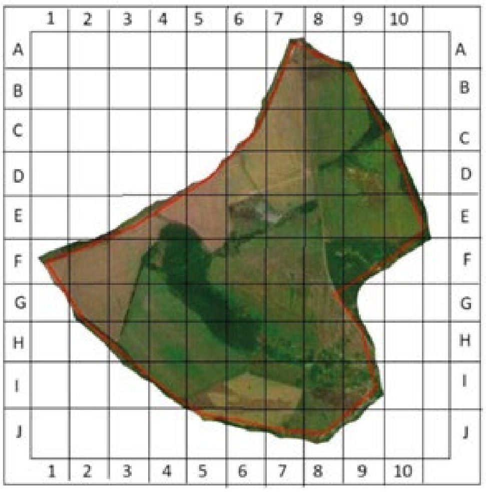



**Fig. 7. Zoning scheme for the study of agricultural lands in the territory of Izium city (Kharkiv Oblast) for detecting explosive devices**

Using such a map, sappers can document in which square EO was found and what it is. For example, EO found / not found in square C-7.

*Aerial photography and results processing.* A UAV equipped with a high-resolution camera performs a fly-over of the territory conducting surveys from different altitudes and angles. A schematic representation of the UAV route to be used for aerial photography of the area is presented in Fig. 8. Scanning is carried out along established routes with zone overlap to ensure full coverage of the territory. Upon detecting metal objects, sappers identify those using additional tools. The obtained aerial photographs are processed using specialized software to create orthophotos and 3D models of the terrain. Afterward, the resulting images are carefully studied to identify visual signs of EO presence (craters, traces of explosions, relief anomalies, changes in vegetation, etc.).

Based on the analysis of satellite images and UAV data using artificial intelligence and geographic information technologies, maps of minefields can be created.

*Image analysis using geographic information systems (GIS) and machine learning methods.* First, image preprocessing is carried out, which includes correcting distortions, adjusting brightness, and enhancing contrast. Next, characteristic objects are extracted, which involves applying computer vision algorithms to search for circular or elliptical depressions on the surface (Fig. 9).

In the next stage, craters are classified using artificial neural networks or other recognition methods to separate them from natural formations such as ravines, depressions, or water bodies.

A key aspect of the study is the analysis of the spatial distribution of craters. A high density of such objects in a limited area may indicate intensive mining or artillery shelling. Using ArcGIS tools or other geographic information programs, one can identify clusters of craters that may indicate minefields, assess the probability of unexploded ordnance presence based on the uneven distribution of explosions, and build risk maps for further demining of territories.

*Visual analysis using metal detectors* involves a thorough inspection of the territory by qualified specialists to detect any signs that may indicate the presence of EO. Sappers equipped with pulse induction metal detectors carefully scan areas identified as potentially hazardous based on aerial photography and thermal scanning results.

This methodology is used in the military sphere to assess danger in deoccupied territories, in agriculture to minimize risks during soil cultivation, and in humanitarian demining missions. The use of UAVs significantly speeds up the process of surveying territories and reduces risks for sappers (Molochko et al., 2021).

*Study Object № 2.* Within the scope of the agricultural land study, the territory of the Hostomel community, which is located in the Bucha district of Kyiv Oblast, was selected. The territory is characterized by flat relief. The soil cover mainly consists of sod-podzolic and chernozem-meadow soils, which is favourable for agriculture (Fig. 6 B). Within the Hostomel community, there are significant areas of arable land, meadows, and pastures used for growing grain, vegetables, and fodder crops. Following the hostilities in the

Hostomel territory, there arose a need for a detailed analysis of agricultural lands.

A field near the outskirts of the Hostomel settlement was chosen as a test site, where shell craters could be identified on an image from 2022. Subsequently, an unsupervised classification was performed (Fig. 10 a) and potentially hazardous areas were identified (Fig. 10 b).

