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THE RESTORATION OF FRUIT AND VEGETABLES GROWING ON LAND AFFECTED BY MILITARY OPERATIONS IN SOUTHERN UKRAINE

S u m m a r y

Background. Military operations in southern Ukraine have caused severe degradation of agricultural soil, leading to reduced fertility, disrupted structure, contamination and increased salinity. These changes threaten the sustainability of fruit and vegetable production and regional food security. Existing studies emphasize the need for integrated restoration approaches; however, there remains a lack of experimentally validated, comprehensive methodologies that combine biological, agrotechnical and ameliorative measures. This study aimed to assess soil degradation processes and compare the effectiveness of three restoration strategies – minimal intervention, biological remediation and comprehensive restoration – under real farming conditions in the Kherson, Mykolaiv and Zaporizhzhia regions.

Results and conclusions. An initial soil analysis revealed significant fertility decline: humus decreased to 2.1 % (vs. 3.4 % in control), nitrogen to 0.12 %, phosphorus to 58 mg/kg and potassium to 82 mg/kg, alongside increased compaction and reduced water permeability. Among the approaches tested, minimal intervention showed limited improvement (humus went up to 2.3 %; recovery effect ≈ 12 %). Biological remediation produced a moderate gain (humus up to 2.8 %; effect ≈ 55 %), demonstrating the role of organic inputs and microbial activity. The most effective approach was comprehensive restoration, combining biological, chemical and physical measures, which increased humus to 3.2 % and achieved an 84 % recovery effect. This approach also significantly improved nutrient balance, reduced salinity and restored soil structure. The findings confirm that isolated mineral fertilization is insufficient for degraded soil, whereas integrated technologies ensure faster and more stable recovery. The study highlights the importance of site-specific, multi-component restoration strategies as a foundation for post-war agricultural rehabilitation and long-term soil productivity in affected regions.

Key words: Agrotechnical measures; biological remediation; fertility; humus; integral effect; land degradation

Introduction

Military actions on the territory of Ukraine have caused significant destruction of agricultural landscapes, leading to a loss of soil productivity and creating risks to food

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security, especially in the southern regions, where agriculture is traditionally based on the use of fertile black soil and irrigation systems, and the leading industries are fruit and vegetable growing. Mechanical damage, contamination and disruption of soil structure and water regime have necessitated the development of scientifically sound approaches to their restoration.

The theoretical basis for studying transformation processes in damaged soil covers changes in humus content, macroelements of nutrition and physical properties, as well as the ability of agroecosystems to self-regenerate. The issue of land degradation is considered in scientific discourse through the prism of ecological, agrochemical and economic consequences, which requires a comprehensive interdisciplinary approach that considers biological activity, restoration of fertility and soil resistance to stress factors [35, 36]. Under these conditions, it is necessary to find remediation technologies that combine biological, agrotechnical and ameliorative measures, considering the level of degradation, the nature of damage and the economic feasibility of their implementation. A substantial scientific task remains the analysis of existing research, which evaluates the effectiveness of different approaches and identifies gaps that require further study.

Shahini et al. [59, 60] emphasize that war has significant, long-term and often irreversible consequences for the environment and human health. The study highlighted that the environmental consequences of military operations manifest themselves in the degradation of natural resources, disruption of ecosystem relationships and reduced land productivity. At the same time, the study has practical significance, as it is considered the basis for planning reconstruction programs in affected areas, including the restoration of ecosystems and natural resources. The researchers emphasize that effective solutions to environmental problems are only possible with a comprehensive approach that takes into account both global and local factors. This is highly relevant for the restoration of fruit and vegetable growing in southern Ukraine, as these activities should be based not only on agrotechnical solutions, but also on a broad ecological vision for the restoration of affected lands.

Kucher and Kucher [31] conducted a bibliometric analysis of scientific works devoted to the impact of war on soil. The study identified the main areas of research: mechanical damage, chemical contamination and changes in physical and chemical properties. The study highlighted the lack of comprehensive land restoration methods combining biological, agrotechnical and ameliorative measures, and pointed to the need for further experimental research.

The consequences of war for Ukraine's agricultural land were examined by Nasibov et al. [46]. The study emphasized that military actions lead to the large-scale degradation of soil cover, the destruction of the humus layer and reduced productivity of agroecosystems. At the same time, they propose directions for agroecological adaptation that could form the basis for the restoration of fruit and vegetable growing on damaged land.

The issue of post-war land restoration in a local context was considered by Didenko [8]. The study analyzed the experience of different countries and concluded that the most effective approaches are the integrated ones that combine biological, agrotechnical and chemical measures to restore degraded soil. Chumachenko et al. [6] addressed the territories of eastern Ukraine, where comprehensive recultivation was tested using mechanical loosening, organic fertilizers and biological products. The study demonstrated that this technology contributes to the partial restoration of fertility even on significantly damaged land. Kalander et al. [29] analyzed the consequences of chemical soil contamination and its impact on the ability of vegetation to support self-recovery processes. The results of the study indicated that without additional restoration measures, soil loses its long-term productivity.

Splodytel et al. [64] studied the long-term effects of mechanical and chemical damage in combat zones in Ukraine. The study concluded that the use of traditional agricultural methods alone does not restore fertility and requires a comprehensive approach. Shebanina et al. [62] assessed the level of contamination of Ukrainian soils before and after the military aggression. The study determined that the intensity of contamination had increased several times, especially in terms of heavy metals and other toxicants. This proved the need for systematic monitoring and implementation of programs for the ecological restoration of agricultural land. Shebanin et al. [61] addressed the issue of restoring the fertility of soil damaged by the war as a substantial factor in Ukrainian food security. The study emphasized that this requires a combination of agrotechnical measures, biological remediation and long-term programs for sustainable land management. The authors confirm that the restoration of agricultural potential in the affected areas is only possible with a comprehensive approach. The global impact of armed conflicts on land use was studied by Zheng et al. [67]. The study determined that wars lead to the degradation of agricultural land and significant changes in the structure of land use in border regions around the world.

