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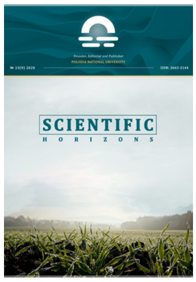

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Methodological and practical aspects of using satellite imagery to assess the military impact on soils

Vitalii Lebed*
PhD in Biological Sciences, Senior Research Fellow
National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky"
61024, 4 Chaikovska Str., Kharkiv, Ukraine
https://orcid.org/0000-0002-1429-4121

Maksym Solokha
Doctor of Agricultural Sciences, Senior Researcher
National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky"
61024, 4 Chaikovska Str., Kharkiv, Ukraine
https://orcid.org/0000-0002-1860-0819

Vadym Solovei
PhD in Agricultural Sciences, Senior Researcher
National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky"
61024, 4 Chaikovska Str., Kharkiv, Ukraine
https://orcid.org/0000-0001-9820-1780

Anatolii Kucher
Doctor of Economic Sciences, Senior Researcher
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky"
61024, 4 Chaikovska Str., Kharkiv, Ukraine
https://orcid.org/0000-0001-5219-3404

Ludmila Vorotyntseva
Doctor of Agricultural Sciences, Senior Researcher
National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky"
61024, 4 Chaikovska Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-0643-8823

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**Corresponding author*

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Abstract. The military aggression of the Russian Federation has caused significant negative impacts on Ukraine's natural ecosystems, including its soils. Comprehensive assessments of soil conditions, the extent, and the scale of damage caused by warfare are essential for documenting the resulting losses. However, the use of traditional field surveys of soil cover is hindered by the significant threat of landmines in areas liberated from occupation. This limitation necessitates the widespread adoption of remote sensing methods, such as satellite imagery. This study aimed to assess the condition of soils and the extent of their damage due to military activity within the Chkalovske territorial community of the Chuhuiv District in the Kharkiv Region. The study identified the optimal combinations of optical bands from Sentinel-2 satellites for monitoring the consequences of military impact on soil cover. A spatial layer of objects was developed to represent various types of military-induced soil degradation within the community, including damage from continuous shelling (craters from shells, rockets, and bombs); soil compaction from the movement of military vehicles (tracks and pathways); fortification structures (defensive fighting positions and dugouts); and fires caused by shelling. Using high-resolution satellite imagery, the number of craters and the soil mass loss caused by explosions, the areas of burned and compacted land, as well as the length of anti-tank ditches and defensive fighting positions with dugouts, were calculated at the test site. On the irrigated lands of the Chkalovske territorial community, the areas affected by shelling and those burned due to military-related fires were also estimated. The information derived from satellite imagery serves as a crucial step in developing measures for the restoration of the soil cover in the pilot area affected by military degradation. The study utilised satellite imagery of varying resolutions and geographic information systems to calculate the damage caused by military actions with sufficient accuracy. It also analysed the temporal and quantitative interrelations among different types of military impact. This research will serve as a basis for assessing the scale and spatial distribution of soil damage, calculating the loss of fertile soil layers, and conducting an economic evaluation of the damage inflicted on soil resources

Keywords: remote sensing; Sentinel-2; vegetation index; military degradation; soil damage; craters

INTRODUCTION

Ukraine plays a strategic role in the global food market and in ensuring global food security thanks to its highly developed agro-industrial complex. Soil resources play a crucial role in affirming Ukraine's leading position in the world in terms of agricultural trade volumes. However, these soils are now facing significant damage and destruction due to the ongoing war. Ukraine has a unique soil cover: more than 60% of its territory is occupied by chernozems, which are unmatched in terms of their root-containing layer, properties, fertility potential, and suitability for growing many field crops. The world's particular attention to the state of chernozems is due to their high suitability for agriculture, thanks to their natural fertility, high organic carbon content, and active soil biodiversity. The beginning of Russia's full-scale armed aggression against Ukraine has caused mass damage to the soil cover, the likes of which have not been seen since the Second World War. Over 5 million hectares of chernozems are located in the war zone, resulting in military (warinduced) degradation of varying intensity and direction – physical, physicochemical, mechanical, chemical, and biological (Baliuk *et al.,* 2024).

The EU Soil Strategy for 2030 (2021) aims to protect and restore soils, ensuring soil health and sustainable management. Numerous problems have jeopardised soil health, including declining carbon content, biodiversity loss, salinisation, acidification, pollution, erosion, and others. In Ukraine, these issues are exacerbated by the ongoing conflict, as the impact of anthropogenic factors on soil condition, properties, and fertility intensifies. It should be emphasised that the availability of reliable information on the condition of chernozems during and after the war will determine the effectiveness of measures to restore their fertility. A necessary condition for assessing the damage and losses from hostilities on agricultural lands is the application of remote sensing of soils, especially high-resolution satellite imagery.

In their research, M. Khalil and J. Satish Kumar (2021) identified the most affected areas in the capital of Syria by analysing two images from the Sentinel satellite using GIS software. The result of the study was a classification of territories into five classes in terms of suitability or unsuitability for reconstruction, as well as determining the percentage of each class. To map and monitor changes in the urban environment due to war, F. Fakhri and I. Gkanatsios (2021) integrated data from Sentinel-1 and Sentinel-2 satellites. The authors determined the percentage of destruction in the city of Mosul (Iraq) using spectral indices, the most important of which is the built-up area index.

A group of studies on the war in Kuwait focused on assessing the impact of hydrocarbons on vegetation resilience, modelling oil pollution in soils, and monitoring reclamation efforts in arid regions. M.M. Abdullah *et al.* (2020) utilised remote sensing to evaluate ecosystem resilience to hydrocarbon pollution caused by the war in Kuwait and the potential for post-war vegetation recovery in arid landscapes. The study identified correlations between vegetation recovery, soil type, geomorphological features, and precipitation levels. E. Kalander *et al.* (2021) found that oil pollution is associated with elevated concentrations of heavy metals in soils, which, in turn, affect the stability of plant communities. In research by G. Kaplan *et al.* (2022) the location and extent of oil pollution were determined to guide subsequent soil cleaning and reclamation measures. Based on an analysis of war-affected lands using remote sensing, H.A. Hasab *et al.* (2020) employed Landsat satellite data and decision tree (DT) classification to conclude that salinity and heavy metal concentrations decreased during the summer and increased in the winter.

Combining remote sensing data, field studies, and historical data, Polish researchers J.M. Waga and M. Fajer (2021) assessed the impact of bombing on forests and wetlands in the Koźle basin during the Second World War. They found that around 6000 well-preserved bomb craters, ranging from 5 to 15 meters in diameter and often exceeding 2 meters in depth, still exist in the region. Analysis of these craters revealed that their diverse morphology depends on the weight of the bombs that created them, as well as the type and moisture content of the soil on which the bombs fell. B. Demissie *et al.* (2022) used a comparison of time-series Sentinel-2 images to assess the impact of the Tigray Conflict (Ethiopia) on agricultural activities. By comparing the NDVI on agricultural fields in the pre-war and wartime spring seasons, they recorded an increase in greenness due to weed infestation.

Initial results of assessing the impact of the Russian-Ukrainian war on the environment, particularly soils, using remote sensing data have been revealed in publications by Ukrainian scientists. For example, S.A. Shevchuk *et al.* (2022) found that between 2021 and 2022, vegetation greenness decreased in areas where hostilities were most intense (Luhansk and Donetsk). M. Solokha *et al.* (2023) demonstrated the damage to vegetation cover caused by bombing using the example of the Kharkiv Region. A.B. Achasov *et al.* (2023), using the example of the Rohan community, identified 916 bomb craters as a result of deciphering satellite imagery data in 2022. Maps were created showing the results of recording the consequences of bombing, a heat map of explosion density, and a hydrological analysis map of the territory that could be contaminated as a result of bombing.

When assessing the impact of the war on the ecosystems of protected areas in Ukraine, O. Trofymchuk *et al.* (2023) found numerous fortifications (trenches, defensive fighting positions, dugouts), burnt-out areas, and tracks formed by the active movement of military equipment in places where the topsoil had been disturbed. A comprehensive methodological approach to assessing military damage to soils in a specific community was proposed in the study of O.S. Bonchkovskyi *et al.* (2023), in which the authors identified the most pronounced physical damage to soils in the form of craters and soil compaction, and identified bombing zones and contamination around craters. The authors concluded that soil reclamation should be carried out taking into account the specific characteristics of each contaminated and disturbed site. Another comprehensive study is the research by A. Sploditel *et al.* (2023), where, using the example of several territorial communities, an assessment of military damage to soils was conducted using high-resolution image analysis, and locations of craters from shelling, fortifications, compaction tracks from heavy military equipment, and fire foci were identified.