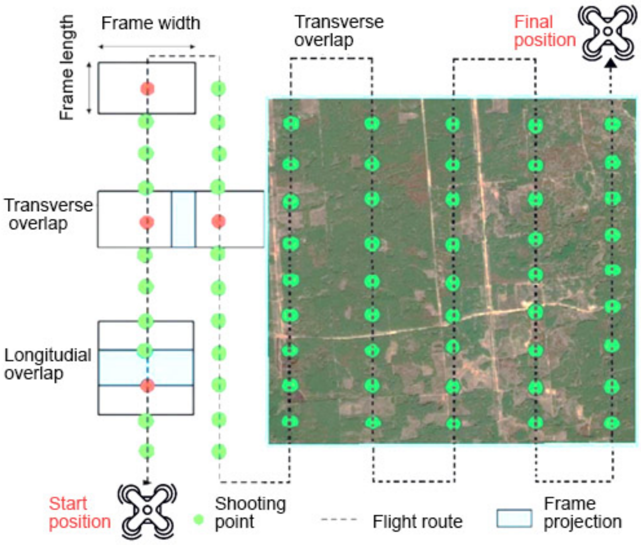
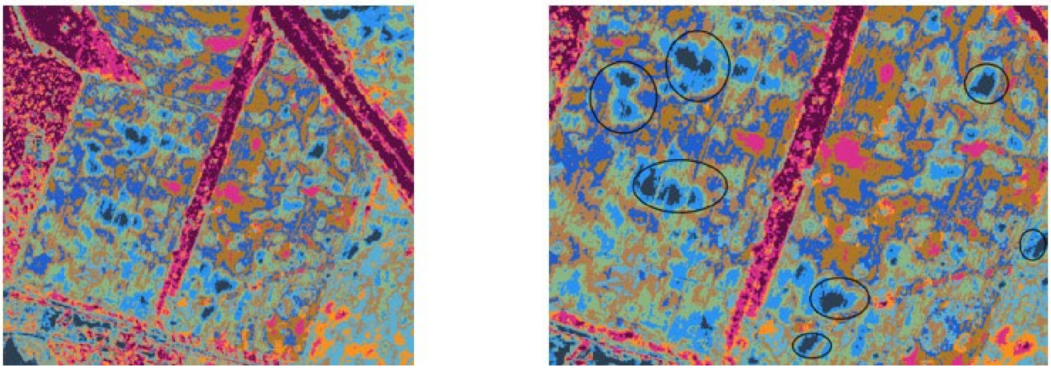



**Fig. 8. UAV movement route for performing aerial photography of the area**

**Fig. 9. Example of identifying craters on agricultural lands based on an orthophoto**



a) b)

**Fig. 10. Unsupervised classification findings:**
a) identification of 10 classes and b) identification of hazardous areas

The conducted image classification using ArcGIS Pro tools is an effective method for the automated detection of shell craters on agricultural lands. Using unsupervised classification allows for rapid segmentation of the territory and identification of potential destruction zones. The use of GIS analysis facilitates not only identifying individual craters but also determining patterns in their location, which can help predict high-risk zones.

To locate the most dangerous zones with a high probability of unexploded ordnance, craters are marked on the image as point features (Fig. 11).

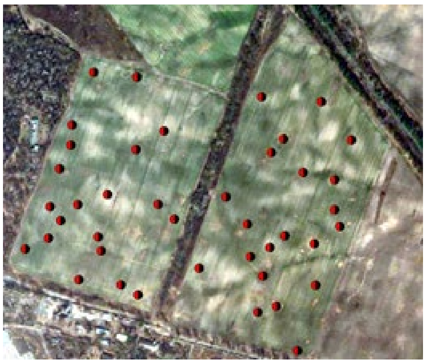


**Fig. 11. Manual identification of craters on a satellite image**

The application of buffer zones is an effective tool for spatial analysis allowing for the determination of potentially hazardous territories around shell craters. Defining zones of different radii helps assess the level of risk in a specific area, considering possible fragment dispersion and the probability of unexploded ordnance presence. Next, a map of buffer zones around craters with shells was constructed with the following buffer zone radii (Fig. 12):

- minimum zone (~ 5 m) – the immediate location of the crater, useful for precise explosion localization;
- medium zone (30 m) – the zone of possible fragment dispersion for most artillery shells (122 mm, 152 mm, 155 mm);
- maximum zone (100 m) – a potentially hazardous zone for large munitions or cluster shells.

