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Advancing soil sampling techniques for environmental assessment of artillery impact zones

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ABSTRACT

Article delved into the environmental impact of artillery fire, proposing an innovative sampling method for assessing its effects. With a focus on minimizing ecological harm from military operations, particularly in light of the ongoing war in Ukraine, it explained a new approach to defining environmental damage based on the detection of the harmfulness of a specific type of ammunition. The proposed approach offers a more accurate determination of environmental impacts than traditional sampling methods that do not identify the specific agent. The article outlined the first step in addressing artillery environmental impacts by introducing a new crater soil sampling methodology, refined through experimental artillery fires. This method ensures enough samples are collected for valid chemical analysis and identification of soil pollution caused by specific types of ammunition. In addition to the sampling methodology, the article explained the nature of the execution of experimental artillery fire and the necessary considerations in relation to the shape of the crater and defining of its center, which is a necessary step to the layout of the sampling scheme. Applying the method will precisely define the environmental impacts of each projectile type, enabling accurate determination of post-war restoration requirements for artillery-affected areas.

Keywords: ammunition, artillery, ecology, contamination, military operations, pollution, sampling.

INTRODUCTION

The environmental impacts of military activities have been widely known for a long time (Hupy, 2006; 2008). Especially in the greatest conflicts of modern history, such as the First World War (Heiderscheidt, 2018; Keller, 2014), Second World War (Swintek, 2006), War in Vietnam (Frey, 2013; Kiernan, 2010) or the Gulf War (Al-Shammari, 2016; Mitchell, 2007) the enormous effects of using military equipment and particularly military ammunition on flora, fauna, and humans have become evident.

The pollution produced by military units not only during armed confrontations, but also in peaceful times, is specific in a fact that military equipment and materials are primarily aimed at achieving maximum military efficiency with minimal, or mostly no, regard for the environmental impacts of using a given piece of equipment, technology, or ammunition (Hanáková et al., 2022).

The issue of the environmental impact of military activities began to be significantly discussed again after the invasion of Russian Federation into Ukraine in 2022 (Angurets et al., 2023; UNEP, 2022). These issues were discussed from the environmental point of view as well as in terms of health consequences (Hryhorczuk et al., 2024; Shulga et al., 2024). Given the nature of combat activities, the organization, and the equipment of both armies, it quickly became apparent that artillery constitutes the primary, and often the only, means of providing fire support for maneuvering units (Cranny-Evans, 2023; Karber, 2015).

The war in Ukraine, referred to by many experts as the “artillery war,” (Gady and Kofman, 2023) represents a unique case of massive artillery ammunition deployment with severe consequences for the environment (Hryhorczuk et al., 2024; Shulga et al., 2024). The daily consumption of thousands of shells (Hrnčiar et al., 2023; Šlouf et al., 2023) not only causes direct physical damage, but also leaves long-term contamination of soil and ecosystems, which can persist for decades.

Determining the environmental impacts of artillery fires is a research task, the foundation of which is the comprehensive collection of samples from the areas affected by artillery ammunition (Hewitt and Walsch, 2003; Jenkins et al., 2004a). Over the past several decades, several studies and scientific articles have been published addressing sampling from impact areas where military munitions are used (Pennington et al. 2006; Jenkins et al. 2004b). Comprehensive work in this area has been published by the US Army Corps of Engineers, which, in addition to determining sampling methodologies (Hewitt et al. 2005; USACE, 2021) also proposed sampling procedures in snowy and cold areas (Jenkins et al., 2000; Walsh et al., 2005b) defined the materials for sampling, and conducted sampling at several impact sites across the USA (Jenkins et al. 2005; Jenkins et al. 2004c).

Although a number of studies and scientific papers have been published in the field of sampling, it is important to emphasize that only a portion of them addresses the methods and procedures for sampling directly from the craters created after the recent explosion of artillery ammunition. Given that the main goal of the research team from the University of Defence, the Brno University of Technology, the Armed Forces Academy of Slovakia, and the Czech Academy of Sciences is to accurately quantify the level of environmental pollution caused by particular types of ammunition, the current state of knowledge is insufficient.

Illustrative study by Hewitt et al. (2007) focuses on the nature of post-explosion sampling of specific 155 mm artillery shells, but it does not mention the types of shells used for sampling. Another shortcoming is that the artillery shells in this study were blown in place (static detonation) by a C4 explosive charge. As a result, the resulting crater may have a different shape than a crater created by a shell fired from the designated effector via indirect fire. Additionally, in the case of static detonation, contamination of the site by explosives intended for detonation is expected.

Another interesting study by Walsh et al. (2008) partially addresses the nature of crater sampling following detonation of munitions being indirectly fired into the river saddle. The approach presented in this study served as an initial sampling procedure, but the analysis proved insufficient results for comprehensive crater sampling.

In summary, while the literature review contains a large number of articles, there is a noticeable scientific gap in the comprehensive determination of the sampling processes of artillery explosion craters. The aforementioned studies serve as examples that underline the value of in-depth research on this topic.