The relevance of the chosen topic determined the aim of the study, namely to search for and identify the consequences of military impact using satellite data of various resolutions.

MATERIALS AND METHODS

The study focuses on the soil cover of the Chkalovske territorial community (TC), which has been impacted by military activities. The community is located in the Chuhuiv District of the Kharkiv Region (Fig. 1). The total area of the territorial community is 38,697.0 hectares, including 32,257.81 hectares of agricultural land. The soil cover of the study area is predominantly represented by typical medium-humus heavy loamy and light clay chernozems. The research was conducted on both irrigated and non-irrigated lands within the TC that have been affected by military activities.

To identify various types of military impact on soils, key sites were selected in different parts of the community, focusing on areas with the highest intensity of disturbance. Craters from shell explosions were identified in the western part of the TC near the villages of Korobchyne and Hrakove. Soil compaction traces were studied in the central part, near the village of Nova Hnylytsia. Fire damage caused by shelling was examined in the central area around the settlement of Doslidne and the urban-type settlement of Chkalovske. Fortifications were documented in the northern part of the community near the village of Yurchenkove. The total area of irrigated lands in the Chkalovske TC is 1,754 hectares. For the study, the primary area of these lands, covering 1,145 hectares, was selected. Irrigation in this area had been conducted over an extended period using water with a salinity of 1.9-2.4 g/dm^3, leading to secondary salinisation in the chernozem soils. The methodology for detecting and analysing military-induced soil degradation differs from traditional field-based soil surveys. In this context, the extensive use of remote sensing methods is essential for obtaining objective data on soil conditions. A wide range of satellite data sources is currently available, varying in accessibility and spatial resolution.

***Figure 1**. Chkalovske community on the map of Ukraine*
***Source:** author's mapping scheme*

The use of remote sensing methods enables the acquisition of preliminary information on the condition of soils affected by military activities. Satellite imagery can be employed to monitor changes in soil cover over specific periods and to generate cartographic materials based on the data obtained. Notably, remote sensing materials most effectively capture evidence of mechanical and physical soil degradation resulting from combat operations. Other forms of degradation, such as chemical and biological, are typically secondary to these primary types.

Mechanical degradation appears in satellite images as anomalous colour features, often circular shapes (craters) or elongated, irregular patterns representing trenches, ditches, and similar structures. Early identification of these features is essential for accurate assessment. Physical degradation, observed throughout the study period, is evident in tracks left by military vehicles on agricultural fields. Indicators of this type include filamentous lines on fields that were absent prior to the onset of hostilities. Abiotic impacts from fires are identifiable as abrupt changes in vegetation colour, transitioning to an intense black on the affected fields. Over time, the colour becomes lighter as the remains of combustion decompose, meaning identification can occur from weeks to months after the initial impact. Chemical impacts are identifiable in cases where signs of burned military equipment are visible in satellite imagery, typically in a random pattern. These are accompanied by black or white smoke in images captured during active combustion or by abrupt black discolouration in affected areas.

For a preliminary assessment of the presence and extent of soil damage, the use of free, openly accessible satellite imagery is advisable. Among such sources, the Sentinel-2 satellites of the European Space Agency provide the most detailed information. These satellites offer a maximum resolution of 10 metres per pixel, enabling the identification of areas with clusters of craters from shell explosions, individual craters from airstrikes, soil surface compaction caused by military vehicles, and large fortifications.

Sentinel-2 allows for image updates every 5 days for the same area. To ensure a high-quality analysis of soil surface damage, it is essential to select images captured on cloud-free days. The timing of observations relative to seasonal changes is also significant. When using Sentinel-2 imagery, the period from mid-spring to mid-autumn should be selected to capture vegetation at various stages of growth. During this time, vegetation serves as a clear indicator of mechanical impacts on the soil, allowing such impacts to be traced through uneven vegetation cover. However, it should be noted that during peak vegetation growth in summer, identifying traces of combat activity can sometimes be challenging due to the overgrowth of the targeted areas. Sentinel-2 provides multispectral imagery comprising 12 optical bands. The following bands were selected for image analysis: blue (Blue-B02), green (Green-B03), red (Red-B04), near-infrared (NIR-B08), and shortwave infrared (SWIR-B11, B12).

The majority of the Chkalovske TC was occupied from 7 April to 10 September 2022, a period of approximately five months (DeepStateMAP, n.d.). To assess soil damage, Sentinel-2 satellite imagery was selected from the post-conflict period, spanning from mid-September to the end of the year. For high-resolution images, the following dates were chosen: 23 and 24 January, and

23 March 2023. These dates were selected to ensure cloud-free and snow-free conditions over the study areas. The winter and early spring periods are particularly suitable for assessing soil surface damage due to the absence of vegetation cover. Satellite images from Sentinel-2 were downloaded and initially processed using the EO Browser online platform (Sentinel Hub EO Browser, n.d.). The creation of maps showing soil damage identified in the imagery was conducted using the licensed version of the MapInfo software and the educational version of ArcGIS (ArcGIS Desktop, n.d.).

To compare and identify changes in the soil cover for 2022, satellite images from the corresponding period in 2021, prior to the onset of hostilities, were selected. EO Browser provides a feature for comparing images from different times by displaying a split-screen boundary between two images or overlaying them with adjustable transparency for smooth transitions (Fig. 2). This comparison enables the identification of military impacts, including shell craters, compaction from heavy equipment, fire damage caused by shelling, and fortification structures.

***Figure 2**. Comparison mode for different-time images in EO Browser*
***Source:** screenshot from Sentinel Hub EO Browser (n.d.)*

The identification (interpretation) of different types of soil damage caused by hostilities involves specific considerations. The most common damages are craters resulting from shell explosions of varying calibres and aerial bombs. Explosion sites on the soil surface are characterised by the displacement of subsurface soil masses from deeper genetic horizons, leading to material mixing. This phenomenon, observed universally, is termed "bombturbation" (Bonchkovskyi *et al.,* 2023; Sploditel *et al.*, 2023).

There is a direct correlation between the size of the craters and the calibre of the explosive device. For example, damage from a mortar shell is significantly smaller than that caused by an aerial bomb. Sentinel-2 satellite imagery lacks the resolution required to clearly distinguish small-diameter individual craters. However, small craters typically occur in clusters, which are visually detectable in Sentinel-2 images. Craters from larger calibres and aerial bombs can be identified by the lighter-coloured areas surrounding them, caused by the exposure of lighter subsoil and parent material ejected during the explosion.

The simplest method for analysing satellite images involves using the combination of blue, green, and red channels (RGB composite), known as "True Colour". However, for studying military-induced soil damage, employing alternative colour combinations (optical channels) is crucial for a more detailed examination of the soil cover condition. One of the most commonly used combinations is "False Colour", which incorporates green, red, and near-infrared (NIR) channels. The NIR spectrum is particularly effective for monitoring vegetation, as it has the highest reflectance in this range. In the resulting images, vegetation appears in shades of red. During periods of active vegetation growth, dense plant cover obscures the soil surface, making it challenging to clearly identify craters formed before the peak growth phase, such as in spring. Damage to fields caused during the summer period can still be identified using specific optical channel combinations. One effective combination is known as "Agriculture", which integrates shortwave infrared (SWIR), NIR, and blue channels. The addition of SWIR expands the analytical range for observing soils and vegetation. When using the "Agriculture" composite, vegetation appears in natural green hues, allowing for clearer identification of soil and vegetation conditions.

Another effective method for analysing soil damage, such as craters, involves the use of indices, particularly vegetation indices. The most well-known and widely used of these is the NDVI, calculated using the equation:

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)}, \quad (1)$$

where *NIR* is the near-infrared and *RED* is the red spectrum, yielding values between -1 and 1.

For Sentinel satellite channels, the equation appears as:

$$NDVI = \frac{(B08-B04)}{(B08+B04)}. \quad (2)$$

NDVI is best suited for assessing the condition of agricultural crops over relatively large areas. Identifying craters as smaller-scale objects can be more challenging, particularly on images with resolutions lower than the diameter of the damage. The primary scenario where NDVI is useful is during the late autumn period when a significant contrast exists between the weed-covered edges of craters and the surrounding area, which is typically free of vegetation. Other vegetation indices, such as the EVI and SAVI, can also be utilised. EVI is an improved and calibrated version of NDVI, while SAVI is particularly useful in areas with sparse vegetation, where the proportion of vegetation to bare soil favours the latter.