Ma et al. [34], using the example of Ukraine with the application of remote sensing and GIS, showed an uneven decline in fertility and transformation of agricultural landscapes. The study confirmed that even within one country, the consequences of armed conflict have varying intensity and spatial dynamics. E. Lin's work [32], dedicated to Cambodia, examines the impact of unexploded ordnance on soil condition. The author proved that physical and chemical damage reduces agricultural productivity in the long term, creating persistent environmental risks. Research by Gamayunova et al. [19] identified significant changes in the fertility structure of soil in southern Ukraine, manifested in a decrease in humus content and the deterioration of agrochemical indicators. The study emphasizes the need for the systematic implementation of agrotechnical and biological measures to restore land productivity, which is particularly relevant for regions affected by military actions.

As demonstrated by the results of a study by Markova et al. [37, 38], one of the most significant factors in increasing agricultural productivity in Ukraine is the introduction of modern irrigation systems. In southern Ukraine, where military actions have destroyed the irrigation infrastructure, the restoration and modernization of irrigation systems is key to the revival of fruit and vegetablegrowing. The study argued that rational water supply can compensate for fertility losses and reduce the risks of further soil degradation.

Biyashev et al. [2] present the results of a chemical analysis of soil in the combat zone. The study determined a significant increase in the concentration of toxic compounds, a decrease in humus content and deterioration in soil structure. These data confirm the profound degradation of land and justify the need for biological remediation and other restoration measures to restore soil productivity.

Thus, an analysis of existing studies showed that the impact of military conflicts on soil was studied at both local and global levels, but most studies focused on the specific aspects of mechanical or chemical damage, changes in land use or the use of remote sensing. Despite numerous experimental and analytical studies, there remains a lack of developed methodology for comprehensive soil fertility restoration in post-conflict conditions that would combine biological, agrotechnical and ameliorative approaches, accounting for the specifics of damage and local agroecosystems.

The study aimed to evaluate the effectiveness of different technological approaches to restoring soil damaged by military actions in southern Ukraine and to identify the most effective strategy for improving soil fertility and stabilizing agricultural production properties. To this end, the following tasks were set: to identify degradation processes and key indicators of soil fertility, to compare the results of applying different restoration methods, and to determine the integral effect of a comprehensive approach on the state of agroecosystems.

Materials and methods

Research on the restoration of fruit and vegetable growing on land affected by military operations was conducted in the southern regions of Ukraine using the actual production facilities of OLVIA Farm Association (Kherson region) [17], Tavria Agroindustrial Company LLC (Mykolaiv region) [33] and Shvetsa Pavla Farming (Zaporizhzhia region) [63]. The selection of these enterprises was determined by several factors. First, they specialize in growing fruit and vegetable crops in a risky farming area using irrigation, which makes them typical representatives of agricultural production in southern Ukraine. Secondly, these farms have different agricultural landscape conditions, ranging from the alluvial soils of the Dnipro terrace to the chestnut and dark chestnut soils of the steppe zone, which can be used to assess the impact of military operations on different types of soil cover. Thirdly, some of their land has suffered damage of varying degrees, ranging from local contamination with heavy metals,fuel and lubricants to disruption of the structure of the arable layer and secondary salinization due to the destruction of irrigation infrastructure. This differentiation created experimental conditions close to the real production situation and to test restoration technologies incorporating various degradation scenarios. Field surveys and soil sampling were conducted in April-June 2025, and laboratory analyses in July-August 2025.

At the first stage, a comprehensive assessment of soil degradation factors was conducted on the test sites. A total of 68 soil samples were collected, including 22 samples from the OLVIA Farm Association (Kherson region), 24 samples from the lands of Tavria Agroindustrial Company LLC (Mykolaiv region) and 22 samples from the plots of Shvetsa Pavla Farming (Zaporizhzhia region). The selection was conducted in the areas of sinkholes, compaction, burnout and salinization, which ensured a representative coverage of various types of damage. The field surveys were conducted using a route method with sampling within the identified areas of degradation. Each of the 68 samples represented a composite soil sample formed from several individual subsamples collected within a visually homogeneous degradation zone at a depth of 0-20 cm, after which the material was pooled, mixed and analyzed as one laboratory sample.

Visual signs of damage were recorded in each zone, including the destruction of the structure of the arable layer, the formation of cracks, the presence of foreign debris and changes in soil color and odor. The samples were taken using a hand-held Eijkelkamp Agrisearch Equipment drill (Netherlands, 2019) and then analyzed in a laboratory. The content of heavy metals (Pb, Cd, Zn, Cu) was determined by atomic absorption spectrophotometry using the AAnalyst™ 400 device (PerkinElmer, USA, 2020) in accordance with DSTU ISO 11047:2005 [12]. The degree of salinity was assessed by the conductometric method using the EC 3000 device (WTW, Germany, 2018) based on the electrical conductivity of the soil water extract in a 1:5 ratio. At the same time, the actual results were compared with the regulatory values of maximum permissible concentrations (MPC) based on the Methodology for conducting agrochemical passportization of agricultural land by O.N. Sokolovsky Institute of Soil Science and Agrochemistry [50].

