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THE DEGREE OF SOIL DEGRADATION AND AEROSOL FORMATION FROM EXPLOSION PRODUCTS RESULTING FROM HOSTILITIES IN UKRAINE

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

Background. ***On the territory of Ukraine, where large-scale hostilities are taking place, industrial production and developed transport infrastructure are concentrated, in particular, every tenth enterprise has an increased (1st or 2nd) hazard class. Arable fields suffered no less damage from shelling and mining, which negatively affects food security in the world. The degree of ecological hazard of the territory where hostilities took place is determined primarily by the level of surface concentrations of pollutants entering the natural environment. Concentrations, as well as the range and area of dispersion of pollutants depend on the parameters of the explosion, the height of the explosion product clouds, and meteorological conditions.***

Methods. ***For war-affected areas, mechanisms for assessing the degree of mechanical damage to soils and dust from a gas-dust cloud into the environment were proposed based on methods used at mining enterprises to analyze environmental hazards.***

Results. ***The studies were carried out in the field, where ca.1000 craters of various diameters were identified. The main parameters of the explosion were estimated based on the morphological shapes of the craters: the volume of displaced (or destroyed) soil, the mass of aerosol and dust that entered the atmosphere, the width and height of the pile - the scattering of soil from the centre of the explosion. The height of the gas-dust cloud from large explosions was calculated, which is extremely important for modelling the dynamics of solid particles in the cloud and solving problems of regional pollution transportation.***

A sequential algorithm was developed for assessing the destruction and damage to soils and the release of aerosol and dust into the atmosphere, which is formed during ground explosions.

Conclusions. ***An algorithm for calculating the degree of soil damage and dust ingress into the atmosphere from artillery weapons of various calibers has been proposed. Calculations of the height of the gas-dust cloud from large explosions and the scattering of earth from the crater have been obtained. The cumulative effect of soil damage and atmospheric pollution by substances from explosion products per day, month and year has been estimated. The results of comparing the damage caused to soils and emissions of harmful substances into the atmosphere as a result of the war are comparable in scale to the operation of an average quarry in Ukraine for a year. Given the scale of the battle lines environmental pollution would have catastrophic consequences.***

Keywords: ***Russian-Ukrainian war, aerosol, dust, soil degradation.***

Background

As a result of the war, large areas in Ukraine were subjected to massive bombardment with various types of weapons, and more than 30 % of its territory has been contaminated with mines and unexploded ammunition (Fig. 1). The ecological consequences of military actions in Ukraine are primarily related to soil damage, emissions of aerosols and dust during explosions, urban and forest fires, and burning of oil storage facilities. Under constant fire and without proper maintenance, there are enterprises and areas of storage of dangerous substances, which are a potential source of ecological disaster both on a local and regional scale (Savosko, 2016; Dytłow, & Górka-Kostrubiec, 2021; Splodytel et al., 2023).

The soils are the most impacted by a warfare (Hupy, & Schaetzl, 2006; Hupy, & Koehler, 2012; Broomandi et al., 2020; Williams, & Rintoul-Hynes, 2022; Menshov et. al, 2024 a,b; Bonchkovskyi et al., 2025). Shell bursts contaminate the ground cover with numerous chemicals and metal fragments. At the place of projectile ruptures in the soil craters or recesses are formed. In some places, the density of sinkholes is so condensed that they can be easily detected in space images. According to their morphometric forms, the caliber of ammunition is determined, which provides the information about its basic chemical composition and other characteristics. In places where the density of sinkholes is significant, soil destruction and contamination occur (Splodytel et al., 2023, Bonchkovskyi et al, 2023; Bilyi et al., 2024). A very low detoxification capacity for heavy metals is characteristic of soils. Chemical substances that have entered the soil are dispersed, which contributes to their rapid entry into the soil, and from there into surface water. The study of soil pollution in the developed areas of the metallurgical industry of Ukraine is given in (Savosko, 2016) and (Bondar et al., 2023). The authors (Bondar et al., 2024; Datsko et al., 2024; Hlavatskyi et al., 2024; Menshov et al., 2024, b; Solokha et al., 2024; Bonchkovskyi et al., 2025) published the results of pollution studies of soils with heavy metals as a result of the acute phase of the Russian-Ukrainian war. In addition, active hostilities almost triple the aerosol load on the atmosphere, which is confirmed by satellite data of the absorption index (ABI) (Boychenko, 2024). Clouds of explosion products, rising into the atmosphere, drift with the wind, leaving traces of dust on the ground, which leads to the spread of pollution, including heavy metals, at a considerable distance from the places of explosions (Hurin et al., 2007; Kolesnik et al., 2014). Aerosols and dust cause anthropogenic stress on land cover (Turner et al., 1980; Yang et al., 2021; Gao et al., 2023), scatter and absorb solar radiation (Pittock et al., 1990); as a result, the understory surface does not receive solar energy, which can lead to local changes in the growing season. In addition, surveillance and environmental monitoring in connection with potential danger are not carried out in combat zones and adjacent territories. In such territories, the analysis of the damage caused by the Russian invasion is possible with the help of space images with a high spatial resolution, which, thanks to various techniques, calculate the number of sinkholes, destroyed buildings, damage to the soil cover, etc. (Splodytel et al., 2023; Bonchkovskyi et al., 2023; Kozlova, & Velikodsky, 2024; Kravchenia et al., 2024). Thus, morphometric parameters of the craters are obtained, the volume of displaced soil is calculated, and the caliber of the ammunition is tentatively identified.

