

Research Article

Physical Degradation and Organic Matter Loss in Soils Impacted by Bomb-Induced Disturbances in Ukraine

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Abstract

This study investigates the physical degradation and organic matter loss in soils subjected to explosive disturbances in Ukraine, with particular focus on bomb crater zones. Soil samples were collected from impact sites (CR) and adjacent undisturbed reference areas (NT) across four representative soil types: Albic Arenosols, Luvic Greyzems, Luvic Chernozems, and Haplic Chernozems. A comparative analysis was conducted to evaluate changes in particle-size distribution, the silt-to-clay ratio, soil organic matter (SOM), and the structural saturation index (St). The results reveal notable textural alterations, characterized by reductions in coarse fractions (very coarse and coarse sand) and enrichment in finer particles, including very fine sand, silt, and clay. The most significant transformations were recorded in Haplic Chernozems (−3.44% sand, +2.09% silt, +1.35% clay) and Albic Arenosols (+6.08% very fine sand), indicating intense aggregate fragmentation induced by explosive forces. SOM content declined across all soil types, with the most substantial loss observed in Albic Arenosols (−55%, from 1.82% to 0.82%) and the smallest in Haplic Chernozems (−36%). Structural integrity was also compromised: in all disturbed profiles, St values dropped below the 5% erosion-risk threshold, indicating increased vulnerability to degradation. Despite these changes, the silt-to-clay ratio remained relatively stable, suggesting conservative behavior of fine particles under mechanical stress. These findings provide important insights into the ecological consequences of warfare-related soil disturbance and offer a scientific basis for post-conflict land restoration strategies. The documented decline in SOM and structural stability poses a serious threat to soil fertility, water retention capacity, and erosion resistance. Targeted remediation efforts and adaptive land management practices are essential to restore soil functionality and support long-term agricultural sustainability in affected regions.

Keywords

Soil Structure, Particle-Size Distribution, Aggregate Stability, Bomb-Induced Disturbance, Erosion Risk

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1. Introduction

Armed conflicts inflict severe and often irreversible damage on terrestrial ecosystems, with soils being among the most affected components. The full-scale invasion of Ukraine has triggered both a humanitarian catastrophe and an environmental crisis. Soils in combat zones have been subjected to physical destruction, displacement, contamination, and significant losses of organic matter [37]. The most severe degradation occurs in crater zones resulting from explosive ordnance, characterised by disrupted morphology, altered granulometry, compaction, structural loss, and persistent contamination by heavy metals and explosive residues [6].

Even before the war, some of Ukraine's agricultural land was undergoing degradation. According to the FAO [10], 20% of arable land was affected by erosion, compaction and the loss of organic matter. The pre-existing anthropogenic pressure had already made the soil more vulnerable to the damage caused by the conflict [12, 25]. Military activities have accelerated this degradation through explosions, the use of heavy equipment, and the deposition of hazardous substances [22].

War-induced soil degradation represents a distinct form of land disturbance [24]. Its monitoring is complicated by variability in soil types, intensity of hostilities, and access constraints [1, 2]. Soils differ in their resilience and buffer capacity, which are determined by their physicochemical and biological traits [29]. Visual analysis of satellite imagery reveals widespread disruption and loss of soil functionality in many war-affected areas [19].

Bombturbation describes the mixing of soil horizons induced by explosions [13], which is highly relevant to Ukrainian soils impacted by war. Explosions fragment soil aggregates, cause dehumification and introduce heavy metals, thereby disrupting the soil's ecological and physicochemical regimes [18]. Craters ranging from 0.54 to over 70 m³ [7] displace large soil volumes, often bringing subsoil to the surface and carrying contaminants upward. Increased levels of cadmium, copper, lead, and zinc have been reported [4, 34].

A key impact of explosions is the shift in soil granulometry. Redistribution of particles reflects aggregate breakdown and changes in porosity and surface area [14, 35]. These physical changes are closely tied to SOM loss—an essential driver of aggregate stability. SOM degradation compromises structure, porosity, and water retention capacity [20, 26].

Explosive events can generate fireballs exceeding 1,800 °C, with surrounding soils reaching 500–600 °C—sufficient to ignite and oxidise SOM [16]. However, SOM alteration begins at 250–460 °C due to volatilisation and thermochemical reactions [11]. Even small changes in SOM may significantly influence the global carbon cycle.

Military action causes multiple disturbances to soil cover, resulting in significant structural damage and loss of SOM. These changes not only threaten soil fertility but also the long-term resilience and sustainability of agroecosystems.