To determine the initial level of soil fertility, an agrochemical analysis was performed on samples taken from a depth of 0-20 cm. The humus content was determined using the Tyurin method, which is based on the oxidation of organic matter with a chromium mixture and titration of excess potassium dichromate [10]. Total nitrogen was determined by the Kjeldahl Method using a classical chemical method with the conversion of nitrogen to ammonium sulfate and its titration [47]. Mobile phosphorus was determined by a classical colorimetric method and exchangeable potassium by a flame photometric method in accordance with state standards. The physical properties of the soil, in particular its granulometric composition, density and water permeability, were assessed using the Kachinsky method, known for its scientific validity [11]. For comparison, control samples from undamaged areas were used: 22 samples from each study area, for a total of 66 samples, which made it possible to objectively assess the impact of different types of degradation on the physical characteristics of the soil.

In the second stage, three technological options for soil restoration were developed, each of which differed in the intensity and complexity of agrotechnical measures. Option 1 (minimal intervention) involved basic soil cultivation (ploughing to a depth of 25 cm, disc harrowing) and the application of mineral fertilizers according to the N60P60K60 scheme, which corresponds to the recommended doses for improving fertility in southern Ukraine [13]. Option 2 (biological remediation) included sowing green manure crops of white mustard, peas and phacelia, followed by ploughing in the green mass. White mustard was selected as a fast-growing green manure crop capable of rapidly forming above-ground biomass, improving soil structure through its root system, reducing nutrient leaching and providing a phytosanitary effect due to the biological activity of cruciferous residues. Peas, in particular, enrich the soil with 80-120 kg/ha of biological nitrogen and $2.5 \div 4.0$ t/ha of organic matter after ploughing [25]; phacelia is recommended to be sown in autumn in the southern region, as even after winter frosts, it can rot and act as mulch and an organic fertilizer [52]. Additionally, organic fertilizers (30 t/ha of cattle manure) were applied, and microbiological preparations based on *Azotobacter* and *Bacillus subtilis* were used to promote nitrogen fixation and enhance the agroecological potential of soil. Option 3 (comprehensive restoration) combined biological remediation with land improvement measures: in the presence of salinity, gypsum (3 t/ha) was applied, deep chisel ploughing was performed and drip irrigation systems were partially restored to optimize the water regime and increase the efficiency of crops.

To quantify the degree of visible soil degradation, a field degradation index was additionally used. Four degradation components were assessed for each study area: mechanical disturbance expressed as craters or funnels, soil compaction, burnout of the surface layer and secondary salinization. Each component was scored on a five-point scale from 0 to 4, where 0 indicated the absence of the feature, 1 weak manifestation, 2 moderate manifestation, 3 strong manifestation and 4 very strong manifestation. The total degradation index was calculated as the sum of the four component scores and could therefore range from 0 to 16 conventional units. The index was used as a diagnostic field tool for comparing the relative intensity and structure of degradation between the study areas, rather than as a universal standardized soil-quality index.

The experimental plots were established based on a factorial design with three replicates, with each technology option being implemented on an area of 0.1 ha. The allocation of restoration options to plots was performed using a stratified field approach rather than complete randomization. Before the establishment of the experimental plots, the sites were grouped according to the dominant degradation factors, including salinization, compaction, burnout and mechanical disturbance. Within each comparable degradation group, the three restoration options were assigned to plots with three replicates, while also considering practical field constraints, such as irrigation access, plot configuration and the possibility of applying gypsum or deep chisel ploughing. This approach ensured that the compared options were tested under broadly comparable degradation conditions, while reflecting real production limitations. Crops were selected based on zonal specialization: Rio Grande table tomatoes, California Wonder sweet peppers, Almaz eggplants, as well as fruit and berry crops such as peaches, apricots and apples.

The effectiveness of restoration was assessed based on changes in agrochemical indicators and crop yields. For this purpose, the soil fertility restoration index was used, calculated using the formula (1):

$$\mathrm{I}_{restor} = \frac{\mathrm{P}_{after} - \mathrm{P}_{before}}{\mathrm{P}_{reference} - \mathrm{P}_{before}} \times 100\ \% \qquad (1)$$

where: P_{after} – value of the indicator after restoration measurements, P_{before} – value before restoration, a $P_{reference}$ – average value for undamaged soil in the region.

The data were processed using descriptive statistical procedures, including the calculation of arithmetic means, absolute differences, percentage changes relative to the initial condition and control plots and the soil fertility restoration index (Irestor). Comparisons between restoration options were based on the dynamics of key agrochemical and physical indicators across the three replicated plots for each technological option. Since the study focused on a field-based comparative assessment under production conditions, the results were interpreted mainly through descriptive comparisons rather than through broad inferential generalization. Data visualization was performed using bar charts.

Results

An initial analysis of soil in the study areas revealed various types of degradation caused by military operations. Areas with mechanical damage, local compaction, burnout and secondary salinization were identified, as well as areas with increased chemical stress. These observations formed the basis for comparing the effectiveness of the soil restoration technologies used.

Table 1 presents summarized indicators of the chemical and physical condition of soil at three production bases, including heavy metal content, soil solution reaction, humus fraction, the availability of essential nutrients, electrical conductivity and bulk density. The approximate maximum permissible concentrations or reference ranges are also provided, which facilitates the assessment of the degree of deviation of actual values from normative parameters and the identification of priority areas for remedial measures.