The aim of this paper was to bridge the existing scientific gap by demonstrating the possibility of sampling from craters formed after the explosion of artillery ammunition fired from artillery weapon by indirect fire. The focus of the proposal was the execution of experimental artillery live fire exercise, based on which the initial proposal for the sampling method was evaluated. Owing to the experimental firing of artillery, there is no distortion of crater shapes or contamination by explosive elements used in the static method of detonating artillery ammunition. Using statistical and chemical-analytical methods, this work presents a comprehensive proposal for a methodology for taking samples from craters, which can be used for the quantification of elements that remain in the soil after an explosion without the intention of investigating one of the artillery shell components, such as explosives or heavy metals.

The proposed method thus represents an initial step in addressing the problem of specifying the environmental impacts caused by specific types of artillery shells (mortar bombs, rockets).

MATERIALS AND METHODS

The design of the sampling method represented one of the initial and necessary outputs of the entire approach. To obtain the most precise data, the research team agreed that it is necessary to sample soil mainly from the crater, created after the shell explosion and together with this to sample from at close vicinity of the crater (Walsh et al., 2005a). The reason for this is that by doing so, it is the only possible way of quantifying the environmental effects of specific type of artillery ammunition.

The research team thus identified the need to define a new sampling method based on the information from studies published by US Army Corps of Engineers and focused on the crater created by the impact and explosion of munitions (Hewitt and Walsh, 2003; Jenkins et al. 2004c). The reason for this focus on the crater after the explosion of artillery munitions is twofold: to associate the contamination detected from the samples with a specific type of munition, and to obtain data as quickly as possible, as changes can occur over time due to weathering and other environmental factors. For this reason, the proposal of a sampling method was a necessary step to obtain valid data.

When designing the sampling method, it was necessary to define two main aspects of the sampling method – the design of the sampling method itself and the design of experimental live fire to obtain the samples and evaluate the efficiency of the proposed sampling method. Since these are two completely different but complementary procedures, two sub-teams worked on the design of the sampling method. The design of the character of the live fire was created by members of the Fire support department of the University of Defense and Slovak Armed Forces Academy, while the design of the sampling method was carried out by experts from the Brno University of Technology and the Czech Academy of Sciences.

After the end of preparation phase, the research team agreed on the steps required to obtain valid results and to propose a sampling method of artillery ammunition. Development of the sampling method must be done in two steps – initial design and subsequent design which will incorporate discovered issues of initial design. For these reasons, the research team designed the overall sampling method in these steps:

- design of the artillery live fire for experimental sampling,
- initial design of the sampling method,
- design of upgraded sampling method,
- design of the artillery live fire for experimental sampling.

Since the goal of the research is to obtain valid data on environmental contamination associated to specific ammunition types, the experimental live fire design was the first step to achieve valid data.

Possible approaches to ammunition initiation

When designing the live fire for the purpose of the sampling a key requirement was that shell must be initiated in the standard way, i.e. there must be an initiation of an explosive charge through the fuze socket so there will be regular explosion and scattering of fragments (Palasiewicz et al., 2023; Sýkora et. al, 2023. This requirement can be practically done in two ways – by live fire or by static initiation (blown in place) of shell with an explosive charge placed instead of the fuze (Hewitt and Walsh, 2003). In the case of static initiation, the main advantage is the possibility of execution in a controlled environment, i.e. placement of ammunition in a precise location and detonation is controlled according to all needs (Fig. 1).

However, in regard to sampling, the static initiation method has one major disadvantage. Flying artillery projectiles have kinetic characteristics upon impact that can significantly affect

Figure 1. Static initiation of 152 mm artillery shell and 120 mm mortar bomb

the scattering of fragments and their resulting distribution in the terrain (Vajda, 2023; Varecha and Majchút, 2019). The results of sampling of shells initiated by this method would be characterized by a relatively significant degree of error due to different pollution. At the same time, in the case of static initiation, other chemical components (explosives) are used for detonation, which may have an impact on the resulting soil contamination by energetic compounds at the blast site (for the static initiation, the plastic explosives are used as standard). These chemical components can then affect the sampling results, as they will be present at the point of detonation and at the same time they can react during the explosion with the components of the artillery ammunition and further distort the measurement results. Regarding these facts, it was decided that to obtain valid results, it would be necessary to conduct an experimental live fire exercise.

Experimental live fire determinants

To obtain valid results, the experimental artillery live fire exercise had to be specifically designed. This is demanding process not only because of obtaining the data but because artillery live fires must strictly adhere to safety measures. The specifics of the experimental live firing were based on several factors that were necessarily taken into account. Specifically, these factors include the position of sampling (target) point, fuze setting, trajectory and calculation of firing data.

Position of sampling (target) point

All live artillery firings during peacetime are conducted in the impact zones of military training areas. From the outset of designing the issue of crater sampling after munitions impact, it was clear that sampling would need to be carried out in locations where a wide range of weaponry has been used over an extended period. In the Czech Republic, many impact zones have been in use for over 100 years, leading to significant contamination from previous firings. Therefore, the first step in designing the experiment was to address sampling in the affected areas to ensure that the data obtained would be valid. The approach to designing the experimental firing was based on the principle that sampling areas must be located in the areas with minimal prior contamination from previous firings. For this reason, it was essential to select a marginal part of the target area in which targets for standard artillery firing are not usually located, which is simultaneously hidden from the impacts of ammunition fired from small arms or other weapons. At the same time, the sampling area was not allowed to be forested with trees and other mature vegetation.