Although existing research has examined specific aspects of this degradation in certain soil types, a comprehensive, comparative assessment of its impact on Ukraine's most widespread and affected soils is lacking.

This study aims to evaluate the physical degradation and SOM loss in Ukrainian soils resulting from bombardment and explore the implications of these changes for ecological functionality and agricultural potential. A comprehensive, comparative evaluation of the dominant soil types affected by warfare is necessary to understand the full extent of the degradation and to inform future land management and restoration efforts.

2. Material and Methods

2.1. Soil Sampling

Soil samples were collected from four distinct locations in Ukraine, each selected to represent a primary soil type and administrative region affected by recent military activity. The objective of the sampling was to ensure comprehensive coverage of pedological diversity across areas impacted by the war. The selected sites included: Albic Arenosols in the Chernihiv Region (northern Ukraine), Luvic Greyzems in the Kyiv Region (north-central Ukraine), Luvic Chernozems in the Sumy Region (northeastern Ukraine), and Haplic Chernozems in the Dnipropetrovsk Region (central-eastern Ukraine).

The average samples were collected from five soil samples from each experimental site:

- 1) within an impact crater (CR), formed by a strike during the spring–summer of 2024, and;
- 2) from a nearby undisturbed location (NT), representing the soil's natural state.

Both sampling points were situated in comparable landscape settings to ensure consistency. This design enabled a direct comparison of the physical and chemical properties of soils under military-disturbed and undisturbed conditions, with a particular focus on changes in particle size distribution.

2.2. Laboratory Analysis

Soil sampling and analyses were conducted at Prime Lab Tech, LLC, an agrochemical laboratory specialising in precise soil testing and providing expert recommendations for sustainable land resource management (<https://plt.land/uk>). The laboratory is accredited following the DSTU EN ISO/IEC 17025:2019 standard (equivalent to EN ISO/IEC 17025:2017 and ISO/IEC 17025:2017, IDT), and holds Accreditation Certificate No. 201741.

This study uses the particle-size classification presented in

Table 1.

The particle size distribution (PSD) of mineral soil samples (<2 mm) was determined according to ISO 11277:2020. The samples were air-dried and pretreated according to ISO 11464:2006/DSTU ISO 11464:2007, which involved the removal of organic matter using 30% H₂O₂ and carbonates using 1 mol/L HCl. The pretreatment procedures and subsequent sedimentation steps were performed automatically using a Skalar Robotic Analyser SP2000 (Skalar Analytical B.V., Netherlands).

Table 1. Particle-size fractionation according to the particle diameter.

Particle-size fraction	Abbreviation	Particle diameter	
		µm	mm
Clay	C	<2	<0.002
Silt	Si	2-63	0.002-0.063
Sand	S	63-2000	0.063-2.0
very fine sand	VFS	63-125	0.063-0.125
fine sand	FS	125-200	0.125-0.2
medium sand	MS	200-630	0.2-0.63
coarse sand	CS	630-1250	0.63-1.25
very coarse sand	VCS	1250-2000	1.25-2.0

The sand fraction (0.063–2.00 mm) was separated by wet sieving with distilled water and further divided into sub-fractions by mesh size using standard sieves. The silt and clay fractions (<0.063 mm) were separated by sedimentation with 0.05 mol/L sodium pyrophosphate (Na₄P₂O₇) as a dispersing agent. All measurements were performed in replicates, and the results were expressed as weight percentages of sand, silt, and clay. The analytical error of particle size determination did not exceed 5%.

The determination of soil organic matter (SOM) content was conducted using the oxidimetric method, as specified in DSTU 4289:2004. Air-dried soil samples (0.2 g), crushed and passed through a 0.25 mm sieve, were treated with 10 cm³ of a chromic acid mixture (0.4 M potassium dichromate in concentrated sulphuric acid) and heated at 150–160 °C for 20 minutes. The titration was performed using a Mohr salt solution with 0.2% phenylanthranilic acid as an indicator.

2.3. Indicators of Soil Structural Stability and Degradation Risk

To assess the resilience and degradation potential of soils affected by explosive impacts and anthropogenic disturbance, the soil structural index (St) was calculated following the

equation [27]:

$$St, \% = \frac{SOM}{Clay + Silt}$$

where SOM is the soil organic matter content (%), and clay and silt are the respective particle-size fractions (%), determined via granulometric analysis.

The St index serves as an indicator of soil structural stability and risk of degradation.

The following classification thresholds were applied based on established criteria [21]:

St < 5% – loss of soil structure and high susceptibility to erosion,

St = 5–7% – unstable structure and risk of degradation,

St > 9% – stable and well-structured soil.