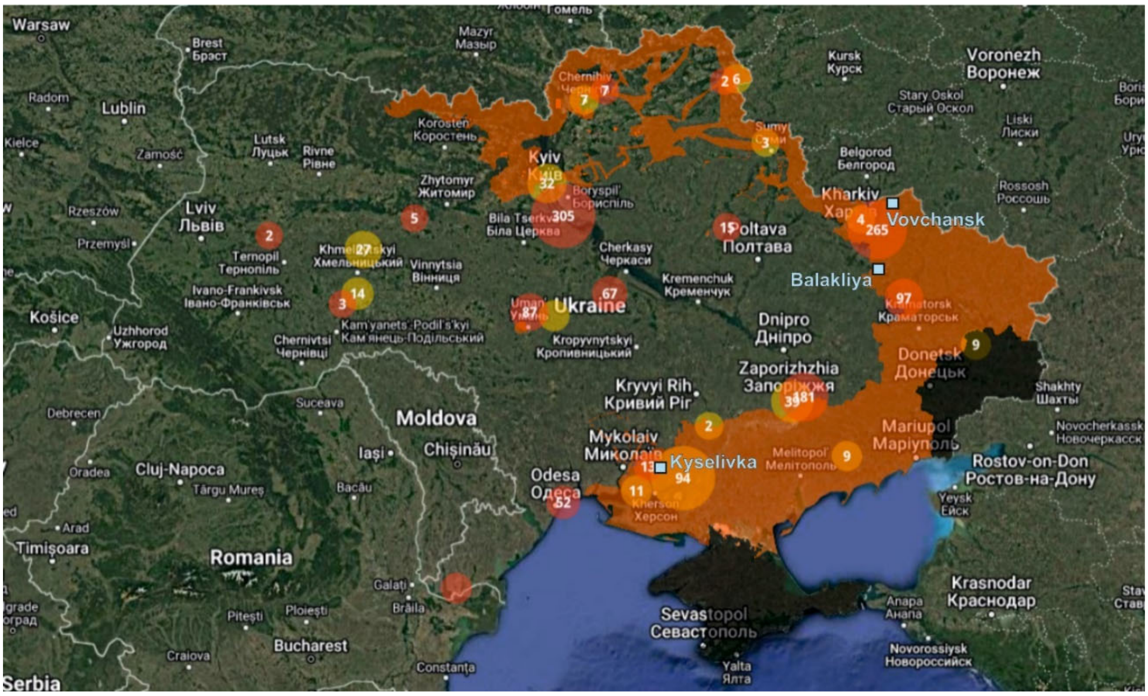


Fig. 1. Map of dangerous zones and territories affected by the war (as of November 2024, State Emergency Service of Ukraine, https://mine.dsns.gov.ua/, date of access 12.12.2024)