Table 1. Agrochemical and physical indicators of soil before restoration (baseline survey)

Reference [unit]	MPC/Reference*	OLVIA Farm Association (Kherson region)	Tavria Agroindustrial Company LLC (Mykolaiv region)	Shvetsa Pavla Farming (Zaporizhzhia region)
Lead Pb [mg/kg]	32	28.0	35.0	31.0
Cadmium Cd [mg/kg]	0.50	0.62	0.40	0.55
Zinc Zn [mg/kg]	100	95	110	140
Copper Cu [mg/kg]	55	50	58	62
pH (H_2O) pH scale	6.5 ÷ 7.5 (reference)	7.9	7.6	8.2
Humus % (Tyurin)	≥ 3.0 (preferable)	2.1	1.8	1.6
Total N [%]	0.15 ÷ 0.20	0.13	0.11	0.10
Mobile P [mg/kg]	≥ 25 ÷ 30	18	15	12
Exchangeable K [mg/kg]	≥ 120 ÷ 150	110	95	90
EC 1:5 [mS/cm]	≤ 0.40 (unsalted)	0.85	0.65	1.20
Density of composition [g/cm³]	1.20 ÷ 1.40	1.45	1.48	1.55

Explanatory notes: MPC/reference values are presented as reference guidelines for arable loamy soils with a neutral to slightly alkaline reaction; specific thresholds depend on the granulometric composition and pH. Total N refers to total nitrogen content in soil, expressed as a percentage. Mobile P denotes plant-available phosphorus, expressed in mg/kg of soil. Exchangeable K refers to the exchangeable form of potassium available for plant uptake, expressed in mg/kg of soil. EC 1:5 denotes the electrical conductivity of a soil-water extract prepared at a 1:5 soil-to-water ratio and is used as an indicator of soil salinity.
Source: compiled by the author based on [32, 19, 37, 17].

The baseline diagnostic assessment showed that the studied soils were affected by a combination of chemical and physical degradation factors. The most important limiting factors were local exceedances of heavy metal thresholds, alkaline soil reaction, increased electrical conductivity, reduced humus content, insufficient nutrient availability and the compaction of the arable layer. These changes indicate that the degradation was not limited to a single factor, but reflected the combined effects of mechanical disturbance, salinization, contamination and a loss of organic matter. Therefore, the subsequent restoration strategy had to address both chemical fertility and the physical condition of the soil.

Assessing the initial fertility of soil was crucial for determining their restoration potential and developing an effective strategy for recultivation measures. Humus content and nitrogen, phosphorus and potassium reserves are basic indicators of soil ability to support crop growth, while physical properties such as particle size distribution, density and water permeability directly affect aeration, moisture retention and erosion resistance [21, 27]. An analysis of these parameters revealed the extent to which degradation processes have disrupted the balance of nutrients and the physical structure of the soil, and helped to determine restoration priorities, ranging from improving the organic component to correcting physical characteristics. The summary results of the study are presented in Table 2.

Table 2 presents averaged fertility indicators for the experimental plots selected for the restoration trial and the corresponding undamaged control plots. These values are not calculated as a simple arithmetic mean of the three farm-level diagnostic values shown in Table 1. Table 1 characterizes the initial agrochemical and physical condition of the most visibly degraded zones at each production base, whereas Table 2 summarizes the baseline fertility status of the experimental plots used for the comparative restoration assessment.

Table 2. Soil fertility indicators before restoration

Indicator	Experimental plots	Control plots	Optimal value*
Humus content [%]	2.1	3.4	3.5 ÷ 4.5
Total nitrogen [%]	0.12	0.21	0.20 ÷ 0.25
Mobile phosphorus [mg/kg]	58	92	90 ÷ 120
Exchangeable potassium [mg/kg]	82	138	130 ÷ 180
Density of composition [g/cm³]	1.46	1.28	1.20 ÷ 1.30
Water permeability [mm/hour]	5.8	9.4	≥ 8.0

Explanatory notes: The optimal values are given based on generalized data from agrochemical standards.
Source: compiled by the author based on [2, 17, 38].

The comparison between experimental and control plots confirmed a substantial decline in soil fertility in the degraded areas. The main agronomic limitations were associated with reduced organic matter reserves, lower nitrogen, phosphorus and potassium availability, increased bulk density and poorer water permeability. These patterns indicate that the productive capacity of the affected soil was constrained not only by nutrient depletion, but also by the structural deterioration of the arable layer. This justified the use of restoration measures combining organic inputs, biological remediation, ameliorative practices and physical loosening.

To assess the practical effectiveness of different approaches to reclamation, three technological scenarios were compared in terms of their expected impact on the key indicators of fertility restoration. These indicators – humus, N-P-K availability, electrical conductivity of water extract (EC 1:5) as a marker of salinity, and compaction density as an indicator of physical degradation – directly determine the ability of soil to support crops and its stress resistance. Table 3 summarizes the composition of each variant and provides an integrated quantitative assessment of their effect in the form of a recovery index (Irestor) according to Formula (1), which highlights which scenario provides the greatest progress in the 1st season and in the 2nd ÷ 3rdseason.

Table 3. Technological options for soil restoration, key measures and expected integral effect (Irestor [%])

Variant	Key measures	Expected integral I_{restor} [%] (1st season → 2nd÷3rd season)
1. Minimum intrusion	Ploughing 25 cm, disc harrowing; mineral fertilization N60P60K60	32 → 36
2. Biological remediation	Green manure (mustard, peas, phacelia); cattle manure 30 t/ha; microbial preparations (*Azotobacter*, *Bacillus subtilis*)	28 → 55
3. Multimodal restoration	Option 2 + gypsum application 3 t/ha (depending on salinity); chiseling; partial restoration of drip irrigation	53 → 84

Explanatory notes: sources: formed by calculations using Formula (1) based on the initial data in Tables 1 ÷ 2.