The silt-to-clay ratio (Silt/Clay) is a widely used parameter in soil science to characterise soil texture and assess structural properties. It is calculated as the ratio of the percentage of silt particles (0.002–0.063 mm) to that of clay particles (<0.002 mm), determined through particle size distribution analysis following standardised procedures [9]. This ratio serves as an indicator of soil structural stability, erodibility, and susceptibility to sealing or crusting.

Higher Silt/Clay values are generally associated with soils more prone to structural degradation and erosion, particularly under mechanical or hydrological stress. In contrast, lower values may indicate better aggregate cohesion due to the binding properties of clay minerals [33, 36].

2.4. Statistical Analysis

All experimental data were processed using Statistica 10 software (StatSoft Inc., USA). The measurements were conducted in five replicates per sample. For each parameter, the arithmetic mean ($\bar{x}$) and standard deviation (SD) were calculated to describe the central tendency and data dispersion. The statistical significance of the differences between natural and disturbed soil samples was assessed using one-way analysis of variance (ANOVA) at a significance level of $p \leq 0.05$.

3. Results

3.1. Particle Size Redistribution Under Military Disturbance

Table 2 presents comparative data on particle size distribution in undisturbed (natural) versus explosion-affected (disturbed) soils collected from bomb craters. The results indicate significant textural changes across all soil types.

In Albic Arenosols (Loamy Coarse Sand), sand content decreased from 82.45% to 80.21%, primarily due to reductions in VCS and CS. These losses were offset by increases in FS, VFS, silt, and clay fractions. Notably, VFS content rose from 3.85% to 9.93%, indicating substantial aggregate frag-

mentation. Luvic Greyzems (Silt Loam) exhibited a dominant silt fraction (55.09%), which increased slightly to 56.87% after disturbance. Meanwhile, sand decreased from 31.30% to 29.15%, while VFS and FS increased moderately (e.g., VFS from 4.14% to 6.41%). In Luvic Chernozems (Loam), textural shifts were less dramatic. The sand content decreased from

34.25% to 31.66%, while silt and clay showed slight increases. Haplic Chernozems (Clay Loam) demonstrated the most substantial enrichment in clay (from 33.63% to 34.98%) and silt (from 38.11% to 40.20%), coupled with a decline in total sand (–3.44%), primarily from reductions in VCS and CS fractions.

Table 2. Changes in particle size composition of soils in military-affected areas.

Particle size fraction	Nature texture (NT)					Destroyed texture (CR)				
	$\bar{x}$	Max	Min	SD $\pm$	VC %	$\bar{x}$	Max	Min	SD $\pm$	VC %
Albic Arenosol Loamy Corse Sand										
Sand	82.45	85.57	79.33	2.51	3.05	80.21	83.14	77.28	2.36	2.94
VCS	16.16	16.93	15.39	0.62	3.81	13.37	14.03	12.71	0.53	3.95
CS	27.50	28.61	26.39	0.89	3.24	22.32	23.07	21.57	0.61	2.72
MS	22.23	23.25	21.21	0.82	3.70	18.22	19.05	17.39	0.67	3.66
FS	12.71	13.43	11.99	0.58	4.59	16.37	17.20	15.54	0.67	4.08
VFS	3.85	4.29	3.41	0.35	9.18	9.93	10.76	9.10	0.67	6.73
Silt	11.15	11.61	10.69	0.18	1.61	12.77	13.15	12.39	0.30	2.38
Clay	6.40	6.68	6.12	0.23	3.55	7.02	7.34	6.70	0.26	3.68
Luvic Greyzems Silt Loam										
Sand	31.30	32.28	30.32	0.79	2.52	29.15	30.18	30.52	0.83	2.85
VCS	4.39	4.82	3.96	0.34	7.82	2.06	2.34	2.47	0.23	10.96
CS	9.91	10.37	9.45	0.37	3.78	7.13	7.68	5.24	0.45	6.26
MS	6.32	6.75	5.89	0.34	5.46	5.13	5.69	5.70	0.45	8.78
FS	6.54	6.95	6.13	0.33	5.01	8.42	9.10	6.82	0.55	6.52
VFS	4.14	4.59	3.69	0.36	8.71	6.41	7.17	9.02	0.62	9.60
Silt	55.09	55.89	54.29	0.64	1.16	56.87	57.61	42.68	0.60	1.05
Clay	13.61	13.89	13.33	0.23	1.69	13.98	14.31	23.96	0.26	1.88
Luvic Chernozems Loam										
Sand	34.25	35.35	33.15	0.89	2.59	31.66	32.80	30.52	0.92	2.91
VCS	4.67	5.15	4.19	0.34	8.25	2.88	3.29	2.47	0.33	11.36
CS	7.17	7.62	6.72	0.42	5.01	5.62	6.00	5.24	0.31	5.49
MS	7.56	7.98	7.14	0.47	4.50	6.23	6.76	5.70	0.42	6.81
FS	6.83	7.35	6.31	0.53	6.13	7.42	8.02	6.82	0.48	6.49
VFS	8.02	8.60	7.44	0.64	5.87	9.51	10.00	9.02	0.39	4.15
Silt	41.81	42.47	41.15	0.39	1.27	43.66	44.64	42.68	0.79	1.80
Clay	23.94	24.74	23.14	0.36	2.68	24.68	25.40	23.96	0.58	2.36
Haplic Chernozems Clay Loam										
Sand	28.26	29.13	27.39	0.70	2.49	24.82	25.81	23.83	0.80	3.21
VCS	2.05	2.31	1.79	0.21	10.31	1.35	1.53	1.17	0.14	10.68