The soils are the most impacted by a warfare (Hupy, & Schaetzl, 2006; Hupy, & Koehler, 2012; Broomandi et al., 2020; Williams, & Rintoul-Hynes, 2022; Menshov et. al, 2024 a, b). Shell bursts contaminate the ground cover with numerous chemicals and metal fragments. At the place of projectile ruptures in the soil craters or recesses are formed. In some places, the density of sinkholes is so condensed that they can be easily detected in space images. According to their morphometric forms, the caliber of ammunition is determined, which provides the information about its basic chemical composition and other characteristics. In places where the density of sinkholes is significant, soil destruction and contamination occur (Splodytel et al., 2023, Bonchkovskyi et al., 2023; Bilyi et al., 2024). A very low detoxification capacity for heavy metals is characteristic of soils. Chemical substances that have entered the soil are dispersed, which contributes to their rapid entry into the soil, and from there into surface water. The study of soil pollution in the developed areas of the metallurgical industry of Ukraine is given in (Savosko, 2016) and (Bondar et al., 2023). The authors (Bondar et al., 2024; Datsko et al., 2024; Hlavatskyi et al., 2024; Menshov et al., 2024, b; Solokha et al., 2024) published the results of pollution studies soils with heavy metals as a result of the acute phase of the Russian-Ukrainian war. In addition, active hostilities almost triple the aerosol load on the atmosphere, which is confirmed by satellite data of the absorption index (ABI) (Boychenko, 2024). Clouds of explosion products, rising into the atmosphere, drift with the wind, leaving traces of dust on the ground, which leads to the spread of pollution, including heavy metals, at a considerable distance from the places of explosions (Hurin et al., 2007; Kolesnik et al., 2014). Aerosols and dust cause anthropogenic stress on land cover (Turner et al., 1980; Yang et al., 2021; Gao et al., 2023), scatter and absorb solar radiation (Pittock et al., 1990); as a result, the understory surface does not receive solar energy, which can lead to local changes in the growing season. In addition, surveillance and environmental monitoring in connection with potential danger are not carried out in combat zones and adjacent territories. In such territories, the analysis of the damage caused by the Russian invasion is possible with the help of space images with a high spatial resolution, which, thanks to various techniques, calculate the number of sinkholes, destroyed buildings, damage to the soil cover, etc. (Splodytel et al., 2023; Bonchkovskyi et al., 2023; Kozlova, & Velikodsky, 2024; Kravchenia et al., 2024). Thus, morphometric parameters of the craters are obtained, the volume of displaced soil is calculated, and the caliber of the ammunition is tentatively identified.

The aim of this study is the development of a consistent algorithm for assessing the degree of soil damage and atmospheric air pollution with dust from explosions as a result of military operations in Ukraine.

The research methodology is based on the common methods of assessing the ecological danger of atmospheric and soil pollution that are used at mining enterprises.

The scientific novelty involves the integration of methods for assessing the mechanical destruction of the upper layers of the soil, formation of craters and accumulation of soil, as well as the parameters of the gas and dust cloud, which are used for the first time to assess the man-made consequences of Russian aggression.

Firstly, the proposed algorithm will allow assessing the degree of soil damage in the territories, where hostilities took place. Secondly, it helps to evaluate the quantitative indicators of man-made load on the ground cover due to dust entering the atmosphere during explosions, which then settles on the surface of the soil. The obtained data will be useful in the assessment of environmental hazards and in the development of effective solutions for the purpose of localization of contaminated areas and their restoration.

Explosion in the soil. Soil explosions can be of two types: a crater explosion (sometimes called the soil ejection explosion), and a relatively deep explosion, where no visible changes to the soil surface are observed, i.e., the camouflage explosion. There are three types of disturbances in the soil: explosion due to soil release, explosion destruction of underground structures, and seismic action of the explosion.

Let's focus on the main parameters of the destructive effect of the explosion on the allocation of soil. This type of explosion is used both for civilian and military purposes, to damage ground and underground objects. One should expect the formation of craters of increased emission of a larger volume, which is observed on the battlefields. The shape and dimensions of the crater depend on a large number of factors, the main of which are the power of the explosion and the composition of the soil (Bull, 1983; Persson et al.,1994). The ejection charge must have sufficient energy not only to crush the rock, but also to eject it from the resulting craters. Depending on the magnitude of the explosion action index $n=r/W$, the discharge charge is divided into three types: reduced when $n<1$, normal when $n=1$, enhanced when $n>1$ (see Fig. 2), where r is the radius of the craters, W is the depth of the crater.

The ejection crater is a cone-shaped recess in the rock, formed by the explosion of an explosive charge (Fig. 3). There are three stages of the allocation crater: theoretical – used to calculate the explosive charge; real – craters formed at the moment of soil ejection (the soil is in the air); visible – craters formed in the Earth's crust after the fall of the soil, i.e. after the explosion ends.