Fuze setting

Fuzes of artillery ammunition can be set to several different types of initiation. The three main types of fuze settings are point detonation, delayed, and air burst. Point detonation is the standard type of fuze setting. This initiation method is based on the fact that the fuze immediately initiates the explosive charge upon impact with the ground, causing the projectile to explode on the surface (Varecha, 2020). This type of initiation results in the maximum dispersion of fragments, especially sideways and upwards. This method is primarily used for the engagement of personnel and unarmored targets.

Delayed initiation is another option how to initiate artillery ammunition. Delayed initiation is used in artillery to initiate the shell with a small delay (0.01 to 0.063 seconds after the impact), thereby increasing the penetration of the shell (Svehlík et al., 2024). This setting is mainly used when engaging protective structures and fortified objects. Air burst is in general third possible option for initiating artillery ammunition. This solution requires specific radar proximity or time fuze, which will initiate the shell in flight very close to the target. This solution is often used in modern artillery, because it increases the destruction effect since the fragments are not blocked by the ground.

The two most standard methods of initiation are point detonation and delayed, as discussed by Ivan et al. (2022). Since the character of explosion and fragments distribution can be different between these two options, the research team decided to shoot artillery ammunition set on both of these fuze settings. Owing to this step, it will be possible to determine the environmental impact of artillery ammunition when set to both main methods of initiation and at the same time to compare them with each other.

Trajectory

The trajectory is a function of the elevation of the howitzer barrel and muzzle velocity which results in shell flying to a specific distance (Ivan et al., 2022). Artillery is often able to hit a target located at a specific distance by two trajectories – low angle and high angle. This is caused by the ability to change propellant charges, thereby achieving different muzzle velocities. This allows for targeting at varying gun elevations. From a sampling perspective, the trajectory plays a role due to the differences in impact speed and angle, which affect the size and shape of the crater (Fig. 9) (Ivan et al., 2022). Given the specific requirement for accurate targeting of a small impact zone, carefully selected for sampling, the low-angle trajectory was chosen as the most suitable for experimental live firing. The reason is that the projectile is less affected by meteorological influences, resulting in more accurate shooting.

Calculation of firing data

In order to achieve the maximum accuracy of artillery fire, the live fire firing data calculation procedure was designed so that the impact of the shells occurred as close as possible to the reference site. For this reason, the howitzer firing data were determined by registration fires at a reference point located in a distance of 500 meters from the sampling area. After obtaining the results of registration, the fire was shifted directly to the reference site.

CASE STUDY

Alongside proposing the method for conducting the experimental firing, the research team also devised the initial sampling plan for craters created by the impact of artillery munitions. The sampling plan and its sub-parts were prepared based on the current studies from US Army Corps of engineers (Hewitt and Walsh, 2003; Jenkins et al., 2004c; Walsh et al. 2005a) and expert experience in sampling various wastes, both treated and untreated, and following the research that was carried out for the needs of soil sampling. The research team proposed the following procedure and defined three procedures:

- reference sampling of the soil in the potential impact area of the shells,
- soil sampling after the explosion of artillery ammunition set on point detonation,
- soil sampling after the explosion of artillery ammunition set on a delayed function.

Reference site

The research team realized that due to sampling occurring in the areas previously affected by the use of ammunition, it would be necessary to establish a reference site for collecting background reference samples. These samples would then be compared with the samples taken from the actual craters created by artillery munitions. To ensure accurate data acquisition, it was crucial to clearly define the requirements for the location and methodology of collecting these reference samples. The reference site was designed with dimensions of 10×10 m (i.e. a total of 100 m^2), which was specifically segmented as shown in Figure 2.

From the reference site there will be a total of 19 samples were taken and segmentally marked:

- Segment 1: 1A – 4A – lower left corner,
- Segment 2: 1B – 4B – lower right corner,
- Segment 3: 1C – 4C – upper right corner,
- Segment 4: 1D – 4D – upper left corner,
- Segment 5: 1E – 3E – central strip.

Shell crater sampling approach

The approach to soil sampling after the explosion of artillery shells was based on a prepared sampling plan and conducted expert research. Given the scarcity of information on soil sampling focused on wartime conflicts and the limited amount of available data, the findings from the conducted research were accepted. Simultaneously, a proposed approach was developed to ensure the samples collected were both feasible and representative. This approach thus combined the research team's extensive practical experience with a researched methodology.

On the basis of the analyzed procedures, four possible sampling approaches were considered:

- collection of profile samples – this type of sampling involves collecting soil samples from various depths to obtain information on the potential vertical migration of contaminants in the soil profile. Samples are taken at different depths (e.g., 0–5 cm, 5–10 cm, 10–20 cm) near the impact site of the shell. This method was dismissed, because the terrain at the impact site was too rocky in some areas, making it impractical to collect samples from multiple layers.
- systematic sampling – this approach includes systematic collection of soil samples within a specific range around the shell impact site. Samples are gathered from various points