Particle size fraction	Nature texture (NT)					Destroyed texture (CR)				
	$\bar{x}$	Max	Min	SD $\pm$	VC %	$\bar{x}$	Max	Min	SD $\pm$	VC %
CS	3.42	3.76	3.08	0.28	8.06	1.95	2.19	1.71	0.19	9.82
MS	4.54	4.98	4.10	0.35	7.77	3.14	3.46	2.82	0.26	8.15
FS	8.01	8.57	7.45	0.45	5.61	7.56	8.11	7.01	0.44	5.84
VFS	10.24	10.95	9.53	0.57	5.60	10.82	11.43	10.21	0.49	4.57
Silt	38.11	38.94	37.28	0.67	1.75	40.20	40.96	39.44	0.61	1.51
Clay	33.63	34.50	32.76	0.70	2.07	34.98	35.49	34.47	0.41	1.17

Note: $\bar{x}$ – mean; Max – maximum value; Min – minimum value; SD – standard deviation; VC – coefficient of variation. Differences are statistically significant at $p \leq 0.05$; Fisher's test.

Table 3 demonstrates the shifts in particle-size fractions, reflecting intense physical fragmentation caused by explosive forces. All soil types demonstrated increases in very fine sand (VFS), particularly in Albic Arenosols (+6.08%) and Luvic Greyzems (+2.27%), indicating the breakdown of coarser particles into finer constituents. The most pronounced reduc-

tions in total sand content were observed in Haplic Chernozems (–3.44%) and Luvic Chernozems (–2.59%). Concurrently, increases in silt and clay content across all soil types—most notably in Haplic Chernozems (silt: +2.09%, clay: +1.35%)—suggest an accumulation of finer material resulting from the disintegration of aggregates.

Table 3. Soil particle-size fractions differences between natural (NT) and disturbed (CR) soils (calculated as $NT - CR$, expressed in absolute percentage values).

Soil particle– size fractions	Soil types			
	Albic Arenosol Loamy Corse Sand	Luvic Greyzems Silt Loam	Luvic Chernozems Loam	Haplic Chernozems Clay Loam
Sand	-2,24	-2,15	-2,59	-3,44
VCS	-2,79	-2,33	-1,79	-0,70
CS	-5,18	-2,78	-1,55	-1,47
MS	-4,01	-1,19	-1,33	-1,40
FS	3,66	1,88	0,59	-0,45
VFS	6,08	2,27	1,49	0,58
Silt	1,62	1,78	1,85	2,09
Clay	0,62	0,37	0,74	1,35

3.2. Changes in Soil Organic Matter and Structural Indices

All soil types experienced a reduction in SOM after disturbance (Table 4). The most significant relative decrease occurred in Albic Arenosols, where SOM dropped by 55%

(from 1.82% to 0.82%). The smallest loss was found in Haplic Chernozems (–36%).

The St declined in all cases, falling below the 5% erosion-risk threshold post-disturbance. The most pronounced decline in St, from 10.39% to 4.13%, was observed in Albic Arenosols, indicating a shift from structural stability to a degradation-prone condition.

Table 4. Changes in SOM, St, and Silt/Clay in natural (NT) and explosion-disturbed (CR) soil textures.