To better highlight signs of military impact in satellite images, it may be necessary to create custom optical channel combinations. The most effective way is to use equations to calculate the resulting raster of optical channels. The first method is the division (ratio) of one channel by another according to the equation:

$$Ratio = \frac{A}{B}, \quad (3)$$

where *A* is the first channel and *B* is the second channel.

There are two rules for such division. If the calculation involves channels of the visible and infrared spectral ranges, then the optical channel with a smaller number is placed first. When both channels are within one of the named ranges, then the channel with a larger number should be placed first. For example, in the case of Sentinel satellites, the substitution into the formula should look like B04/B11 in the first variant, and B11/B08 or B04/B02 in the second. If these rules are not followed, the resulting image will be displayed incorrectly.

The second method involves creating custom indices based on the equation:

$$Index = \frac{(A-B)}{(A+B)}, \quad (4)$$

where A is the first channel and B is the second channel.

In this approach, the channel with the higher number is placed first, similar to the NDVI index calculation described earlier. Failure to follow this rule will result in an inability to generate the image. Traditionally, vegetation index images are displayed in shades of green, achieved by applying an RGB colour scheme. However, the output in this case is a monochrome (blackandwhite) raster, which allows for greater detail to be observed when identifying features such as craters caused by shell explosions. The described approaches to using optical channel combinations and calculations based on formulas are also applicable for identifying other types of military-related damage, including traces of military vehicles, fortifications, and fires caused by shelling.

The movement of military vehicles results in soil compaction, the traces of which can also be identified on satellite imagery. Military-induced compaction can often be mistaken for the effects of agricultural machinery on the soil. To accurately distinguish the impact of military vehicles, it is essential to compare images captured before the onset of active hostilities in the area with those taken immediately after their conclusion. Another critical condition for the clear identification of compaction traces is the presence of sparse vegetation. Dense vegetation causes significant overlap between neighbouring pixels in the image of the analysed area, thereby complicating the detection of this type of damage.

The principles for identifying fortifications (such as defensive fighting positions and dugouts) are similar to those for recognising compaction pathways caused by military vehicles. On satellite images, fortifications appear as distinct linear features resembling broken lines with numerous branches. The primary condition for successful identification of fortifications is their size, which must exceed the pixel resolution of Sentinel-2 imagery (10 m or larger). The aftermath of fires is identifiable on satellite images as distinct enclosed areas of irregular dark shapes, resulting from soot deposits on burned surfaces. These features are most evident during active burning due to additional indicators such as rising smoke. Another favourable period for detecting fires is during active vegetation growth, as the vegetation indices decrease sharply in affected areas.

For each type of military-induced soil damage, it is necessary to establish a set of optimal combinations and calculations of optical channels. It should be noted that the set of ratios and indices will vary depending on the season and the specific timeframe following the cessation of hostilities. In this study, it is proposed to use channel combinations that are optimal for the autumn period. After identifying areas of soil damage through the synthesis and calculations of Sentinel-2 optical channels, spatial layer contours of military impact are created within the EO Browser environment. These contours are then transferred to GIS software for further customisation of data layer visualisations representing different types of military-induced degradation.

The next stage, following the identification of damage and the delineation of areas affected by military activity using Sentinel-2 imagery, involves obtaining higher-resolution images to refine the boundaries of the damage. At the initial stage, satellite imagery in the form of "base maps" in GIS software is sufficient. Currently, satellite images capturing the consequences of military actions with a resolution of 1-5 m are available in open access. However, these images have limitations: they cannot be downloaded for further analysis, and they represent a single timeframe (late August to early September 2022), which prevents tracking changes in soil conditions over time. Such imagery is hosted on platforms like Google Maps, Google Earth, and the ArcGIS Online web service. In Google Earth Pro, it is possible to delineate areas with the highest concentration of soil damage and save them in kml/kmz format for subsequent use. Another resource, ESRI Images, is available as a base map in ArcGIS software, such as ArcMap (educational version). While these images cannot be analysed directly, they can be employed to refine the localisation of soil damage.

In-depth research on the impact of combat activities requires the use of satellite data with a resolution of 1 metre per pixel or higher. To identify small craters and determine the area of soil damage caused by other types of impacts, high-resolution satellite imagery from the Jilin Kuanfu-01 spacecraft (Chang Guang Satellite Technology Co, China) was used. The resolution of these images is 50 cm, which allows for the detection of craters caused by shell explosions with diameters smaller than 1 metre. The methodology for identifying damage in high-resolution images is similar to that used for analysing Sentinel-2 satellite data, but it does not require the use of numerous combinations and calculations of optical channels. This is due to the enhanced clarity of the images, which allows for the detection of more details. The study of military impact on irrigated lands in the Chkalovske TC was conducted using the same methodologies as for non-irrigated areas, with Sentinel-2 satellite imagery and the ArcMap "base map" being employed.

The publication contains the results of the research obtained during the implementation of the project "Assessment of the Impact of Armed Aggression on the State of Black Soils and the Development of Measures for the Accelerated Restoration of Soil Fertility in the Context of Ensuring Food Security" No. 2022.01/0031 of the competition "Science for the Recovery of Ukraine in the War and Post-War Periods" under the grant support of the National Research Foundation of Ukraine (Draft Plan for the Recovery of Ukraine, 2022).

RESULTS

Using the described methodology, an analysis of military-related soil damage was conducted in the Chkalovske community area with the help of satellite imagery. The study focused on soil damage caused by shell explosions in autumn (15 October), when sparse vegetation is observed. At the initial stage, combinations of optical channels "True colour", "False colour", and "Agriculture" were applied. The analysis of satellite images for this period revealed that the NIR values at the edge of craters were higher than in adjacent areas. This is supported by the fact that most of the soil material settles at the edge of the crater after the explosion and serves as a substrate for the growth of herbaceous vegetation, such as weeds. Therefore, the use of the "False colour" combination allowed craters from shell explosions to be more clearly distinguished compared to the "True colour" combination (without NIR) (Fig. 3).

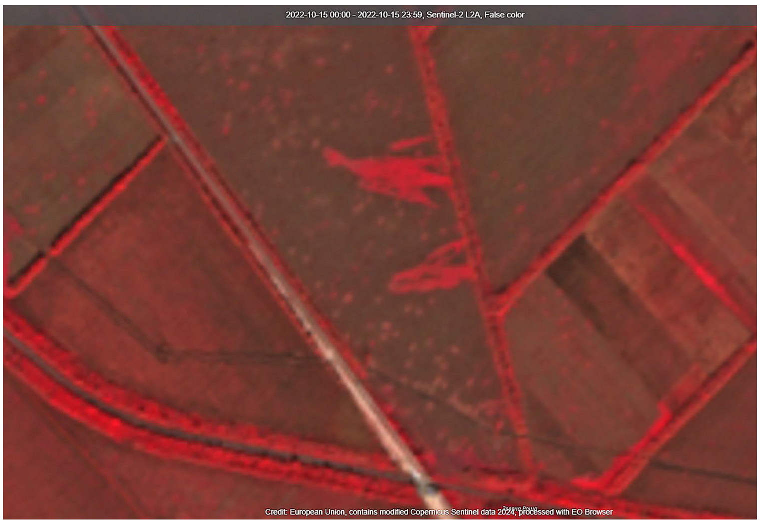


***Figure 3**. Shell explosion craters in the "False colour" combination*
***Source:** image from Sentinel Hub EO Browser (n.d.)*

The use of the "Agriculture" combination, which includes the SWIR range, provides the best tracking of changes in vegetation and soil, as evidenced by the resulting image (Fig. 4).