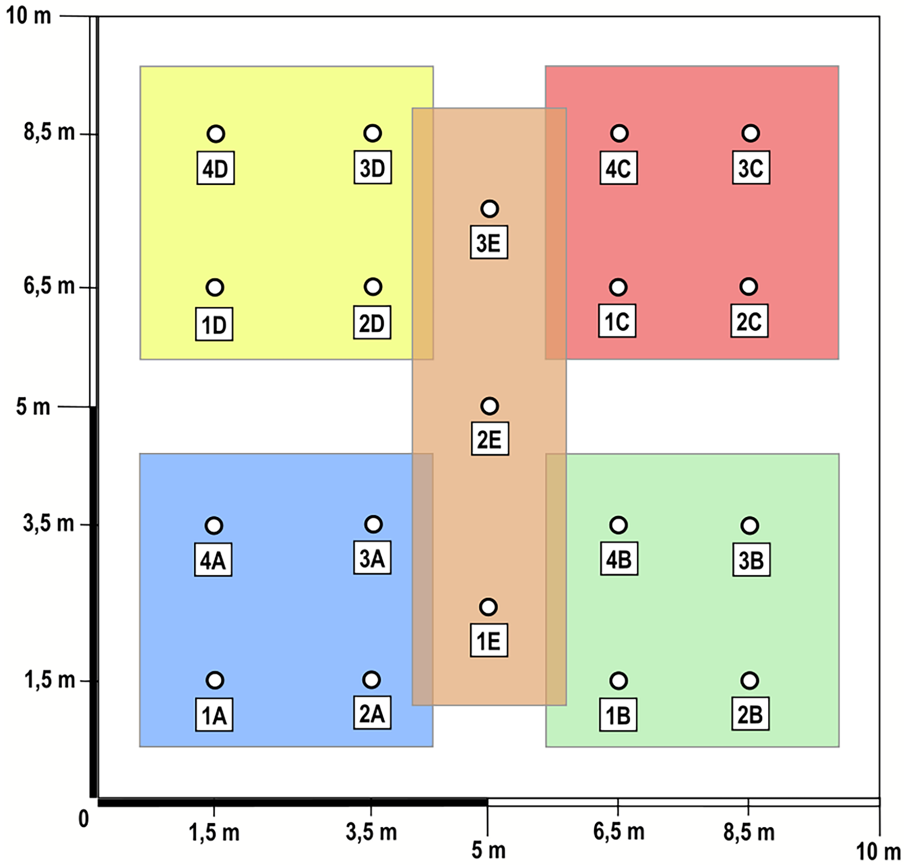

Figure 2. Segmented marking of sampling points in the reference site

within the affected area according to a predefined grid sampling plan. This method was deemed most suitable, particularly for reference sample collection.

- gradient contamination sampling – this type of sampling focuses on collecting soil samples in the direction where contamination is expected to be greatest. Samples are taken from the impact site outward towards the outer boundaries of the affected area. This approach is a suitable solution, especially for sampling irregular craters.
- sampling in selected zones – this approach involves the targeted collection of soil samples in the areas with a high likelihood of contamination or in strategic locations within the affected area. It entails more comprehensive sampling across a larger area (the impacted zone), such as natural waterways or ecologically sensitive areas.

The choice of a specific sampling method had to consider the characteristics of the shell impact crater, expected contamination levels, available resources, and the technical feasibility of sampling. Ideally, a combined sampling approach would be preferred, utilizing multiple types of sampling to obtain the most comprehensive information about soil contamination.

After evaluating all options, the research team decided to conduct systematic sampling at regular spatial intervals for the reference sampling. For crater sampling, a combination of methods was employed, specifically systematic sampling and judgment-based sampling. This approach aims to cover the entire crater effectively, including the central area, periphery, and the area affected by shrapnel dispersion (Fig. 3). The goal was to analyze and collect samples from these critical zones to understand the extent of contamination.

The crater sampling site was proposed to be circular, as shown in Figure 3. The number of samples collected within the analyzed set was be specified based on research studies (Hewitt and Walsh, 2003; Jenkins et al., 2004c; Walsh et al., 2005a), as well as the actual situation and practical considerations associated with sampling.

Sampling was carried out in food-grade plastic buckets with a volume of 500 ml (primary packaging), the aim was to remove the surface soil to a depth of max. 10 cm, while observing

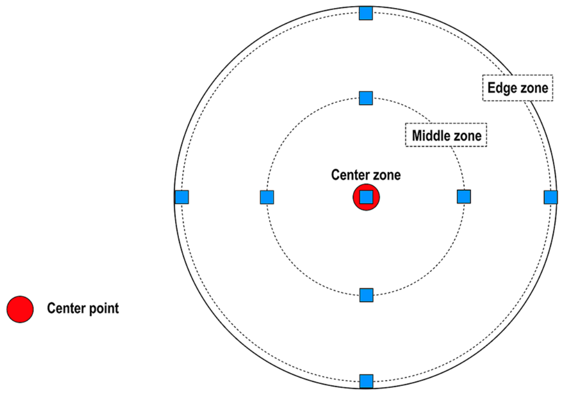

Figure 3. Initial shell crater sampling proposal

all safety measures that may occur when handling ammunition or other explosives. At the same time, a pyrotechnician was present, who supervised the overall collection and suitability of the equipment. Sampling was carried out in an antistatic coat, sturdy shoes, and gloves, with the help of plastic equipment (hoe and shovel) and other necessary protective equipment.

All samples were labeled according to the segment markings and safely stored in a transport box (secondary packaging). The weight of one sample was approximately 1 kg.

Initial experimental live fire sampling

Experimental verification of the proposed sampling method was carried out in May 2023 at an artillery range in the military training area Hradiště (Doupov) in the Czech Republic. 152 mm self-propelled howitzers M-77 (DANA), fired 5 OFd high explosive shells for the needs of the experimental sampling.