A comparison of the three scenarios revealed significant differences in both the speed and depth of recovery of key soil indicators. After just one season, the integral recovery index (Irestor) for the comprehensive option reached 53 %, which significantly exceeds the minimum intervention (32 %) and biological remediation (28 %). Over 2-3 seasons, the difference increases: the comprehensive approach grows to 84 % (Δ+31 p.p.), biological remediation to 55 % (Δ+27 p.p.) and minimal intervention to only 36 % (Δ+4 p.p.). Thus, a maximum growth is achieved where physical and chemical barriers (salinization, compaction) are removed and biological potential is increased.

The post-restoration indicators presented in Table 4 confirm that the comprehensive restoration option produced the most balanced improvement across both agrochemical and physical soil parameters. Biological remediation mainly improved humus accumulation and nutrient availability, whereas the comprehensive option additionally reduced salinity and bulk density. This indicates that the highest restoration effect was achieved when biological measures were combined with ameliorative and physical interventions.

Table 4. Agrochemical and physical indicators of soil after restoration under different technological options, Season 3

Indicator	Before restoration	Minimal intervention	Biological remediation	Comprehensive restoration	Reference/control value
Humus content [%]	2.10	2.30	2.80	3.20	3.40
Total nitrogen [%]	0.12	–	0.20	0.21	0.21 ÷ 0.22
Mobile phosphorus [mg/kg]	58	75	85	95	92 ÷ 100
Exchangeable potassium [mg/kg]	82	–	130	145	138 ÷ 150
EC 1:5 [mS/cm]	0.90	0.80	0.70	0.45	0.40
Bulk density [g/cm³]	1.46	1.44	1.40	1.32	1.28
Water permeability [mm/hour]	5.80	–	–	–	9.40

Explanatory notes: "–" indicates that the value was not explicitly reported in the current dataset and should be completed using the authors' primary calculations if available. EC 1:5 denotes the electrical conductivity of a soil-water extract prepared at a 1:5 soil-to-water ratio.

In terms of organic matter, the initial humus deficit was 1.7 percentage points (2.1 % compared to the reference value of 3.8 %). Over 2 ÷ 3 seasons, biological remediation compensated for about 0.7 percentage points (2.8 %), which corresponds to ≈ 41 % of the gap elimination, while the comprehensive option compensated for ≈1.1 percentage points (3.2 %) or ≈ 65 % of the deficit. Minimal intervention showed only a marginal increase (≈ 0.1 percentage points in the first season), indicating the weak effect of mineral nutrition alone on the restoration of the soil carbon pool. Therefore, the accumulation of organic matter is an inertial process and requires systematic biological and ameliorative actions.

The dynamics of nutrients are also differentiated. For nitrogen, the initial gap (0.12 % vs. 0.22 %) was reduced by ≈ 80 % in the biological and ≈ 90 % in the complex variants (to 0.20 ÷ 0.21 %) over 2 ÷ 3 seasons, while the minimum scheme provided mainly short-term improvement without a lasting effect. For mobile phosphorus (58 mg/kg → reference 100 mg/kg), the complex approach reached ≈ 95 mg/kg (≈ 88 % gap elimination), the biological approach ≈ 85 mg/kg (≈ 64 %), while minimal intervention provided only an intermediate level after the first season (≈ 75 mg/kg). A similar picture for potassium (82 → 150 mg/kg): the comprehensive option brings the indicator to ≈ 145 mg/kg (≈ 93 % of the gap eliminated), biological to ≈ 130 mg/kg (≈ 71 %). This indicates that the combination of organic sources, green manure and corrective ameliorative measures creates a synergy of N-P-K availability that is difficult to achieve with mineral nutrition alone.

Physical and chemical limitations proved to be critical. In terms of the electrical conductivity of the aqueous extract (EC 1:5), the initial level of 0.90 mS/cm was reduced to ≈ 0.45 mS/cm in the complex variant (≈ 90 % of the gap to the reference value of 0.40 mS/cm was overcome), in the biological variant to ≈ 0.70 mS/cm (≈ 40 %), and in the minimum variant to ≈ 0.80 mS/cm (≈ 20 %). This difference reflects the key role of gypsum application and irrigation restoration in the redistribution of sodium/salts and profile flushing; without these measures, biological practices work, but are hampered by the salt barrier. In terms of bulk density (1.46 → 1.28 g/cm³), chiseling in the complex scenario reduced the indicator to ≈ 1.32 g/cm³ (≈ 78 % reduction), while the biological option reached ≈1.40 g/cm³ (≈ 33 %), and the minimum was ≈ 1.44 g/cm³ (≈ 11 %). This confirms that the restoration of the structure of the arable layer requires mechanical compaction in combination with biological "bonding" of aggregates with organic matter [5, 30].

A pattern can be observed across variants: when high EC and increased density are maintained (minimum scheme), the response to mineral nutrition is limited, and the root system operates under the stressful conditions of osmotic pressure and air deficiency. Biological remediation gradually removes structural constraints and increases humus, but progress slows down in the presence of salinity. Only comprehensive intervention simultaneously removes salt and physical barriers, opening a "window of opportunity" for mineral and organic nutrition and accelerating the approach to reference parameters [22, 23, 44].

From the point of view of time dynamics, the minimum option demonstrates a "fast but shallow" effect, which tends to plateau after the first season. The biological approach is characterized by cumulativeness: the effect increases in the second and third season along with the accumulation of organic matter and the stabilization of microflora [48; 49]. The complex option combines a quick start (due to land reclamation and mechanical compaction) with subsequent biological stabilization, which explains the highest integral indicator. Thus, the interpretation of the numerical values in Table 3 shows that in the cases where degradation is caused not only by nutrient depletion, but also by salinization and compaction, priority should be given to comprehensive measures; if biological depletion dominates without significant salinization, biological remediation may be a sufficient basis; the use of mineral nutrition alone without the correction of physicochemical barriers provides a partial and unstable effect.