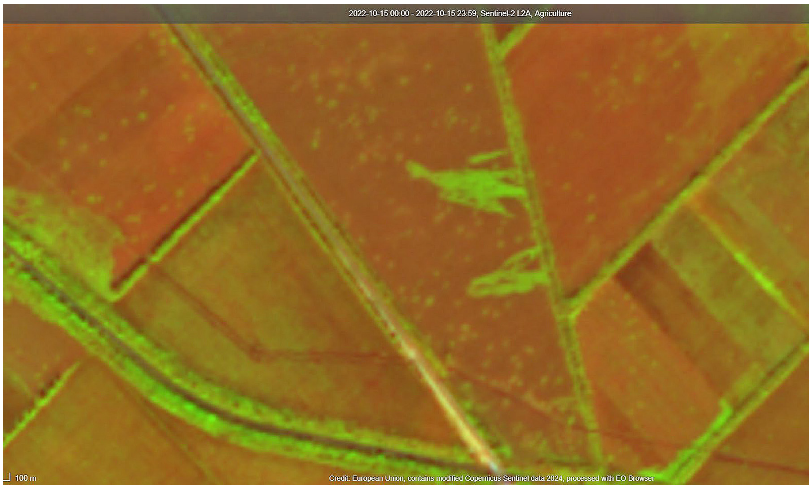


Figure 4. *Shell explosion craters in the "Agriculture" combination*
Source: *image from Sentinel Hub EO Browser (n.d.)*

Next, vegetation indices such as NDVI, EVI, and SAVI were tested. Among them, NDVI was found to be most suitable for identifying bombturbated soils in the autumn period. However, none of these indices provided the same level of accuracy in depicting craters as the "False colour" and "Agriculture" combinations. The next stage of crater identification involved the application of custom calculations of optical channels based on formulas. As a result of the selection, the use of the Red (B04) and NIR (B08) channels was determined to be most optimal. With a ratio of channels (B04/B08), the locations of shell explosions are displayed as black dots, and when using the index formula (B08-B04)/(B08+B04), they are displayed as white dots (Fig. 5). As a rule, this allows for a clearer visualisation of craters compared to using a simple combination of channels.

Ratio Index

Figure 5. *Appearance of craters depending on the applied optical channel equations*
Source: *image from Sentinel Hub EO Browser (n.d.)*

Beyond detecting shell craters, this study also focused on identifying tracks of heavy military vehicles, fortifications, and fires caused by shelling. Combinations of optical channels and image synthesis based on calculations were used. Unlike craters, military roads are clearly distinguishable on the terrain using channel combinations like "True colour" (Fig. 6), "False colour", and to a lesser extent, "Agriculture". However, the use of vegetation indices such as NDVI, EVI, and SAVI did not yield satisfactory results for deciphering vehicle tracks. This can be partially attributed to the lack of dense vegetation in the study fields, which did not provide the desired contrast between overgrown parts of the fields and compaction tracks. Similar to the previous decryption of craters, custom ratios of optical channels were applied to identify vehicle tracks. The ratio of channels B04/B12 performed quite well, while B04/B08 performed slightly worse. Regarding the use of custom indices, the calculation of a raster using the equation (B08-B04)/(B08+B04) yielded a more or less acceptable result. However, none of the custom combinations of optical channels showed better results in displaying compaction tracks than the already-known "True colour", "False colour", and "Agriculture".

Figure 6. *Tracks of military vehicle movement*
Source: *image from Sentinel Hub EO Browser (n.d.)*

The study also involved the identification of various fortification structures (defensive fighting positions, dugouts etc.). Several fortifications were identified within the Chkalovske TC and could be detected in Sentinel-2 imagery due to their significant size (Fig. 7). The combinations and calculations of optical channels described in this study were applied and found to be suitable for identifying fortifications. This can be explained by the significant amount of soil removed during the construction of such structures, resulting in a significant contrast with the surrounding undisturbed areas.

Figure 7. *Fortifications in the image*
Source: *image from Sentinel Hub EO Browser (n.d.)*

Analysis of already-known optical channel combinations and indices showed nearly identical clarity in decoding the effects of fires on fields. Among the custom ratios and indices, B04/B08 and B04/B12 yielded good results. In these cases, the burned areas appeared darker than the surrounding background. However, the most distinct burn areas are highlighted in infrared optical channel ratios – B12/B08 and B08/B12. In the first case, the fire damage appears as a white spot on a grey background. A similar image is provided by the “Barren soil” channel combination, which identifies areas devoid of vegetation (appearing red against a green background). In the second case, the resulting raster exclusively displays areas with fire damage in the form of dark patches, the area of which can be calculated quite clearly, making the B08/B12 ratio the best for decoding this type of damage (Fig. 8).

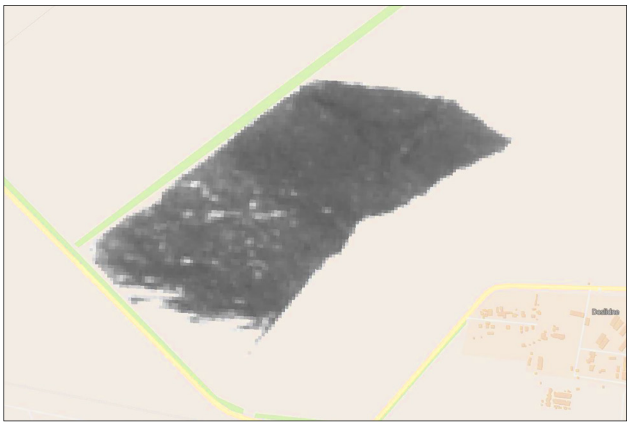


Figure 8. *Fire damage on agricultural land*
Source: *image from Sentinel Hub EO Browser (n.d.)*

However, it should be noted that when using any of the channel sets described above, it is still essential to know the exact location of the fire, as some fields, even in the absence of vegetation, can also stand out clearly when applying the aforementioned algorithms. The use of vegetation as an indicator of fire is most effective during the active growing season and shortly after the event (until the end of the growing season and the onset of winter). As a result of selecting different spectral combinations, optimal channel ratios and indices for displaying military-induced soil damage were calculated (Table 1).

***Table 1**. Optimal combinations of optical channels for different types of military damage*

Type of damage	Ratio (A/B)	Index (A-B)/(A+B)
Crater damage from shell explosions	B04/B08	(B08-B04)/(B08+B04)
Compression traces (paths) from military vehicle movement	B04/B12; B04/B08	(B08-B04)/(B08+B04)
Fire damage caused by shelling	B12/B08; B08/B12	(B12-B04,03,02)/(B12+B04,03,02) (B08- B04,03,02)/(B08+ B04,03,02)
Fortifications (defensive fighting positions and dugouts)	All combinations listed above	All combinations listed above

***Source:** author's results*

After identifying the features of military impact, contours were drawn around the highest concentration of each type of soil damage. As a result, spatial object layers were created and overlaid on the base map in ArcMap (Fig. 9), specifically showing the consequences of constant shelling (craters from shells, rockets, and bombs); compaction from military vehicle movement (tracks); fortifications (defensive fighting positions and dugouts); and fires caused by shelling (traces). Thus, a map was prepared depicting the consequences of military soil degradation in the Chkalovske TC.

Based on information about the locations of the most damaged areas due to military impact, further analysis of soil damage was carried out using higher-resolution satellite images. Initially, available high-resolution satellite image sources from ESRI Images were analysed, using ArcMap as the base map (Fig. 10).

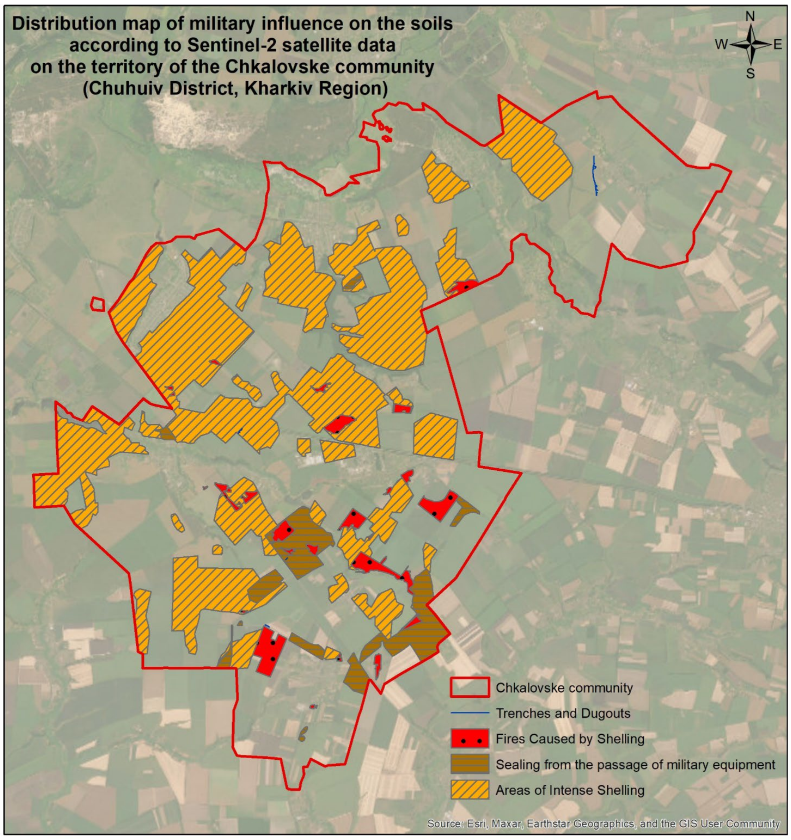


***Figure 9**. Areas with the most pronounced military impact on soils in the Chkalovske TC, Kharkiv Region*
***Source:** author's mapping scheme*