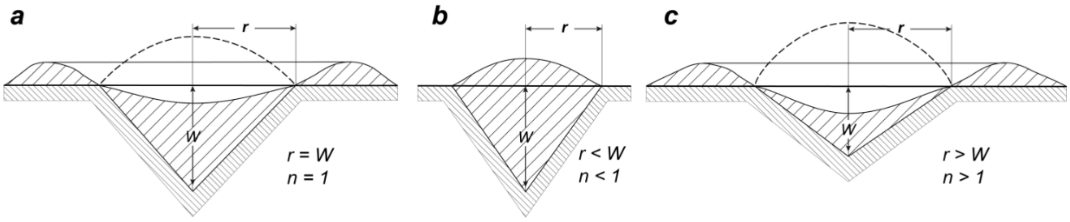


Fig. 2. Scheme of soil emission charges from the explosion action index. *r* is the radius of the craters, W is the depth of the crater, n=r/W is the explosion action index (adapted from (Technical …, 1972))

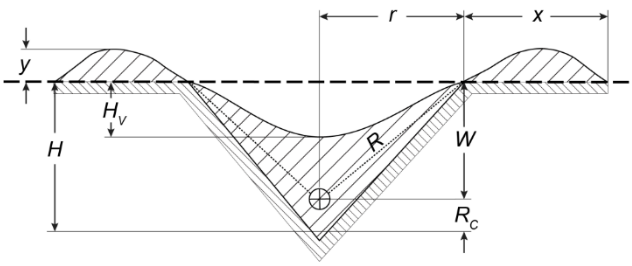


Fig. 3. Definitions of the crater dimensions (designation in the text: adapted from (Technical …, 1972)

The following elements are distinguished in the ejection crater (Glasstone, & Dolan, 1977): r – the upper radius, which is equal to the radius of the circle that forms the upper base of the crater; R is the radius of the explosion degree which is the distance from the center of the charge to any point on the edge of the crater; W is the shortest distance from the charge center to the original ground surface; H_v is the apparent depth of the crater; H is the depth of the actual crater; x is ejecta portion of lip, y – height of the lip crest; R_c is the compression radius, the distance from the center of the charge to the bottom of the crater.

The dimensions of the crater vary tens of times when moving from one type of soil to another, or with variations in the depth and/or height of undermining (Ambrosini et al., 2004; Bjelovuk et al., 2015). Therefore, the identification of an exploded projectile based on the morphological features of the crater is approximate, but the volume of the ejected soil will correspond to the volume of the formed crater. For example, the notch from an 82-mm mine explosion, even if the mine sinks into the soil to the optimal depth, is small: with a diameter of 1 meter and a depth of about 50-60 centimeters. However, usually the crater is smaller in size since the 82-mm mine is not intended for firing at the destruction of objects but is designed only for fragmentation and bursts before it penetrates the soil.

Methods

The explosive substance is a highly concentrated chemical energy source. One kilogram of explosive substance of medium power releases during the explosion in t~10^{-5} s of the order of $4 \cdot 10^3$ kJ of heat energy and destroys about 1 m^3 of the substance. The products of the explosion have significant pressure (~$4 \cdot 10^{10}$ N/m^2) and high temperature (~ 4000 K). This leads to the crushing and scattering of the substance, which consumes about

90% of the energy of the explosion. The size of the formed crater mainly depends on the power of the explosion and the properties of the soil. The empirical equation for calculating the volume of the crater has the following formula (Orlenko, 2002):

$$V=1.4r^2H_v, \qquad H_v=0.35W(2n-1),$$

where V is the volume of the crater m^3, r is the radius of the crater, m, H_v is the apparent depth of the crater, m. The radius of the explosion can be calculated as follows:

$$R^2=W(1+n^2)=r^2+W^2$$

After the explosion, a small part of the ejected material falls back into the crater, the latter is concentrated at a distance of about 3÷5 radii from the center of the explosion. In conditions of horizontal relief, the ejecta portion of lip and height of the lip crest (see Fig. 3) during the explosion on the allocation are approximately determined by the formulas (Technical…, 1972):

$$x=5nH_v\text{, m,}$$
$$y=0.7H_v/n\text{, m.}$$

The height of the lip crest above the crater increases the size of the crater by increasing the land on the surface. If the volume of the crater is known we can find the mass of the thrown soil:

$$M=V\cdot\rho,$$

where M is the total mass of allocated soil, kg; V – soil volume, m^3; ρ is soil density, kg/m^3. When the explosion is powerful enough, it is necessary to take into account the volume and mass of the annular crest where the soil is compacted. The equations for crest volume and soil compaction mass are as follows:

$$V_c=\pi r^2h,\ M_c=V_v\rho \text{ where } h=0.25W.$$

Then the mass of the allocated soil will be $M_{es}=M–M_c$, where M_c is the mass of the soil of the ring shaft. Taking into account the mass of the detonating substance, the energy of the explosion is calculated as $E_d=\varepsilon_d\cdot m_d$, where m_d is the mass of the explosive substance, ε_d is the specific energy release of $4.18\cdot10^6$ J/kg. We estimate the mass of the destroyed substance using an expression borrowed from the study (Chernogor, 2003):

$$M_r=E_d/\varepsilon,$$

where $\varepsilon=5\cdot10^3\div10^5$ J/kg is the specific crushing energy, which depends on the rock class.

Dust emissions are significant only in the case of a near-surface or shallow explosion. Dispersed composition of clouds formed from explosions are very diverse and large particles settle immediately after the explosion, and small particles and dust are captured by the rising flow to significant heights due to convection and atmospheric turbulence. From the point of view of social and ecological danger caused by atmospheric pollution, the greatest threat is the total mass of aerosols – particles with characteristic sizes of r~20÷200 µm. For this range, the particle mass distribution is close to lognormal (Kolesnik et al. 2014; Yang et al., 2021; Gao et al., 2023), and their mass M_a is 10–15% of the mass of the destroyed substance M_r. It is believed that the mass of dust that "hangs" in the atmosphere for a long time is $M_{dust}=M_a/4$ (Chernogor, 2003). Particles, smaller than 20 µm, can travel tens and hundreds of kilometers.

The thermal energy released during the explosion leads to the release into the atmosphere of the hot products of the explosion together with the destroyed substance. For a standard atmosphere, the height of the cloud lift is related to the energy of the explosion, which is described by the relation:

$$H=1.87E_d^{\ 1/4},$$

where H is the height of the cloud, m; E_d – explosion energy, J. According to Gould & Tempo (1983), 120 s after the explosion the diameter of the cloud and its volume will be $D_x=335\ E_d^{0.25}$ m, $V_x=3\cdot10^{-2}E_d^{0.75}$ km^3. When the density of the rising air equals the density of the environment, the further evolution of the cloud will be determined mainly by diffusion. At this stage, the wind and its distribution over height play the biggest role.

Results

Field observations of the consequences of intensive warfare were conducted in the Mykolayiv Oblast – near the village of Kyselivka in the Pervomayska Hromada of the Mykolaiv Rayon, and in the Kharkiv Oblast – around the city of Balakliya of the Izyum Rayon. In Fig. 4, typical craters, left on the battlefield by artillery, bomb and missile strikes, are shown.

The main parameters of the explosion depending on the mass of the explosive substance in the soil of medium hardness are calculated on the basis that the projectiles have a high-explosive fragmentation effect (Tab. 1). The radii and depths of the craters are represented by the average value for each type of ammunition. The mass of the explosive substance was taken from open sources.

Fig. 4. Craters near the village of Kyselivka in the Pervomayska Hromada of the Mykolaiv region:
a) crater from a shell approximately 200–230 mm, b) crater from a cannon shell approximately 122 mm, c) crater from the explosion of a saltpeter compound after a shell hit it. Pictures made in March, 2024

Table 1

Dependencies of the main parameters of the explosion on the mass of the explosive substance

Caliber, mm	m_d, kg	E_d, J	r, m	W, m	V, m^3	M	M_r	M_a	M_{dust}
M-82	0.465	$1.94\cdot10^6$	0.4÷0.6	0.1÷0.2	0.11	0.132	0.39	0.039	0.001
G-76-107	0.74	$3.09\cdot10^6$	0.75÷1	0.4÷0.5	0.30	0.363	0.68	0.068	0.002
G-122	4,54	$1.89\cdot10^7$	2.5÷4	0.4÷0.7	6.7	7.9	3.8	0.379	0.095
G-152	8,78	$3.67\cdot10^7$	3÷5	1.5÷1.8	10.7	12.8	7.3	0.734	0.183
G-203	16,73	$6.99\cdot10^7$	3	2,2	16.7	20.1	13.9	1.4	0.349

Note: In the left column, the letter *M* indicates a mortar mine, the letter G a gun shell. To the right, *M* is total mass of displaced soil, tons, M_r is mass of the destroyed substance, tons, M_a is mass of the aerosols, tons, M_{dust} is mass of the dust, tons.