The experiment was carried out on the target area Kozlovský kopec which is located at coordinates 50.2960869 N, 13.1403925 E and has an altitude of 699 m above mean sea level (AMSL). Experimental live fire for sampling was carried out on a slope facing south.

In the first step, a suitable location for creation of a reference sampling site was selected. This location had to be visible from the observation post. The effort was to choose a place that is not in the direct impact of frequent shooting and that is ideally on a gentle slope. This requirement was established primarily for the reason that rain or other weather effects do not have a major influence on future chemical analyses and do not affect the given location. It should not be located in a valley or on a plain (increased pollutant contamination due to rain or snow). The slope of the hill was approx. 9.46°.

The following day, experimental live fire was carried out with an effort to approximate or to directly hit the reference site, so that the sampling of the impact craters of the shells could be sampled directly on the created reference site. A total of five shots were fired and from these, a total of three were selected for sampling:

- Sample 1: 152 mm OFd HE shell, delayed initiation fuze setting (impact #1)

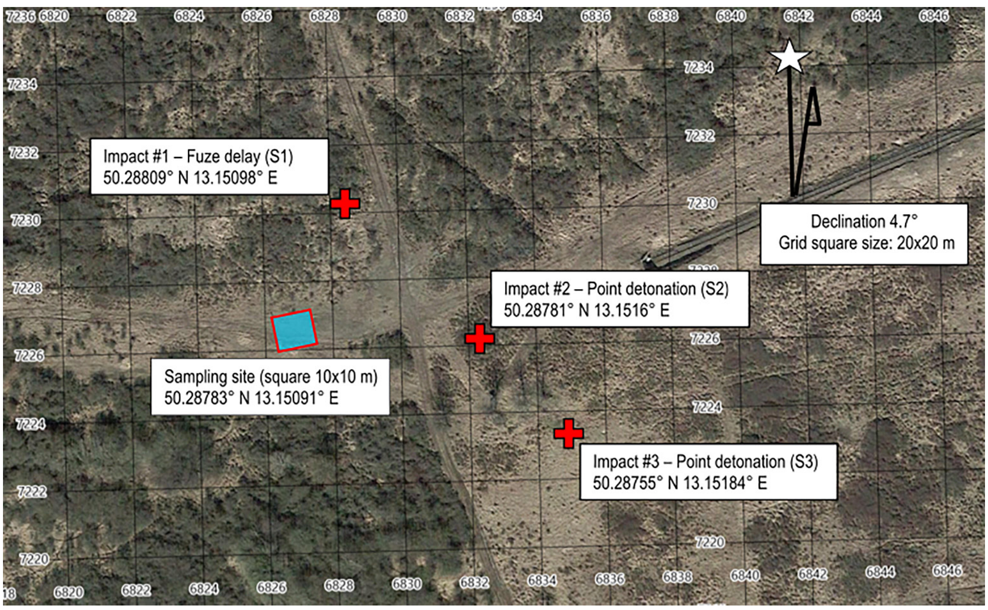

Figure 4. Target (impact) site scheme with reference site and impact points

- Sample 2: 152 mm OFd HE shell, point detonation fuze setting (impact #2)
- Sample 3: 152 mm OFd HE shell, point detonation fuze setting (impact #3)

The map showing the reference site and the impacts of individual shells is shown in Figure 4. As it can be seen, the shells impacted from approximately 40 to 80 meters out of the reference site.

The live fire was conducted in a low angle ballistic trajectory at a distance of approximately 13 km. The impact angle of the shell was 39°. When taking into account the angle of the slope of the terrain (9.46°), the resulting angle of impact was 48.46°, which is the optimal value for the function of the fuze and the prevention of projectile ricochets.

The basic information for the live fire in the experiment was as follows:

1. Sample S1: 152 mm shell OFd, delayed fuze (impact #1)
   - date and time: 16/05/2023, 13:20,
   - location: 50.28809° N 13.15098° E,
   - temperature: 11.9 °C,
   - air pressure: 933 hPA.
2. Sample S2: 152 mm shell OFd, point detonation fuze (impact #2)
   - date and time: 16/05/2023, 13:51,
   - location: 50.28781° N 13.1516° E,
   - temperature: 12.6 °C,
   - air pressure: 933 hPA.
3. Sample S3: 152 mm shell OFd, point detonation fuze (impact #3)
   - date and time: 16/05/2023, 13:58,
   - location: 50.28755° N 13.15184° E,
   - temperature: 12.6 °C,
   - air pressure: 933 hPA.

In total, 45 sub-samples were taken, 19 of which were reference soils and 26 were soils from artillery craters. All these sub-samples were subjected to detailed chemical analyses, which had to be preceded by appropriate treatment for the creation of a laboratory sample. The goal of chemical analyses was to determine the potential for contamination from ammunition and shells from military equipment. The key idea was to find out how soil contamination can be detected and analyzed, what methods can be used, and what can be detected. The key is the simulation of war, or post-war conditions, from the point of view of soil contamination, which must be appropriately modified to make the soil suitable again, for example, for agriculture or to prevent groundwater contamination. The same applies to the potential danger for people who will be in the given area. Graphical documentation of resulting shell craters and division of sampling points is attached to the supplementary material.