Assessing the effectiveness of restoration measures requires the quantitative determination of changes in the key soil fertility indicators. One such indicator is humus content, which reflects the organic matter reserve and the soil ability to self-regenerate. An analysis of humus dynamics compared the effectiveness of technological options for restoration (minimal intervention, biological remediation and comprehensive restoration) and assessed the integrative effect of the applied agrotechnical and ameliorative measures. The data are shown in Figure 1.

The data obtained indicate significant differences in the impact of restoration technologies on soil humus content. Minimal intervention resulted in an increase in humus content from only 2.1 % to 2.3 % (+ 0.2 percentage points), which corresponds to a humus-specific recovery of approximately 12 %; however, as shown by the integral restoration index used in Table 3, the overall restoration effect of this option in the 3rd Season was 36 %. Biological remediation showed a significantly higher growth result, from 2.1 % to 2.8 % (+0.7 percentage points, index 55 %), confirming the effectiveness of green manure and microbiological preparations. The most noticeable effect was achieved by comprehensive restoration: humus content increased from 2.1 % to 3.2 % (+1.1 percentage points, index 84 %), which indicates the synergistic effect of biological, ameliorative and water measures and their impact not only on the accumulation of organic matter, but also on the improvement of the physical properties of the soil.

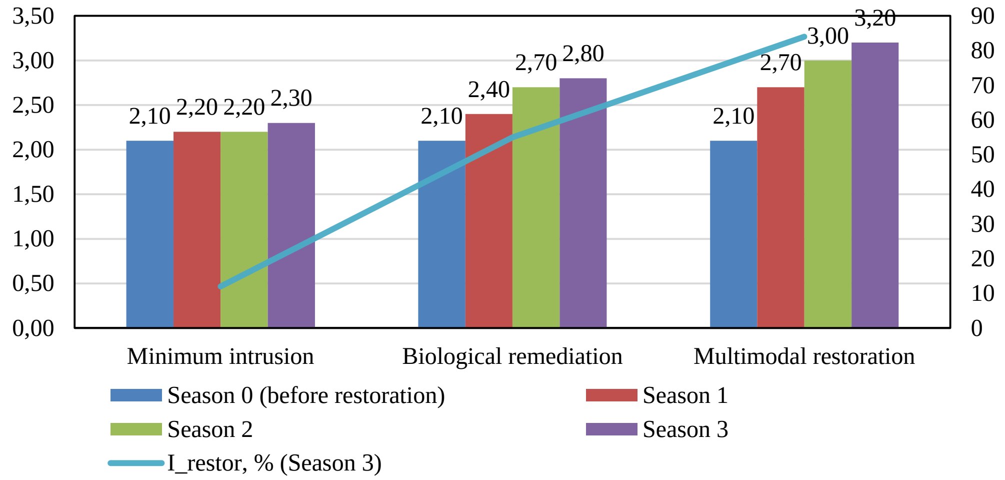

Figure 1. Dynamics of humus content (%) by technology options
Explanatory notes: sources: calculations using Formula 1 based on [12, 33, 63].

A comparison of indicators between the options indicates a linear relationship between the complexity of measures and the rate of humus composition recovery: each additional intervention (biological, ameliorative, water) significantly increases the effectiveness of the processes, and the maximum result is achieved with an integrated approach. The difference between options 1 and 3 is + 0.9 percentage points, which reflects the practical significance of including green manure, organic fertilizers and land reclamation for the restoration of degraded soil in southern Ukraine. Thus, the analysis demonstrated that the assessment of humus changes is a reliable integrated indicator of the effectiveness of restoration technologies, and comprehensive soil restoration provides the most stable and long-lasting effect, adjusting damaged areas to the reference indicators of undamaged soil.

Data on the degree of soil degradation are presented in Figure 2, which illustrates the spatial heterogeneity of damage in the study areas. They reflect the integrated impact of mechanical damage, secondary salinization and burnout on agroecosystems and can identify critical areas for priority restoration.

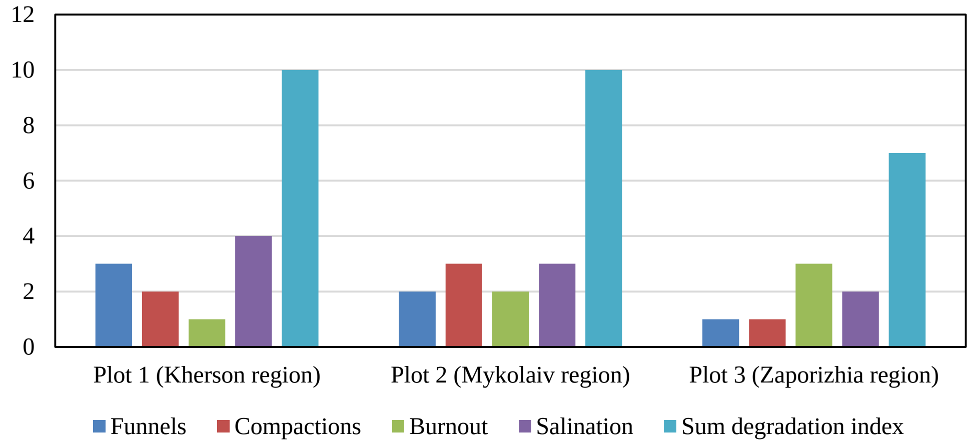

Figure 2. Soil degradation degree
Explanatory notes: based on the author's field research.