As can be seen from Tab. 1, the greater the mass of the explosive substance (caliber of the projectile) is, the more damage was done to the soil and more products of the explosion enter the atmosphere. Our calculations are in good agreement with the results obtained in previous studies (Sploditel, 2022; Bonchkovskyi et al., 2023, p. 481; Kravchenia et al., 2024). However, if the mass of the explosive substance is known, it is possible to calculate the mass of the destroyed substance without involving the parameters of the craters. These calculations could be helpful in comparing with those obtained from satellite images, as well as in estimation of the amount of aerosol that enters the atmosphere. It is significant that the mass of destroyed substance M_r has an underestimated value compared to the total mass of displaced soil M, calculated according to the volume of the crater (Tab. 1). This is due to the fact that when calculating the energy of the explosion, we use energy that is a multiple of the TNT equivalent. But nowadays, shells use an explosive substance more powerful than TNT – phlegmatized hexane A-IX-1-2 (1.22–1.55 in TNT equivalent). Thus, if the coefficient of the TNT equivalent of hexane is taken into account in the calculations, the difference between the masses is equalized.

Considering how powerful explosions affect the soil and atmosphere, we will perform two calculations (Tab. 2). In the first case, the explosion of a FAB-500 aerial bomb, in the second, the explosion of saltpeter storage (Fig. 4, c) are listed. Fig. 5 illustrates a typical extent of the rise of a dust and gas cloud from the explosion of an FAB-1500 aerial bomb.

Table 2

Dependence of the main parameters of the explosion on the mass of the explosive substance

Value, units	FAB500 aerial bomb	The explosion of the saltpetre composition
m_d, kg	500	12873
r, m	11,5	25
W, m	4.3	11
V m^3	796	9625
V_c ,	446	5396
M , tons	955	11550
M_c , tons	535	6476
M_{es} , tons	420	5079
x, m	57.5	125
y, m	1.12	3.39
E_d , J	$2.09 \cdot 10^9$	$5.38 \cdot 10^{10}$
M_r, tons	418	10762
M_a , tons	41.8	1076
M_{dust} , tons	10.5	269
H_c	400	900
$^*E_d$, J	$2.55 \cdot 10^9$	$9.14 \cdot 10^{10}$
$^*M_r$, tons	409	18295
$^*H_c$	420	1028

Note: m_d – mass explosive substance, r, W – radius and depth of the crater, V – crater volume, V_c – volume of the ring shaft of rock, M – total mass of displaced rock, M_c – mass of the ring shaft of rock, M_{es} – mass of ejected rock, x, y – ejecta portion of lip and height of the lip crest, H_c – height of the cloud, M_r, M_a, M_{dust} is mass of the destroyed substance, aerosols and dust, tons. * – calculations were made for phlegmatized hexogen A-IX-1-2 and saltpeter.

Fig. 5. Explosion of FAB-1500 guided aerial bomb, Vovchansk, Kharkiv region.
(Source: https://ua.korrespondent.net/ukraine/4720531-rosiiany-skynuly-nadpotuzhnu-bombu-na-vovchansk, date of access 12.12.2024)

The morphometric dimensions of the crater, which are formed during bombing from heights of 1200–3500 m by aerial bombs at a set deceleration of the detonator of 0.2 s, follow (Balaganskyi, & Merzhnevskyi, 2004). The mass of nitrate that exploded was calculated according to (Technical …, 1972): $Q=K_V W^3(0.4+0.6n^3)$, kg, where K_B is the estimated specific consumption of the explosive substance, kg/m^3; W – crater depth, m; n is the index of the explosion. For the discharge charge, K_V has average values from 1 to 1.5 according to the discharge charge, the K_V has average values from 1 to 1.5 according to the classification of building standards and regulations (dense sand, loam, loam clay, loess).