RESULTS

After sampling, chemical analysis of the individual samples was immediately carried out. The aim of this analysis was not only to determine the content of foreign substances in the soil but also to use statistical methods to assess the quality of the initial sampling design. The main tool for statistical evaluation was the Statistica software. During the chemical analysis, the individual samples were prepared and processed in following steps:

- Drying of samples at 40 °C for evaporation of moisture and preparation of samples for further sieving. Low temperature was used to prevent evaporation of volatile elements, for example Hydrargyrum.
- Sieving of samples using analytical sieves (mesh size 0.5 mm, Retsch). Samples were sieved for removal of oversize fraction (stones, pieces of shrapnel etc.).
- Preparation of representative samples by manual sample splitting. Representative samples were taken to reduce the amount of material.
- Milling of samples using batch mill (IKA) and preparation of analytical samples. Samples were milled for reduction of particle size and homogenization of material.

Processed samples were analyzed by digestion using a microwave system (Berghoff Speedwave Xpert). For 0.500 g of sample, a mixture of 10 ml of Aqua Regia with 0.5 ml of HF was used. Each sample was digested in triplicate. After cooling, the solutions were filtered through a nylon syringe filter (pore size 0.45 μm), transferred to 50 ml volumetric flasks and diluted with demi-water (conductivity below 0.1 μS/cm). Elemental composition of samples was analyzed using ICP-OES (Perkin Elmer). Each sample was measured in triplicate. The contents of the following 28 elements were analyzed: Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Se, Sr, Ti, V, Zn, Sn, Sb, Tl, W, Zr and the results were evaluated.

Descriptive statistics were calculated separately for each variable. This was aimed to provide basic information as the mean, minimum and maximum values, different measures of variation, as well as data about the shape of the distribution of the variable with the crater and its surroundings. Detailed results of chemical and subsequent statistical analysis are not the subject of this article and will be published in individual study.

During the evaluation, it was found that the content of individual elements varied significantly across the samples, even among samples located next to each other. This finding confirmed the idea that the initial design method did not have a sufficiently dense sampling grid. Therefore, to solve this problem, it was necessary to significantly increase the number of sampling points so that it would be easier to identify correlations between individual locations in the crater. In this context, it was also found that the angle of impact of the artillery shells needs to be considered when designing the sampling grid. The impact angle of artillery shells can range from angles close to 90° (toward the terrain) to very sharp angles, causing the shells to ricochet off the terrain. Depending on the impact angle, the dispersion of fragments and other components of the ammunition will also change. Additionally, the shape of the crater formed after the explosion of the ammunition will differ – it will be circular at impact angles close to 90°, but as the angle decreases, it will take on an oval or pear-like shape (Fig. 5) (Varecha, 2020; Blaha et al., 2021).

For this reason, it was crucial to define the shape of the crater and its center in the first step, because from the center point the sampling grid were to be laid out. Although it is often challenging (especially in rocky terrain) to determine the shape of the crater, this step had to be done very precisely to accurately pinpoint the center of the explosion.

Another finding was that it is also necessary to address the wider surroundings of the crater. This aspect was already apparent to the research team from the initial concept, as the fragments of artillery shells travel considerable distances. However, the initial sampling effort aimed to cover the crater itself exclusively. The problem with expanding the sampling grid was determining the distance curve for sampling coverage.

The distance curve, however, only covers the pollution from shell fragments, which primarily involves metal contamination. The main pollution is concentrated in the crater after the explosion, where the highest concentration of contaminants is expected, including not only metals but also remnants of explosives and non-fragmenting parts of the shell, such as fuze remnants, stabilizing fins or remnants of propulsion systems.

Upgraded reference sampling site

The initial reference sampling site was designed by systematic sampling procedures. Sampling locations were distributed over an area of 10×10 meters with 1.5-meter intervals to adequately cover this area (Fig. 2). A total of 19 samples were collected as part of the initial design. The evaluation findings by statistical analysis indicated that the 1.5-meter intervals between sampling locations were insufficient and needed to be significantly increased. This was highlighted by information suggesting possible contamination at one of the reference sampling locations. In the effort to isolate the contamination site, it became evident that, due to the distance between individual sampling locations, it was not possible to isolate this contamination and clearly define its spatial extent. This step is essential, because these contaminating points can ruin the whole pollution determination process.