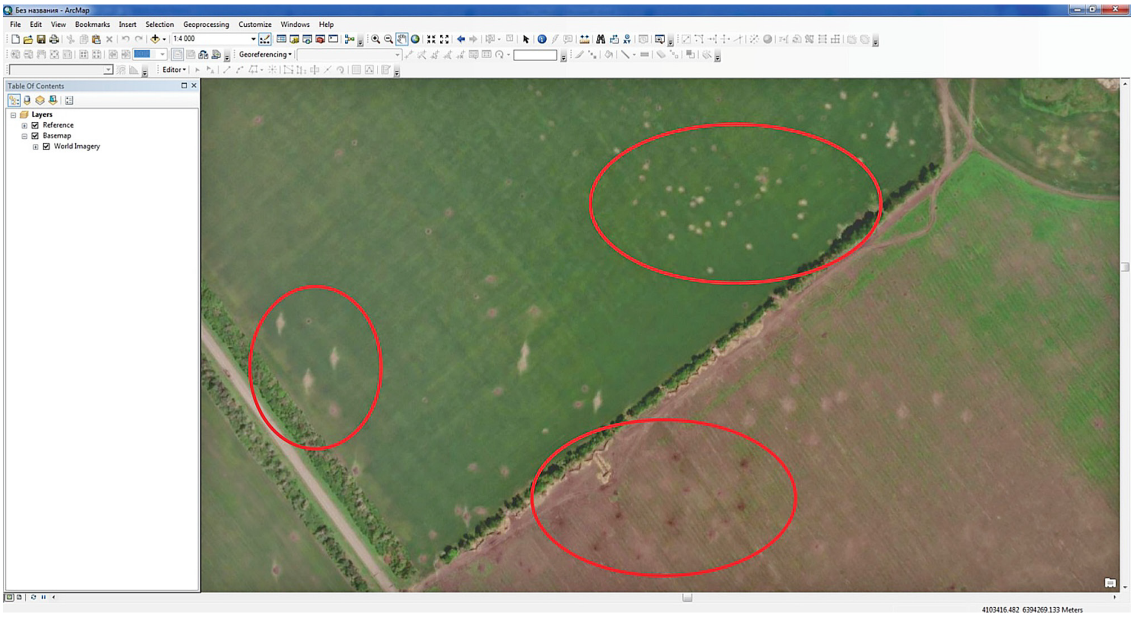


***Figure 10**. Fragment of ESRI Images clearly showing traces of craters (near Nova Hnylytsia Village area)*
***Source:** image from ArcMap program*

Using the specified satellite images, individual contours of areas with military damage, created from Sentinel-2 images, were refined. To conduct a more in-depth analysis of the impact of military actions on the soil cover, a high-resolution satellite image of a 51 km^2 area of the Chkalovske TC was obtained from the Jilin Kuanfu-01 spacecraft (Chang Guang Satellite Technology Co, China) (Fig. 11). According to the authors' estimates, the area covered by the satellite image exhibits practically all types of military impact on the soil cover and can be used as a pilot area for impact assessment. Approximate calculations of soil damage were carried out based on averaged impact data.

Firstly, the identification of aviation and artillery craters in the pilot area was conducted (Fig. 12). These craters are clearly visible in the high-resolution images.

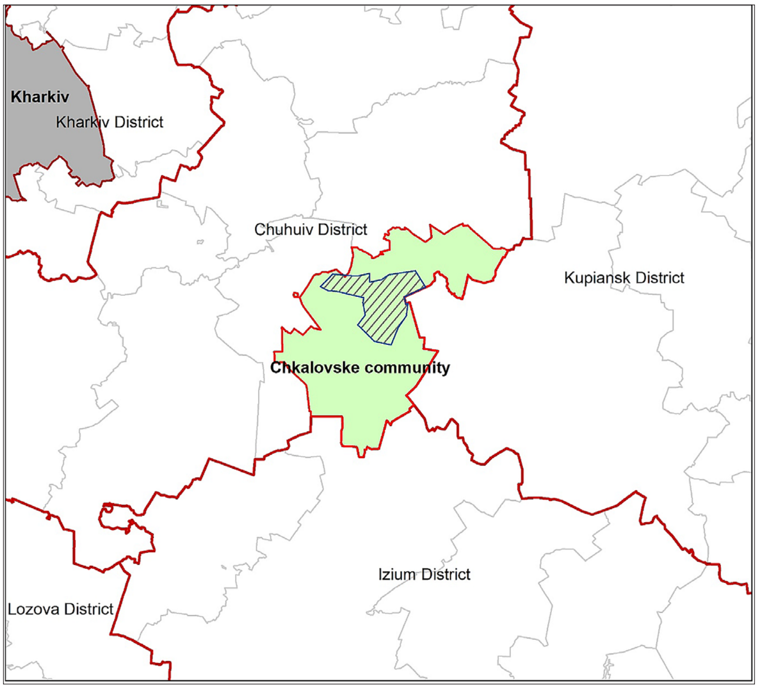


***Figure 11**. Location of the satellite image within the Chkalovske TC of the Chuhuiv District, Kharkiv Region (marked with hatching)*
***Source:** author's mapping scheme*

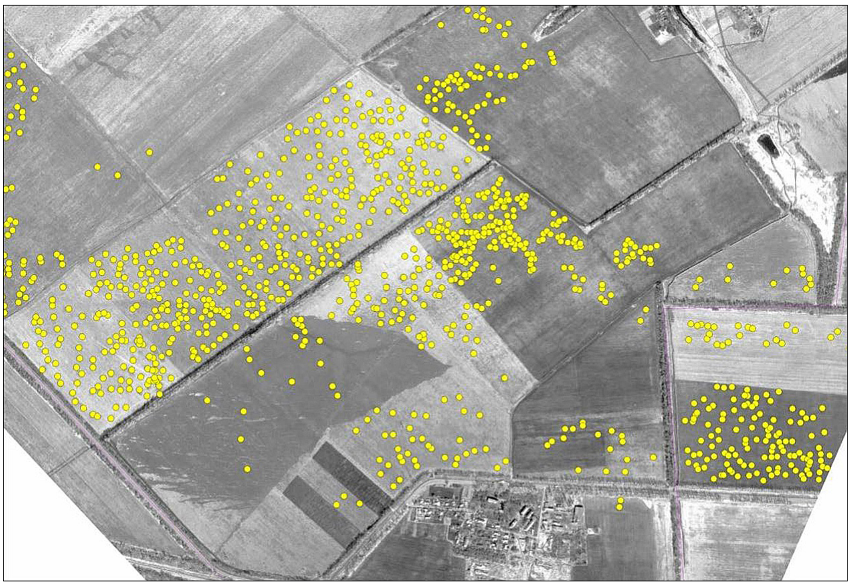


__Figure 12__. Fragment of the satellite image with identified traces of artillery and aviation damage
***Source:** author's mapping scheme based on Jilin Kuanfu-01 image*

Overall, 3,844 craters of various origins were counted (Fig. 13). In the locations of these craters, anomalies such as secondary explosions or post-strike fires were observed. It is known that the size of the craters is directly related to the calibre of the shells. In the study area, these are mainly 76, 105, 152, and 155 mm calibres, with the diameter of the crater ranging from 6 to 15 meters, averaging 10.5 meters. The average depth of the craters, according to the authors' observations, is 0.85 meters. Thus, according to calculations, 40,362 cubic meters of soil are damaged in the study area.

The overall distribution of artillery craters is quite varied, but it clearly correlates with the location of military units in forest belts, around dug-in armoured vehicles, and field fortifications. Therefore, adjacent agricultural fields suffer first and foremost. Fields located near paved roads have even more damage, as they were additionally mined even as of late 2023.