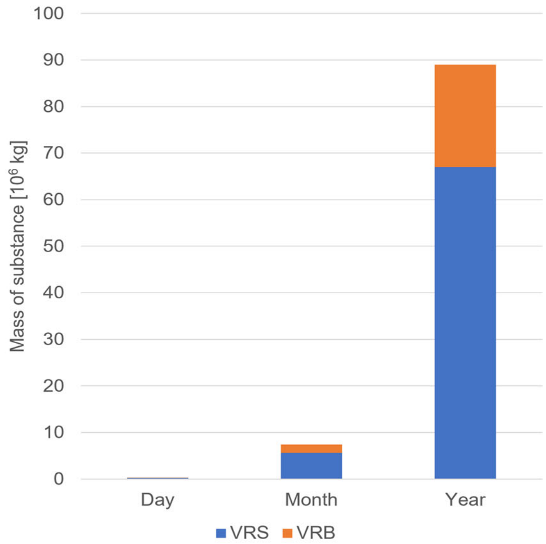
According to Tab. 2, high-power explosions are tens to hundreds of times greater than mortar and barrel artillery explosions. Consequently, the explosion of several FAB-500, FAB-1500 aerial bombs causes more damage than hundreds of shells in a certain period of time. Nowadays, Russia drops more than 30 guided aerial bombs per day which causes irreparable damage to the environment. The accumulative effect of soil damage and atmospheric pollution with substances from explosion products as a result of hostilities is presented in Fig. 6.

Fig. 6 is given according to the following calculations:

1. The average amount of artillery ammunition that Russia spends per day is 30000 units (see https://suspilne.media/818001-rosia-vitracae-za-dobu-vtrici-bilse-boepripasiv-niz-ukraina-sirskij/, date of access 12.12.2024). The average explosive substance of one artillery projectile is 6.25 kg (calculated as the average of the sum of the masses of the explosive substance given in Tab. 1). Cumulative values for the month and for the year are calculated similarly.

2. The average number of FAB-500 and FAB-1500 aerial bombs that Russia uses per day is 30. The average explosive substance of one aviation bomb is 2000 kg (based on 15 FAB-500 bombs and 15 FAB-1500 bombs) (https://tsn.ua/ato/skilki-rosiya-maye-kerovanih-aviabomb-ekspert-prigolomshiv-zayavoyu-2516278.html, date of access 12.12.2024).

The results shown in Fig. 6 can be compared with emissions of harmful substances into the atmosphere, obtained at the quarries of Ukraine. For example, on average, about 6000 tons of explosives are used and about 7500 m^3 of rock is destroyed per quarry in Kryvbas region (Kolesnik et al. 2014). In our case, only due to the FAB-500 and FAB-1500 aviation bombs, the total mass of explosives for a year will be about 7500 tons. Therefore, with an explosive consumption of 09–1.0 kg/m^3, we have about 7500 m^3 of destroyed soil, and the volume of dust will be about 2500 tons. The total mass of explosives of rocket, mortar and barrel artillery, fires of oil storage facilities and forests must be added as well. Thus, we will have along the entire line of combat clashes in addition to background pollution, soil damage and atmospheric pollution as a result of military actions equivalent to the consequences of the operation of hundreds of average statistical quarries in Ukraine for a year.



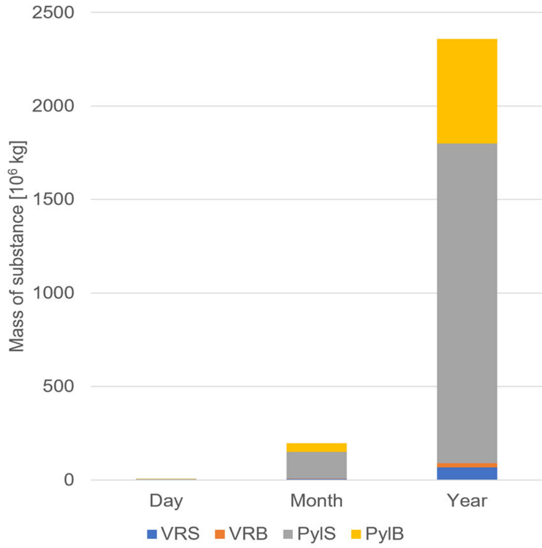


Fig. 6. Accumulative effect of soil damage and dust pollution of the atmosphere

VRS –mass of the explosive substance of artillery ammunition; VRB –mass of the explosive substance of aviation bombs; PylS – mass of dust from artillery ammunition; PylB – mass of dust from aviation bombs

Discussion and conclusions

The affected area is mainly a loess-soil cover, which occupies 74.8 % of the territory of Ukraine (Khotynenko, 2014). Loess contains more than 50% dust particles. Since there is a high density of industrial enterprises and hazardous substance storage areas (dumps and sludge storages) in the research region, soil disturbance as a result of military operations is a source of dangerous effects for humans and the environment due to high rates of dust and gas emission, and transfer of dangerous compounds from explosions and from the surfaces of man-made landscapes.