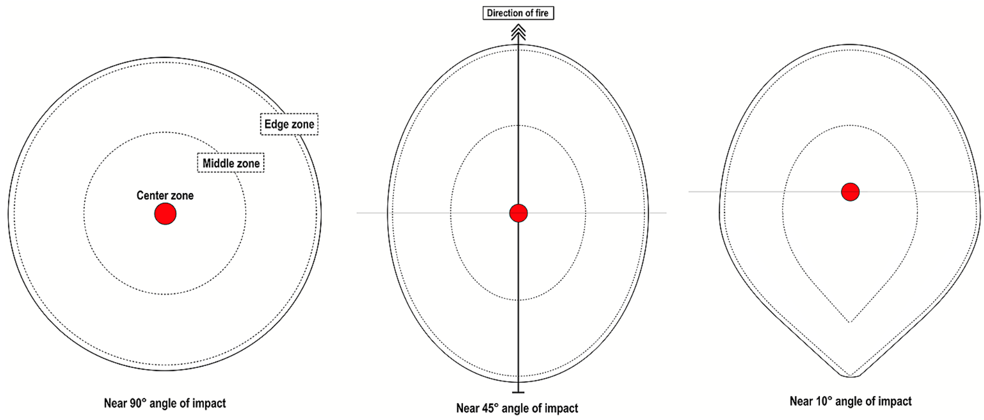

Figure 5. Shell crater shapes according to angles of impact

For this reason, the distribution of sampling locations was quadrupled. The sampling grid was reduced to a size of 4×4 meters, with the distance between sampling points being only 50 cm. This arrangement of sampling points within the reference grid ensures a valid definition of soil composition in the reference area and simultaneously allows for the isolation and exclusion of potential contamination sites from previous shelling. The upgraded reference site is shown in Figure 6.

Upgraded shell crater sampling method

The findings from the chemical analysis of craters formed by artillery shell indicate the same information as the findings from the reference grid. The main insight is the need to increase the number of sampling locations. In the original design, the research team worked with the assumption that the crater from the shell explosion will be circular. This crater was subsequently divided into three zones (center, middle, and edge) and further spatially divided using two axes. Sampling locations were then positioned at the intersections of the zones and axes across the crater (Figure 3).

However, this distribution of sampling locations was insufficient, and a statistical comparison of the levels of individual elements indicated areas within the crater that needed to be isolated. For this reason, it was necessary, same as with the reference grid, to increase the number of sampling points. In the context of statistical evaluation, the research team concluded that more zones were needed. The upgraded method of shell crater sampling thus divides the crater itself into 5 zones, which are placed at equivalent distances from the center to the edge of the crater. The horizontal division of the crater is additionally divided by axes intersecting at 45° angles (as opposed to the original 90° division).

In addition to sampling within the crater, sampling locations were also established outside the crater at distances of twice (2R) and three times (3R) the crater radius (Fig. 7). Initial sampling method worked with 26 samples taken from the crater. The upgraded method increased this number to 45 samples.

The proposed distribution of sampling locations, presented in Figure 7, also needed to reflect the shape of the crater itself (Fig. 5) in crater sampling, as the shape of the crater will significantly alter the distribution of individual sampling locations. In this context, it was necessary to determine only the center of the crater and base the layout of the sampling zones on it, as the axes across the different types of craters remain unchanged.