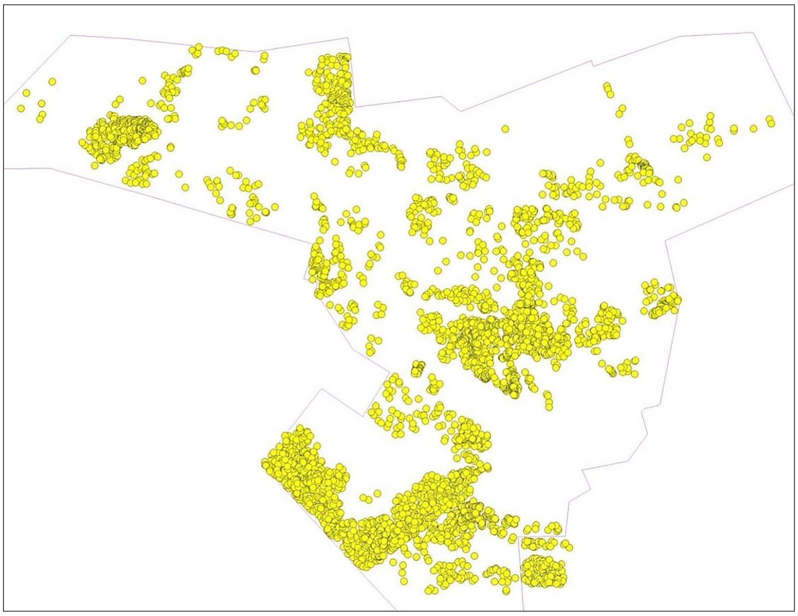
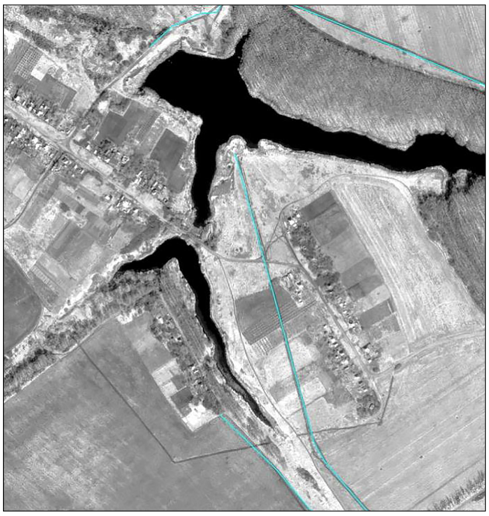
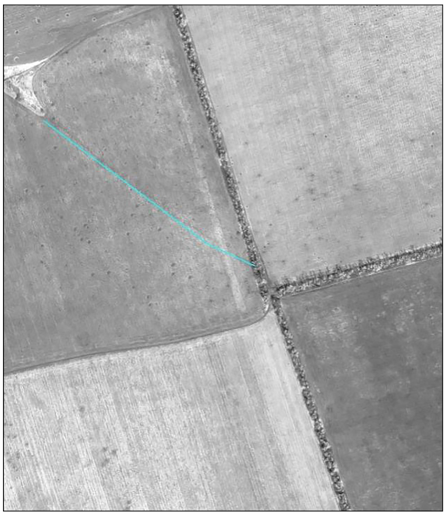


__Figure 13__. General view of the pilot area with identified traces of artillery and aviation damage
***Source:** author's mapping scheme*

Next, the identification of soil surface compaction caused by the passage of heavy military equipment was carried out. In the case of the Chkalovske TC, the most compacted soils are found under military roads and even in residential areas (Fig. 14). According to the authors' calculations, the total length of vehicle tracks in the fields is 7.76 km ± 0.5 (total road length, m) × 3 m (track width) = 23.28 ha, or the total area of compaction in the pilot area. Burned areas as a result of shelling fires were also identified (Fig. 15). It was established that the burning of stubble, field crops, and weeds occurred primarily in the locations of personnel and defensive structures. That is, it can be indirectly stated that enemy defensive structures are located around these places, which significantly narrows the search area. According to GIS calculations, the area of burned territories is 1.09 km^2.



A



B

Figure 14. *Examples of soil compaction in agricultural land (A – household plots and gardens, B – agricultural fields)*
Source: *Jilin Kuanfu-01 satellite images*

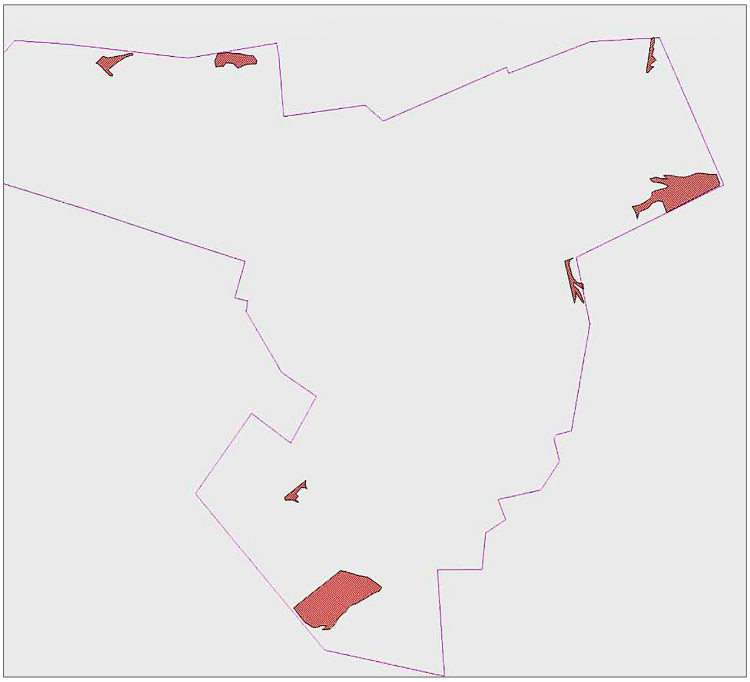
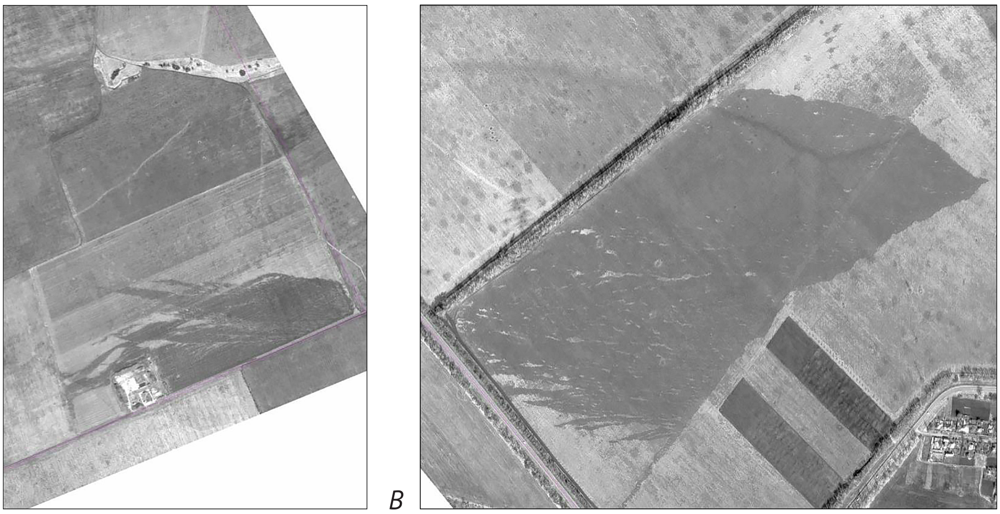


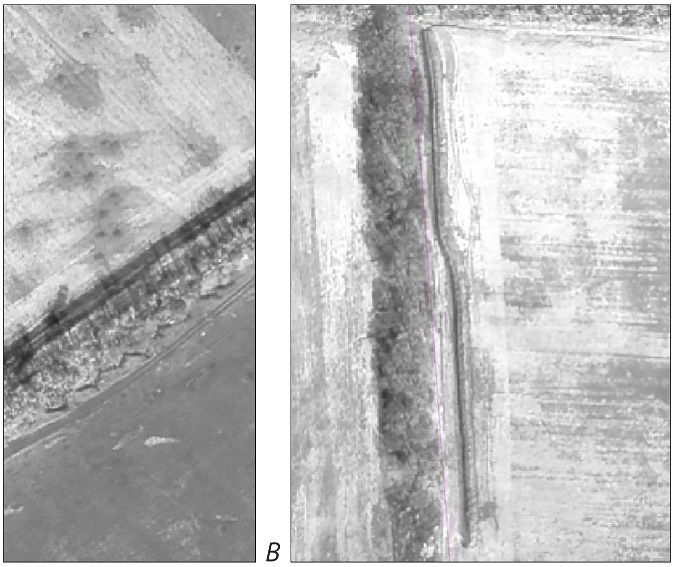
Figure 15. *Location of burned areas in the key site of the Chkalovske TC of Chuhuiv District*
Source: *author's mapping scheme*

Examples of burnt areas in the key site are shown in Figure 16. As a result of the analysis of remote sensing data, defensive structures and military checkpoints of the russian forces were detected (Fig. 17). Calculations show that the length of the trenches is 261 m, and the anti-tank ditch is 1,694 m. The total volume of excavated soil is 11,730 m^3. Overall, based on the calculations of each type of impact on the soil cover, a general picture of soil losses was formed to further calculate the damage caused (Table 2).