The results of field research in the Kyselivka village in the Pervomayska Hromada of the Mykolaiv region, and in the Kharkiv region around the city of Balakliya, indicate that calculations of the degree of soil damage and the ingress of dust into the atmosphere depends on types of aerial bombs and artillery weapons of various calibers. For instance, for the FAB-500 aerial bomb, the height of the gas-dust cloud of explosion products is about 400 m. Soil scattering and height of the crest are 57 m and 1.2 m respectively. This gives an understanding of what area of soil cannot be restored without special reclamation.

Estimates of the accumulative effect of soil damage and atmospheric pollution by substances from explosion products per day, month, and year were obtained. Analysis of the results for the year showed that approximately 3 Mt of substance was destroyed during the explosions of all munitions. The mass of aerosols was about 0.3 Mt. Aerosol particles of the fine-dispersed fraction ~ 20 μm are carried by explosions and convective processes to rather high altitudes (1÷2 km), where the aerosol existence time is 1÷10 days.

Harmful substances that enter the natural environment create tangible negative effects in a radius of tens of kilometers from the places of explosions, which negatively affects agricultural lands and adjacent territories. Therefore, the assessment of man-made load on the atmosphere and soil as a result of bombing is extremely important in the comprehensive study of the "ecological genocide" of Ukrainian territories as a result of Russia's military aggression.

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СТУПІНЬ ДЕГРАДАЦІЇ ҐРУНТІВ ТА УТВОРЕННЯ АЕРОЗОЛІВ ІЗ ПРОДУКТІВ ВИБУХІВ УНАСЛІДОК БОЙОВИХ ДІЙ В УКРАЇНІ

В с т у п . ***На території України, де ведуться масштабні бойові дії, зосереджене промислове виробництво та розвинена транспортна інфраструктура, зокрема кожне десяте підприємство має підвищений (1-й чи 2-й) клас небезпеки. Не менших збитків від обстрілів та мінування зазнали орні поля, що негативно впливає на продовольчу безпеку у світі. Ступінь екологічної небезпеки території, на якій пройшли бойові дії, визначається насамперед рівнем приземних концентрацій забруднювальних речовин, що потрапляють у природне середовище. Концентрації, а також дальність і площа розсіювання забруднювачів залежать від параметрів вибуху, висоти підйому хмар продуктів вибуху та метеорологічних умов.***

М е т о д и . ***Для уражених війною ділянок запропоновано механізми оцінювання ступеня механічного пошкодження ґрунтів та потрапляння пилу від газопилової хмари в довкілля на основі методів, які використовують на гірничодобувних підприємствах для аналізу екологічної небезпеки.***

Р е з у л ь т а т и . ***Дослідження виконано безпосередньо в польових умовах, де ідентифіковано близько 1000 воронок різних діаметрів. За морфологічними формами воронок оцінено основні параметри вибуху: об'єм переміщеної (або зруйнованої) землі, маса аерозолю та пилу, що потрапила в атмосферу, ширина та висота навалу – розліт землі від центру вибуху. Розраховано висоту підняття газопилової хмари від потужних вибухів, що вкрай важливо для моделювання динаміки твердих частинок у хмарі та розв'язання задач регіонального переносу забруднення.***

Побудовано послідовний алгоритм для оцінювання руйнування та пошкодження ґрунтів і потрапляння аерозолю та пилу в атмосферу, який утворюється під час наземних вибухів.

В и с н о в к и . ***Запропоновано алгоритм розрахунків ступеня пошкодження ґрунтів та потрапляння пилу в атмосферу від артилерійської зброї різного калібру. Отримано розрахунки висоти підняття газопилової хмари від потужних вибухів та розльоту землі від воронки. Оцінено накопичувальну дію пошкодження ґрунтів та забруднення атмосфери речовинами продуктів вибуху за добу, місяць та рік. Результати порівняння завданої шкоди ґрунтам та викиди шкідливих речовин в атмосферу внаслідок війни мають зіставний масштаб з роботою середньостатистичного кар'єру в Україні за рік. Враховуючи масштаб лінії бойових зіткнень забруднення природного середовища матиме катастрофічні наслідки.***

К л ю ч о в і с л о в а : ***російсько-українська війна, аерозоль, пил, деградація ґрунту.***

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