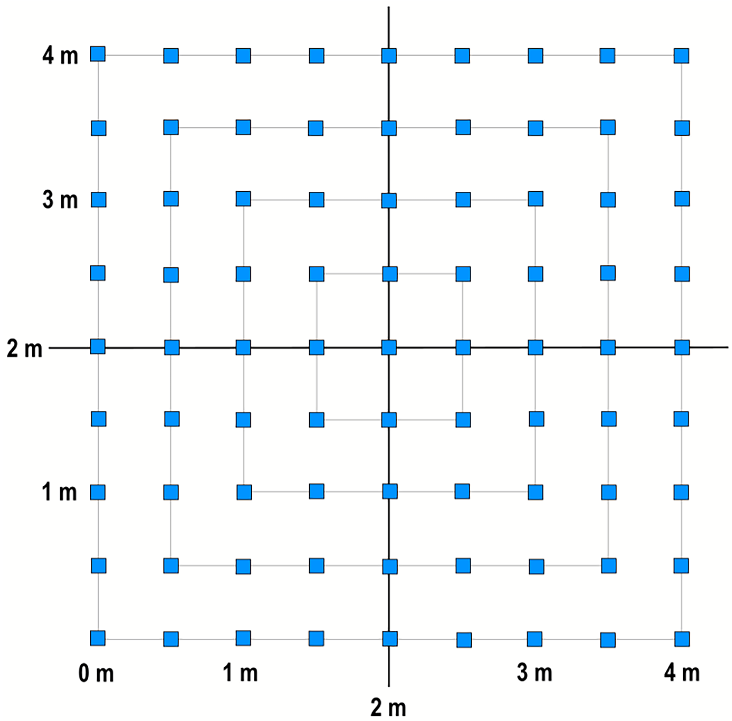

Figure 6. Upgraded reference sampling site

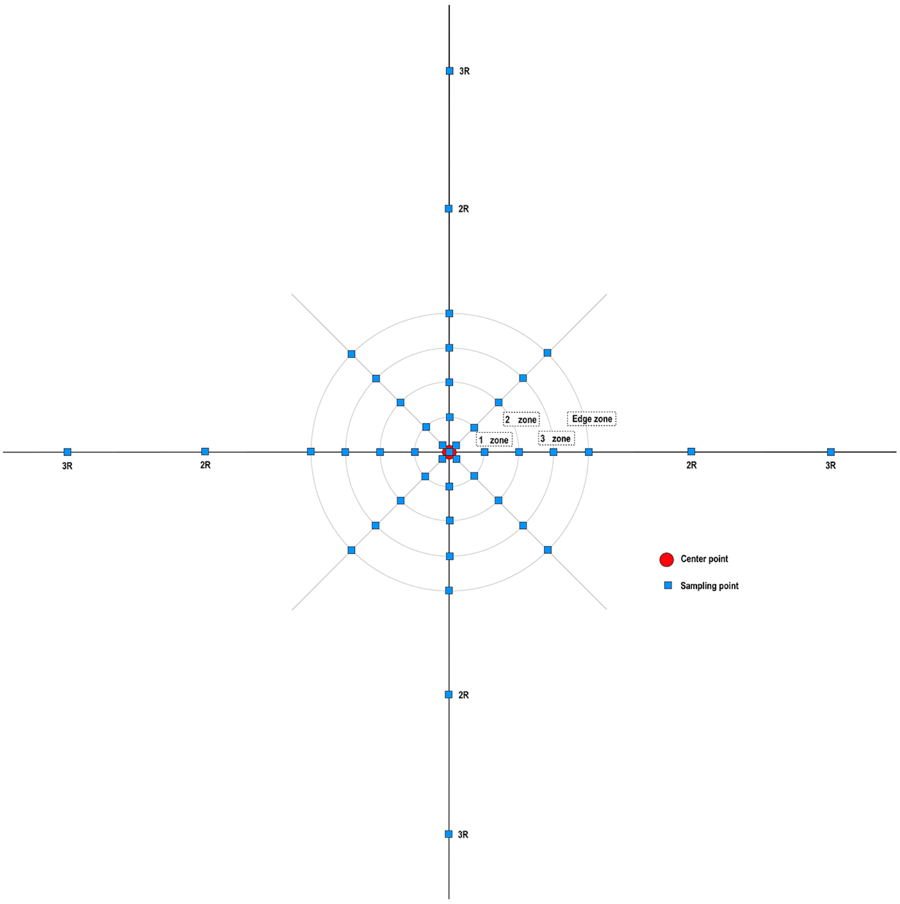

Figure 7. Upgraded crater reference site

DISCUSSION

This paper demonstrates that the methodology for sampling soil from craters created by artillery shell explosions enables the collection of relevant data on soil contamination caused by specific types of ammunition. This methodology, which included both indirect artillery fire and systematic soil sampling from different zones of the crater, has proven essential for accurately analyzing contamination from all elements (not only heavy metals or explosives).

A significant advantage of the proposed method is its ability to capture the environmental impact of individual ammunition types without distorting the craters, as would occur with static explosions. Statistical and chemical analysis of the soil samples confirmed that the initial sampling grid design was not dense enough to detect all sources of contamination, particularly in the central zone of the crater and its surrounding area. This finding led to a revision and improvement of the sampling scheme, which now takes into account the shape of the crater and the dispersion of ammunition fragments. The conducted analysis also highlighted the need to monitor not only the crater itself but also the wider surrounding area, where fragments can be dispersed over significant distances. This corresponds with findings from a previous study by Hewitt et al. (2007), which also indicated that contamination from fragments can be widely distributed. Given these circumstances, the sampling methodology was enhanced to better detect contamination caused by both heavy metals and explosive residues.

The obtained results show that the methodology designed for this study provides more precise and representative data on soil contamination than previously published methods, which often rely on generalized pollution models and do not account for specific types of ammunition. Comparisons with a study by Jenkins et al. (2005) confirm that the adopted approach, based on indirect artillery fire, provides more accurate data than the static detonation method, which distorts the shape of the crater and can lead to inaccurate chemical analysis results. The proposed methodology is applicable not only in the context of current armed conflicts, such as the war in Ukraine, but can also be useful for long-term monitoring of post-war restoration in the areas affected by military operations. This aspect is particularly important for ensuring the safe return of civilian populations and the ecological stability of impacted ecosystems.

CONCLUSIONS

This paper introduces an innovative methodology for sampling soil from craters created by artillery shell explosions, which allows for accurate analysis of contamination caused by specific types of ammunition. The main contribution of the adopted approach lies in its ability to minimize the distortions caused by static explosions, ensuring that soil samples accurately reflect the environmental impact of particular type of ammunition. Through experimental artillery fire, it was possible to develop a valid sampling method that provides reliable data on the extent and nature of soil contamination.

One of the main shortcomings in the current state of research is that many studies focus on sampling from impact areas as a whole, rather than from craters specifically. Additionally, these works often do not distinguish between specific types of ammunition, which can lead to generalized or incomplete conclusions about the environmental impact. The presented article bridges this gap by introducing a sampling method that is tailored to specific types of munitions, providing more precise data on the environmental effects of each.

The proposed method is particularly innovative in addressing key shortcomings of previous sampling methods, such as insufficient data representation caused by inaccurate sampling or crater deformation. By employing a systematic approach that accounts for the crater shape, fragment dispersion, and the surrounding area, the employed method is able to provide comprehensive and accurate data on soil contamination from heavy metals and explosive residues. The practical benefits of this methodology are substantial. It can be used not only for immediate monitoring of the ecological impacts of military operations but also for long-term assessment of post-war restoration efforts in affected areas. This is crucial for prioritizing decontamination work and ensuring the safety of civilians and the protection of ecosystems in artillery-affected regions. Given current conflicts, particularly the war in Ukraine, this methodology takes on increased significance, as it allows for more precise quantification of environmental damage caused by the massive use of artillery ammunition.

In conclusion, the proposed method represents a significant step forward in assessing the environmental impacts of military operations and provides practical tools for ensuring effective decontamination of affected areas. The results of this study can serve as a foundation for future research and policy-making in the areas of environmental protection and post-conflict recovery.

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