An analysis of the total soil degradation index shows significant differences in the nature and intensity of the impact of military operations on the agricultural landscapes of the southern regions. Areas in the Kherson and Mykolaiv regions have the same total index of 10 conventional units, but the structure of degradation factors differs. In the Kherson area, salinization (4) and local mechanical damage in the form of craters (3) prevail, indicating a strong local impact of explosive or destructive actions and disruption of the water regime due to damage to irrigation infrastructure. Soil compaction (2) and burnout (1) are additional, but are not decisive.

In the Mykolaiv area, despite the same total index (10), soil compaction (3) and salinization (3) are more significant, which, together with moderate burnout (2) and local craters (2), reflects a more uniform, but large-scale mechanical impact on the soil cover, probably associated with the movement of heavy equipment and partial disturbance of the structural layers of the arable horizon. This configuration of degradation factors indicates the need to apply restoration technologies capable of simultaneously correcting soil compaction and salinization. The site in the Zaporizhzhia region has a lower total index (7 conventional units), which is due to a lower level of pitting (1) and compaction (1), an average level of burnout (3) and moderate salinization (2). This indicates a relatively moderate mechanical impact and weaker damage to the structural and chemical properties of the soil, but at the same time, burnout is substantial, indicating local losses of organic cover and changes in the water balance.

A comprehensive review of the total index and individual components of degradation made it possible to assess not only the absolute level of damage, but also the specifics of its formation, which is critical for planning priority restoration measures. The Kherson site requires a focus on salinity correction and water regime restoration, the Mykolaiv site requires comprehensive measures to reduce compaction and partially restore soil structure, while the Zaporizhzhia site primarily requires biological restoration measures to restore organic matter and stabilize the topsoil. This differentiated assessment can be used for the integration of field observations and laboratory data, which ensures more accurate prioritization of degraded agricultural landscapes for restoration.

The results of the study at the first and second stages quantified the initial condition of the soil, identified the main factors of degradation and compared the effectiveness of different technological approaches to restoring fertility. The study demonstrated that comprehensive measures combining biological remediation with land reclamation and water regime optimization ensure the maximum restoration of humus and organic matter in the soil, while minimal intervention has a limited effect. The degree of soil degradation shows significant heterogeneity within regions, which determines the need for a differentiated approach to the implementation of restoration technologies. The data obtained lay the foundation for further comparison of agrochemical indicators, crop yields and the integrative index of soil fertility restoration.

Discussion

The study established the effectiveness of various technological approaches to restoring degraded soils in the southern regions of Ukraine and determined the impact of comprehensive agrotechnical, biological and chemical measures on improving fertility and stabilizing agricultural production properties. The identified changes in humus, nitrogen, phosphorus and potassium indicators, as well as improvements in the soil physical characteristics, indicate the potential of integrated methods in restoring agroecosystems after war damage. The comparison identified the aspects in which the results confirm existing ideas about soil degradation and recultivation, and those in which they demonstrate new trends or differences that could be relevant for the development of practical recommendations and methodological approaches. Such an analysis contributed to the research of the mechanisms of fertility restoration, assessed the consistency of the results with foreign and local studies and identified potential gaps that require further study.

Similar results were obtained by a group of scientists led by Bulba et al. [4] in an analysis of soils in the Dnipropetrovsk, Mykolaiv and Zaporizhzhia regions and found significantly higher levels of toxic substances than the maximum permissible concentrations. In addition to chemical changes, the authors recorded deterioration in the physical and chemical properties of the soil, an increase in acidity and compaction of the top layer. They propose systematic monitoring, the use of environmentally friendly technologies and the implementation of programs for the restoration and recultivation of affected land. The results of the study are relevant for the development of measures to restore fruit and vegetable growing in southern Ukraine, as they confirm the need for a comprehensive approach to overcoming the consequences of soil degradation caused by military actions.

An analysis of the impact of conflicts on land use demonstrated that changes in the structure of land resources are largely determined by a combination of anthropogenic and natural factors [39]. These conclusions were made by Zong et al. [68] after studying the potential for land use conflicts in the coastal zone of the Bohai Sea. Their results resonate with the conclusions of the presented study regarding the need to address local characteristics when planning restoration measures on degraded soil.

Mhanna et al. [40] applied machine learning and remote sensing to track land use changes in areas affected by armed conflict. The study demonstrated that land degradation occurs unevenly and depends on the type of damage, confirming the conclusions of this work: integrated measures can increase fertility and stabilize the physical properties of soil in different conditions. Thus, Mhanna et al. [40] and the results of the new study demonstrate the importance of a differentiated approach to recultivation, although the current work additionally assesses the integral effectiveness of technologies through a scoring system. The sustainable management of damaged soil fertility was highlighted by Raghavendra Goud et al. [53], noting the effectiveness of green technologies, in particular the application of organic fertilizers and biological products. Ajmal et al. [1] addressed similar issues, investigating the adaptation of bacteria to heavy metals in soil and their ability to support plant growth. Both approaches reflect the key role of biological factors in the restoration of degraded land and are consistent with the results of this study, where biological remediation significantly increased humus content and the integral effect. At the same time, the newer studies contributed to an assessment of the physical parameters of soil and a comparison of the effectiveness of different technologies in the specific conditions of southern Ukraine.