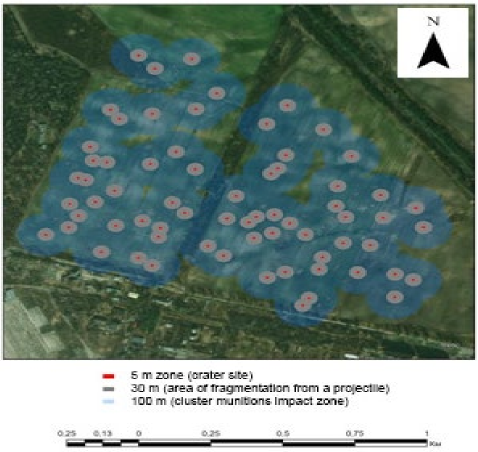



**Fig. 12. Construction of buffer zones around craters**

By optimizing both UAVs and sappers, this map can help in developing the routes for demining.

**Results**

*Results Analysis and Effectiveness Evaluation.* The analysis of the obtained results and the evaluation of the effectiveness of the applied methods is a necessary stage after completing a survey of agricultural lands. This stage is critically important for determining the degree of territory clearance and providing recommendations for its further use. Data obtained by different methods are correlated to confirm the presence of EO.

***Survey of agricultural land territory***

**1. Data analysis using a complex of methods.** *Aerial photography and thermal scanning.* Orthophotos and 3D models of the terrain are analyzed to detect visual signs of EO (craters, traces of explosions, relief anomalies). Thermal images are analyzed to detect temperature anomalies that may indicate the presence of buried EO. Detected anomalies are correlated with the data obtained by other methods.

*Metal detectors.* Data obtained from the metal detectors are analyzed to determine the location and type of metal objects. Detected metal objects are correlated with the data obtained by other methods.

*Geophysical methods (magnetometric survey).* Data from magnetometric surveys are analyzed to determine the location and size of metal objects at depth. Detected magnetic field anomalies are correlated with the data obtained by other methods.

*Biophysical methods (service dogs).* Data obtained from canine teams are analyzed to determine locations suspected of containing explosive substances. These data are correlated with the data obtained by other methods.

**2. Data correlation and verification.** Data obtained by different methods are correlated to confirm the presence of EO. Anomalies confirmed by multiple methods are identified as priorities for further verification. Data verification is carried out through visual inspection and the use of additional tools.

**3. Determination of type, quantity, and location of EO.** Based on data analysis, the type, quantity, and location of detected EO are determined. A mine hazard map is created indicating detected EO and hazardous zones.

**4. Evaluation of the effectiveness of applied methods.** The speed of survey, detection accuracy, and cost of each method are assessed. The advantages and disadvantages of each method under the conditions of the specific study object are determined. The effectiveness of combining different methods is evaluated. The time spent on the survey is assessed.

**5. Analysis of identified problems and shortcomings.** There are problems encountered during the research (weather conditions, technical malfunctions, and human factor). Shortcomings in the planning and organization of operations are identified. Recommendations for improving the demining process in the future are developed.

**Discussion and conclusions**

Contamination of agricultural land with EO as a result of the war unleashed by the Russian Federation poses a significant threat to the life and health of farmers and hinders the restoration of agricultural activities. Detection and neutralization of EO is a complex and dangerous process requiring a comprehensive approach. Applying a combination of different detection methods (UAVs with aerial photography and thermal scanning and other sensors, metal detectors, geophysical methods, service dogs) combined with GIS allows achieving maximum survey efficiency. Each method has its advantages and limitations, while combining them compensates for the shortcomings of individual methods.

The use of UAVs in humanitarian demining has a great potential for reducing risks and accelerating the process of clearing territories from explosive ordnance. Aerial photography and thermal scanning using UAVs are effective for the initial inspection of large territories and identifying potentially dangerous zones. This allows optimizing subsequent operations using metal detectors and geophysical methods. The development of geographic information systems combined with artificial intelligence technology is also complementary and promising. Using satellite imagery and machine learning technologies, artificial intelligence can analyze large datasets to detect and classify changes in the structure of land resources caused by military actions and play a key role in the operational and accurate monitoring of affected territories.

The conducted research confirms the effectiveness of a comprehensive approach to detecting EO on agricultural lands. The research results can be used for planning and conducting demining work in other territories contaminated with EO.

**Authors' contribution:** Vitalii Zatserkovnyi – conceptualization, formulation of research goals and objectives, methodology, editing; Irina Tsiupa – analysis, verification of results, editing, and adding supplements; Mauro de Donatis – writing (review), data validation; Igor Nikoliuk – analysis and systematization of literature sources, writing (original draft). Valentin Kravchenia – calculations and GIS analysis of study object 1, data validation; Oleksandr Tsvyk – calculations and GIS analysis of study object 2, data validation; Tetiana Mironchuk – translation, editing.