A B

Figure 16. *Examples of burnt agricultural land in the key site (A, B)*
Source: *Jilin Kuanfu-01 satellite images*



A B

Figure 17. *Defensive structures of russian forces: A – trenches, B – anti-tank ditch*
Source: *Jilin Kuanfu-01 satellite images*

Table 2. *Calculation of the volume of military impact on the soil cover of part of Chkalovske TC*

No.	Impact Type	Type of impact on soil	Quantity/area
1.	Aviation and artillery craters	Mechanical (soil layer inversion) Chemical (contamination with explosives and heavy metals)	40,362 m^3
2.	Military roads	Physical (soil compaction)	23.28 ha
3.	Burning of vegetation	Pyrogenic (burning)	1.09 km^2
4.	Anti-tank ditches	Mechanical (soil layer inversion)	1,694 m
5.	Strongpoints/trenches	Mechanical (soil layer inversion)	216 m
Total for items 4,5 – 11,730 m^3			

Source: *author's calculations*

An equally important aspect of current research into military degradation is assessing the impact of hostilities on the quality of irrigated chernozems using Earth remote sensing data. The study involved analysing satellite images of the study area, followed by field surveys, and comparing the obtained data with pre-war salinity survey materials. In 2023, a remote study of the condition of irrigated lands and an assessment of their damage as a result of hostilities was conducted using a satellite image (Fig. 18).

***Figure 18**. Satellite image of irrigated lands in the Chkalovske TC, highlighting areas affected by military actions*
***Source:** author's mapping scheme based on ESRI Images*

The map shows areas of irrigated lands in the Chkalovske TC where the soil cover has been subjected to shelling, damage, and destruction as a result of hostilities. According to remote sensing data, the area of land affected by shelling is approximately 80 hectares. As a result, mechanical damage, destruction of the soil cover in the irrigation zone, and disruption of the soil profile integrity have occurred, indicating the development of mechanical degradation. Additionally, remote sensing data clearly identifies areas on the irrigated lands of the study area that have been burned as a result of fires (marked in red), which have damaged the soils and affected their quality. According to the calculations, the area of burned areas on irrigated lands in the Chkalovske TC is approximately 89 hectares. As a result, the development of biological and physicochemical soil degradation is likely in these areas.

DISCUSSION

Modern warfare inflicts significant damage on the environment, and soils, as a component of the environment, are no exception. During hostilities, negative phenomena such as reduced soil fertility, decreased soil organic carbon content and emissions, pollution, erosion, and reduced soil biodiversity, among other degradation processes, intensify. Research by L. Banwari *et al.* (2023) confirms that current agricultural practices contribute to increased degradation and deterioration of "soil health", and that the negative environmental impact of human activities can be reduced through organic farming. This approach may be beneficial in the post-war period when there is a need for rapid and environmentally safe restoration of soil fertility, including in the lands of the Chkalovske community.

It is worth noting that war not only directly affects the environment but also indirectly hinders research that requires field data and measurements. For example, H. Abdo *et al.* (2022) mapped part of the Syrian territory using the Revised Universal Soil Loss Equation (RUSLE) and remote sensing data in a GIS environment to classify erosion-prone areas in the Al-Khash River basin. The obtained data allowed for a reliable assessment of soil loss rates due to erosion, enabling the development of soil conservation measures even before the end of hostilities. Similar methodological approaches were applied by the authors of this study, where the scale of soil damage was assessed with extensive use of remote sensing methods without conducting fieldwork.

Military activities lead to widespread contamination by explosives, which can be absorbed by plants through the soil. Research by S. Via and P. Manley (2023) focused on the physiological effects of explosives on plant tissues, including disruptions to photosynthesis, gas exchange, and nutrient uptake. The authors also noted that further development of remote sensing technology will provide more data on the impact of explosives on plant health. While current studies do not offer a detailed picture of this impact, estimates of the intensity of combat operations in the lands of the Chkalovske community suggest areas with the highest concentration of explosive residue products.

It should be noted that in the author's study, similar to the examples above, the main indicator of the military impact on the environment is the assessment of vegetation conditions using remote sensing methods. However, in the Chkalovske TC, the identification was not of chemical contamination, but of mechanical and physical damage to soils. The degree of contamination based on the obtained data can only be assessed by experts using literature data. An example of a study on the impact of military conflicts on agricultural activities is the article of B. Demissie *et al.* (2022) assessing the Tigray conflict (Ethiopia) using freely available Sentinel-2 satellite data. An analysis of the greenness of agricultural fields was conducted using the NDVI index for the pre-war (2020) and wartime (2021) spring seasons, leading to the conclusion about the role of the war in the increased encroachment of weeds on agricultural land. Similar results were obtained in the current study of craters in the fields of the Chkalovske TC, indicating an increase in weed growth in areas subjected to soil disturbance from bombturbation.

The study by J. Rodrigo-Comino *et al.* (2023) examined trenches from the Civil War era, where archaeological excavations led to the development of ravines and gullies. Using the NDVI index, a decline in vegetation quality was recorded as a result of degradation processes. A similar issue could arise in the long term with defensive fighting positions and dugouts, which are widespread in the Chkalovske community in areas of positional battles. Therefore, it is essential to monitor the condition of the fortifications left behind after the war. Research on ecosystem components is often linked to the use of historical cartographic images, which in some cases provide a clear understanding of environmental changes. F. Chen *et al.* (2022) combined historical military operation maps with Landsat satellite imagery to analyse changes in forest area due to human activity. Thus, the use of historical maps allows the determination of forest cover evolution before remote sensing images are available. This methodological approach enables an assessment of the impact of wars (such as the Second World War) that occurred before the first detailed satellite images were taken and provides a comparison with the consequences of the ongoing Russian-Ukrainian war, including on the lands of the Chkalovske community.

Scientific literature increasingly highlights the impact of the Russian-Ukrainian war on environmental components, particularly soils. P. Pereira *et al.* (2022) indicate that military actions in Ukraine have significant consequences for global food security and have also caused economic and political problems. While the impact on the environment is currently difficult to assess due to ongoing intense fighting, the negative consequences of soil damage, soil contamination, and other degradation processes are already evident. A. Nasibov *et al.* (2024) concluded that the war has led to a reduction in arable land and crop yields, as well as soil and water pollution. The importance of considering regional differences in agricultural productivity is also noted. Assessing the consequences of hostilities helps to determine the scale of the problem and subsequently develop a soil restoration strategy and make the necessary decisions.

Many scholars highlight the issue of using high-resolution satellite imagery to visualise the consequences of armed conflicts. According to M. Bennett *et al.* (2022), very little attention is paid to reflecting the impact of hostilities on rural and forest areas. Using the example of the war in Ukraine, the authors pointed out the advantages of using high-quality images and the importance of archiving such images for scientific purposes to monitor military conflicts. A detailed study of the military impact on the soils of the Chkalovske community also required the involvement of highresolution images, which, due to their cost, do not allow scientists to obtain the necessary data on a regular basis.

Several scientific studies have been published assessing the impact of the Russian-Ukrainian war on soils using satellite data. For example, in the research of S. Shevchuk *et al.* (2022), the impact of the Russian-Ukrainian war on the environment was analysed using publicly available remote sensing data from NOAA-2, Suomi NPP, Aqua and Terra satellites, Sentinel and Landsat, as well as other open sources. In particular, a combination of channels B3, B8, and B11 of Sentinel-2 satellites was used for a clearer detection of fires compared to the use of visible and infrared spectra separately. Similar conclusions were drawn in the current study, however, in the current study, a more complex approach was used, using not only channel combinations but also spectral ratios and indices.