Type of Soil	Nature texture (NT)			Destroyed texture (CR)		
	SOM, %	St, %	Silt/Clay	SOM, %	St, %	Silt/Clay
Albic Arenosols Loamy Corse Sand	1.82	10.39	1.74	0.82	4.13	1.82
Luvic Greyzems Silt Loam	2.76	4.02	4.05	1.49	2.11	4.07
Luvic Chernozems Loam	3.61	5.49	1.75	2.39	3.49	1.77
Haplic Chernozems Clay Loam	4.46	6.21	1.13	2.85	3.79	1.15

Differences are statistically significant at $p \leq 0.05$; Fisher's test.

3.3. Silt/Clay Ratio Stability

Despite the above changes, the Silt/Clay remained relatively stable (Table 4). Disturbance tended to decrease this ratio in both sandy (Albic Arenosols) and heavy clay (Haplic Chernozems) soils. For instance, in Luvic Greyzems, it changed only slightly—from 4.05 to 4.07—indicating limited redistribution between these fine fractions even under intense disturbance.

4. Discussion

The data confirm that military-induced explosions result in significant redistribution of soil particles, with pronounced losses in coarse fractions and enrichment in finer particles across all profiles (Table 2). Sandy soils (e.g., Albic Arenosols) were most susceptible to fragmentation, exhibiting marked increases in VFS and losses in coarse sand, which confirms their high vulnerability to mechanical stress [5].

Loamy and silty soils, such as Luvic Greyzems and Luvic Chernozems, exhibited more moderate textural shifts, suggesting a degree of resistance to catastrophic disaggregation. These observations support findings indicating intra-fractional redistribution without complete structural collapse [28, 31].

Haplic Chernozems, due to their high clay content, exhibited increased compaction and enrichment of the fine fraction. This supports the notion that fine-textured soils are predisposed to secondary compaction and porosity loss under mechanical shock [3].

Table 3 reinforces these patterns, showing consistent declines in VCS and CS fractions as indicators of structural collapse from explosive pressure, consistent with earlier studies [15, 36].

The decline in SOM across all soils confirms direct combustion losses during explosions. Despite minor inputs from dust and plant residues within craters, SOM recovery was incomplete, especially in light-textured soils (Table 4). These

findings align with previous studies that described long-term SOM deficits in disturbed profiles [13, 32].

St was identified as a sensitive indicator of degradation, with all profiles falling below the 9% stability threshold [21], indicating increased susceptibility to erosion. These findings align with studies that underscore the diagnostic importance of St in assessing soil degradation [27].

Recent studies [17] confirm that even in the presence of surface-level organic inputs, mechanical disruption triggers aggregate collapse and heightened erosion risk—a finding validated here by the consistent decline in St.

Interestingly, the Silt/Clay remained largely unaffected. This suggests that while mechanical disturbance disrupts macro-aggregates, the fundamental distribution of fine particles is relatively conserved. These results are in agreement with reports showing minimal impact of physical stress on the silt/clay balance [36].

Finally, although partial pedogenesis may occur in cratered soils through dust deposition and plant colonisation [8, 30], the primary degradation signals remain tied to SOM loss and loss of aggregate stability, rather than particle size ratios. The importance of organo-mineral associations in maintaining structure and fertility is once again underscored [5, 23].

5. Conclusions

These findings contribute to a better understanding of the ecological impact of explosive events on soils and provide a scientific basis for the development of land restoration strategies and erosion control measures in post-conflict regions. From an agronomic perspective, the decline in soil organic matter and aggregate stability directly threatens soil fertility, crop productivity, and the sustainability of agroecosystems. Soils with degraded structure are more prone to compaction, reduced water infiltration, and erosion, all of which can severely limit their agricultural potential. Therefore, identifying vulnerable soil types and implementing targeted remediation is crucial for ensuring long-term soil health and food security in war-affected areas.

Abbreviations

CR	Bomb Crater
NT	Undisturbed Reference (Nature) Sites
SOM	Soil Organic Matter
St	Structural Saturation Index
Psd	Particle Size Distribution
C	Clay
Si	Silt
S	Sand
VFS	Very Fine Sand
FS	Fine Sand
MS	Medium Sand
CS	Coarse Sand
VCS	Very Coarse Sand
ANOVA	One-Way Analysis of Variance
$\bar{x}$	Mean
Max	Maximum Value
Min	Minimum Value
SD	Standard Deviation
VC	Coefficient of Variation

Author Contributions

Liudmyla Vasylenko: Conceptualization, Funding acquisition, Project administration, Supervision

Liudmyla Yashchenko: Data curation, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing

Oleksandr Androshchuk: Software, Validation, Visualization

Yuliya Chornoivan: Investigation, Resources

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Conflicts of Interest

The authors declare no conflicts of interest.

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