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**Віталій ЗАЦЕРКОВНИЙ[1], д-р техн. наук, проф.**
**ORCID ID: 0009-0003-5187-6125**
**e-mail: vitalii.zatserkovnyi@knu.ua**

**Ірина ЦЮПА[1], канд. геол. наук**
**ORCID ID: 0000-0002-8350-6685**
**e-mail: irynatsiupa@knu.ua**

**Мауро ДЕ ДОНАТІС[2], канд. геол. наук, доц.**
**ORCID ID: 0000-0002-9721-1095**
**e-mail: mauro.dedonatis@uniurb.it**

**Ігор НІКОЛЮК[1], асп.**
**e-mail: Histerias@ukr.net**

**Валентин КРАВЧЕНЯ[1], асп.**
**ORCID ID: 0009-0002-4160-361X**
**e-mail: valentyn.kravchenia@knu.ua**

**Олександр ЦВИК[1], асп.**
**ORCID ID: 0009-0006-5464-2078**
**e-mail: oleksandr.tsvyk@knu.ua**

**Тетяна МІРОНЧУК[1], канд. філол. наук, доц.**
**ORCID ID: 0000-0002-5923-1028**
**e-mail: t.mironchuk@knu.ua**

**[1]Київський національний університет імені Тараса Шевченка, Київ, Україна**
**[2]Університет Урбіно Карло Бо, Урбіно, Італія**

## МЕТОДИ ВИЯВЛЕННЯ ВИБУХОНЕБЕЗПЕЧНИХ ДІЛЯНОК ДЛЯ ДОСЛІДЖЕННЯ СІЛЬСЬКОГОСПОДАРСЬКИХ ТЕРИТОРІЙ

**В с т у п .** ***Забруднення земель сільськогосподарського призначення вибухонебезпечними предметами (ВНП) внаслідок війни, розв'язаної РФ створює значну загрозу для життя та здоров'я аграріїв, а також перешкоджає відновленню сільськогосподарської діяльності. Виявлення та знешкодження ВНП є складним та небезпечним процесом, що вимагає комплексного підходу.***

***Розглянуто основні типи наземних мін, що трапляються в Україні. Наведено основні демаскувальні фактори вибухонебезпечних предметів, проведено аналіз існуючих методів і технологій виявлення ВНП на землях сільськогосподарського призначення, оцінено їх переваги та недоліки.***

**Р е з у л ь т а т и .** ***Традиційні методи виявлення та знешкодження мін є трудомісткими, небезпечними та часто неефективними. Застосування комбінації різних методів виявлення ВНП (металодетектори, механічні методи, геофізичні методи, біофізичні, БПЛА з аерофотозйомкою й тепловізійним скануванням та іншими датчиками) та інтеграція сучасних технологій (засоби дистанційного зондування і штучний інтелект) дає змогу досягти максимальної ефективності обстеження та підвищити безпеку. Кожен метод має свої переваги та обмеження, а їх комбінування дозволяє компенсувати недоліки окремих методів.***

***Наведено приклади практичного застосування виявлення ВНП за допомогою даних дистанційного зондування Землі, інструментів просторового аналізу ГІС та машинного навчання для аналізу сільськогосподарських угідь на прикладі тестових ділянок у Київській та Харківській областях.***

**В и с н о в к и .** ***Використання БПЛА в гуманітарному розмінуванні має великий потенціал для зменшення ризиків та прискорення процесу очищення територій від вибухонебезпечних предметів. Аерофотозйомка та тепловізійне сканування з використанням БПЛА є ефективними для первинного огляду великих територій та виявлення потенційно небезпечних зон. Це дає змогу оптимізувати подальші роботи з використанням металодетекторів і геофізичних методів. Розвиток геоінформаційних систем у поєднанні з технологією штучного інтелекту є також допоміжним та перспективним. Використовуючи супутникові зображення і технології машинного навчання, штучний інтелект здатен аналізувати великі масиви даних для виявлення і класифікації змін у структурі земельних ресурсів, спричинених військовими діями і відігравати ключову роль в оперативному та точному моніторингу постраждалих територій.***

**К л ю ч о в і  с л о в а :** ***вибухонебезпечні предмети, російсько-українська війна, мінне забруднення, сільськогосподарські території.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

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