A comprehensive methodological approach to assessing war-induced soil disturbances was also proposed in the study of O. Bonchkovskyi *et al.* (2023), namely the detection of shell craters and tracks from military equipment. The proposed methodology includes the following stages: geospatial analysis, field research, data synthesis and processing, economic assessment, and recommendations. The methodology combines the following methods: remote sensing analysis, cartographic, soil science, geochemical, ecological, geomorphological, and economic. Unlike this study, the current research has developed a detailed methodology for identifying soil damage based on known combinations and the author's ratios and indices of optical channels of satellites.

Due to the impossibility of conducting detailed soil surveys in the combat zone and the high cost of acquiring and analysing high-quality satellite imagery, there is a need to forecast militaryinduced changes in soils. In the article of Y. Dmytruk *et al.* (2023), a preliminary assessment of the consequences of the war in Ukraine was conducted by modelling a predictive soil map at a scale of 1:10,000 in a GIS environment, which was used to estimate the areas of damage to individual soil taxa. This will allow for the initiation of soil restoration, taking into account their resistance to military impact. The current study has a slightly different approach, related to the use of satellite data at a local level within a separate community, which does not involve significant resource expenditure on searching for and analysing remote data.

Thus, to date, scientific research has left unanswered questions about the methodology for assessing the military impact on soils using Sentinel-2 satellite images with the use of an author's approach to combinations of spectral channels. The presented study aims to fill the gaps in the methodological approaches to identifying the consequences of military impact on soils.

CONCLUSIONS

Using the example of Chkalovske TC, with predominantly chernozem soils that have undergone various types of military degradation, the methodological necessity and practical feasibility of using multi-temporal satellite images with different resolutions have been established. Their functional capabilities for diagnosing various types of military degradation of chernozems have been determined. Analysis of satellite images was carried out on the online resource EO Browser, and the display of maps showing the distribution of the consequences of the impact of hostilities on soils was carried out in specialised GIS programs (Mapinfo, ArcGIS-ArcMap).

At the initial stage, freely available data from Sentinel-2 satellites with a maximum resolution of 10 m and an image update frequency of 5 days were analysed. A methodological algorithm for their evaluation was developed and tested in real conditions. Using Sentinel-2 satellite data, the following types of military impact can be established: mechanical, physical, and abiotic – direct identification in the optical range; mined areas by tangent identification of the long-term presence of field plants (weeds) in fields. In the course of the study, 4 types of military impact on soils were identified, which can be identified using Sentinel-2 satellite images: craters on the soil surface from the rupture of munitions, traces of soil compaction due to the passage of heavy military equipment, fires in fields caused by active shelling and burning of equipment, and fortifications of various types (trenches, defensive fighting positions, dugouts). For each type of military impact on soils, the most optimal existing combinations of spectral channels of Sentinel-2 satellites and vegetation indices were selected. Own calculations of channels were also developed using two types of equations – ratios (A/B) and indices (A-B)/(A+B). For the identification of craters, the ratios B04/B08 and the index (B08-B04)/(B08+B04) are optimal; for traces of compaction from the passage of military equipment – B04/B12, B04/B08 and (B08B04)/(B08+B04); for the consequences of fires caused by shelling – B12/B08, B08/B12 and (B12-B04,03,02)/(B12+B04,03,02), (B08-B04,03,02)/(B08+B04,03,02); for fortifications – all of the above.

Based on the identified types of military impact on soils, contours were constructed around the highest concentration of damage in the form of layers of spatial objects, which were applied to a base map in ArcMap. The use of Sentinel-2 images allowed for the identification of the main zones of distribution of military soil degradation. For a more detailed analysis of the military impact on soils using satellites with higher resolution, available ESRI Images satellite images were analysed in the form of an ArcMap "base map", according to which individual contours of areas with military soil damage were refined.

For the analysis of damage using high-resolution commercial satellite data, a plot was selected in the territory of Chkalovske TC, on which all the main types of military impact are presented. As a source of detailed satellite images, data from Jilin Kuanfu-01 satellites with a resolution of 50 cm were used, according to which the locations of explosions of shells of various calibres were determined. This made it possible to identify craters with a diameter of less than 1 m. Also, using Jilin Kuanfu-01 images, the boundaries of the main types of military impact on the selected area were refined. Calculations were made of the volumes of soil losses for all types of military impact for future calculations of the damage caused. The impact of hostilities on the quality of irrigated chernozems of Chkalovske TC was assessed by analysing satellite images, and a mapping scheme was constructed with areas of the main types of military impact on irrigated lands.

Therefore, the complex use of satellite images with different resolutions and GIS platforms has made it possible not only to calculate soil losses with sufficient accuracy but also to analyse the types of military impact both in terms of time and quantity. In this way, a differentiated approach to studying the consequences of military soil degradation is achieved. The information obtained based on satellite images is an important step in developing measures for restoring the soil cover of territories that have undergone military degradation. Further research, is planned to improve the methodology for identifying military-induced soil damage by selecting combinations of optical channels of Sentinel-2 satellites for all seasons of the year.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

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Методичні та практичні аспекти використання супутникових знімків для оцінки мілітарного впливу на ґрунти

Віталій Лебедь
Кандидат сільськогосподарських наук, старший науковий співробітник
Національний науковий центр «Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського»
61024, вул. Чайковська, 4, м. Харків, Україна
https://orcid.org/0000-0002-1429-4121

Максим Солоха
Доктор сільськогосподарських наук, старший науковий співробітник
Національний науковий центр «Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського»
61024, вул. Чайковська, 4, м. Харків, Україна
https://orcid.org/0000-0002-1860-0819

Вадим Соловей
Кандидат сільськогосподарських наук, старший науковий співробітник
Національний науковий центр «Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського»
61024, вул. Чайковська, 4, м. Харків, Україна
https://orcid.org/0000-0001-9820-1780

Анатолій Кучер
Доктор економічних наук, старший дослідник
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
Національний науковий центр «Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського»
61024, вул. Чайковська, 4, м. Харків, Україна
https://orcid.org/0000-0001-5219-3404

Людмила Воротинцева
Доктор сільськогосподарських наук, старший науковий співробітник
Національний науковий центр «Інститут ґрунтознавства та агрохімії імені О. Н. Соколовського»
61024, вул. Чайковська, 4, м. Харків, Україна
https://orcid.org/0000-0003-0643-8823

Анотація. Військова агресія Російської Федерації спричинила масштабний негативний вплив на природні екосистеми України, у тому числі й ґрунтів. Для фіксації збитків, завданих війною, необхідно проводити всебічне обстеження стану ґрунтів, ступеню та масштабів їх пошкодження. Застосування традиційного польового обстеження ґрунтового покриву ускладнене через значну мінну небезпеку на звільнених від окупації територіях. Тому постає необхідність широкого застосування дистанційних методів дослідження, таких як супутникові дані (космічні знімки). Метою даного дослідження було визначення стану ґрунтів та масштабів їх пошкоджень внаслідок ведення бойових дій на території Чкаловської територіальної громади Чугуївського району Харківської області. Було визначено найбільш оптимальні комбінації оптичних каналів супутників Sentinel-2 для відстеження наслідків мілітарного впливу на ґрунтовий покрив. Створено шар просторових об'єктів відповідно до різновидів мілітарної деградації ґрунтів громади: наслідки постійних обстрілів (вирви від снарядів, ракет та бомб); ущільнення від проходження військової техніки (сліди шляхів пересування); фортифікаційні споруди (окопи та бліндажі); пожежі, спричинені обстрілами. За допомогою супутникових знімків високої роздільної здатності на тестовому полігоні підраховано кількість вирв (кратерів) та втрати ґрунтової маси від вибухів, площі спалених ділянок та ущільнення, довжину протитанкових ровів та окопів з бліндажами. На зрошуваних землях Чкаловської територіальної громади підраховано площі земель, уражених обстрілами, ділянок, які зазнали спалювання внаслідок пожеж мілітарного походження. Отримана на основі космічних знімків інформація є важливим кроком у розробленні заходів з відновлення ґрунтового покриву пілотної території, що зазнав мілітарної деградації. Були проведені роботи з використанням космічних знімків різної роздільної здатності та геоінформаційних систем для підрахунку збитків від бойових дій з достатньою точністю та аналізу шляхом поєднання видів мілітарного впливу як за часом, так й за кількістю. Дане дослідження стане основою для оцінки масштабів та просторового поширення пошкоджень ґрунтів, підрахунку втрат родючого шару ґрунту та економічної оцінки збитків, завданих ґрунтовим ресурсам

Ключові слова: дистанційне зондування; Sentinel-2; вегетаційний індекс; мілітарна деградація; пошкодження ґрунтів; вирви