Mosier et al. [42] studied the restoration of degraded land through perennial crops aimed at ensuring food, energy and climate security. The results are consistent with the position of this study on the need for a comprehensive approach that combines biological, agrotechnical and chemical measures. At the same time, the presented study differs in its more detailed assessment of the effectiveness of individual technologies using an integrated scoring system, which improves the accuracy of the comparison of results and the selection of optimal soil restoration strategies in specific agricultural landscapes.

Rathi et al. [55] systematized existing strategies for restoring soil fertility and emphasized the key role of integrated technologies, including organic fertilization and agronomic measures. These results reveal conceptual similarities with the conclusions of the current study, which also confirms the need for a comprehensive approach, although the newer study contributed to an assessment of the effectiveness of specific measures using an integrated scoring system, which improves the accuracy of the comparison of their effects in different agricultural landscapes. A similar perspective was considered by Mrunalini et al. [43] in an analysis of nature-based solutions for soil restoration, such as the use of cover crops, mulching and biological remediation. The results of their study are partly consistent with the presented research, which also found a high effect of biological measures, but the newer article expanded the analysis to include an integrated assessment of physical and chemical soil parameters.

Similar results were obtained by Ukrainian scientists Markova et al. [38], addressing mechanisms for reducing heavy metal toxicity in soil through agricultural techniques and the use of fertilizers. The authors emphasize that such methods are critical for regions with high levels of pollution, particularly on land affected by military operations. This creates opportunities for the safe restoration of fruit and vegetable growing and for ensuring the ecological quality of products [51, 54].

The role of biological products in increasing the yield of vegetable crops and restoring soil fertility in the Southern Steppe of Ukraine is highlighted by Nikonchuk and Samoilenko [46]. The results of the studies confirm that biological products can be an effective tool for biological remediation and restoration of soil fertility, as they stimulate plant growth and increase crop resistance to adverse conditions. The use of biological technologies can become a substantial component of the strategy for restoring vegetable growing in the southern region of Ukraine, particularly on soil that has been degraded as a result of military operations.

Jinger et al. [28] demonstrated the effectiveness of agroforestry in India for the rehabilitation of degraded land, reflecting the practical benefits of multifunctional systems. Similar results are observed in the current study: combining agrotechnical and biological methods increases fertility stability and restores the structure of agricultural landscapes. At the same time, the newer study contributed to an assessment of the spatial differentiation of the effectiveness of methods and the influence of local climatic and soil factors.

In eastern and southern Ethiopia, the effectiveness of planting local trees, terracing and creating grass strips was confirmed by Eshete et al. [16] and Semere et al. [58]. The results demonstrated that comprehensive measures tailored to local conditions ensured more sustainable soil restoration. A similar pattern is evident in the presented study, where multi-component technologies had an advantage.

Sekhohola-Dlamini et al. [57] and Misebo et al. [41] considered phytosanitary and natural land rehabilitation through plant systems and restrictions on economic use. The conclusions emphasized the importance of biological soil stabilization, which is consistent with the results obtained. At the same time, the analysis of physical and chemical parameters improved the accuracy of the assessment of the effectiveness of individual measures in different agricultural landscapes.

The potential of specific plant species for stabilizing and restoring degraded land was investigated by Truong [65] in an analysis of the use of vetiver grass on saline soils. This approach confirms consistency with the conclusions of the current study on the feasibility of using adapted plant species to increase soil stability, however, the new study combined this biological method with agrotechnical and organic measures for an integrated effect.

Dwijendra [14] analyzed the implementation of green infrastructure for the rehabilitation of degraded land in urbanized areas of Bali, focusing on the challenges and role of universities in this process. The results presented are consistent with the integrated restoration approach, where the integration of environmental and management measures is seen as a key factor in improving the sustainability of territories. This highlights the significance of a multi-level system of performance criteria that can be used for the assessment of not only the physical parameters of soil, but also the organizational conditions for the implementation of restoration strategies [15]. Supporting this theme, Bojago [3], in a study on the restoration of degraded land in Ethiopia, emphasized the need to balance the technical and socio-economic aspects of rehabilitation. The results are similar to the conclusions of the presented study, which also emphasizes the importance of taking into account local agricultural landscapes and climatic factors when choosing recultivation methods. Similar approaches were demonstrated by Gholamhosseinian et al. [20], who investigated the role of biological soil crusts in maintaining soil viability and forming a plant-friendly environment. The difference in the newer study is that its assessment also includes physicochemical indicators of soil and integrates biological and agrotechnical measures, which provides a more comprehensive assessment of the restoration effect. In the context of global crises related to wars, Roy Chowdhury et al. [56] emphasized the deterioration of the food-energy-ecosystem balance as a result of conflicts, which directly affects land degradation. These observations are consistent with the presented study, which also found that conflicts accelerate degradation processes and require a more systematic approach to agricultural landscape restoration.

Local causes of soil degradation, in particular agronomic irrationality and construction activity, were highlighted in studies by Gafurova and Juliev [18] and Dai et al. [7]. The study proposed targeted measures to minimize these impacts, emphasizing that individual methods do not guarantee long-term fertility stabilization. Technical and biological solutions must be integrated, as confirmed by the results obtained, where comprehensive strategies demonstrated the greatest effectiveness.

The significance of conservation tillage and water regime maintenance as key factors in soil fertility and sustainability was noted by Hussain et al. [26] and Diop et al. [9]. These approaches were consistent with the analysis conducted, but were supplemented by the integration of nature-based methods, which covered not only physical and chemical parameters, but also biological parameters, ensuring more systematic restoration of degraded land.

Hossini et al. [24] emphasized the multifactorial nature of erosion and land degradation processes, highlighting the importance of assessing geographical, climatic and anthropogenic factors. The presented study supports this concept, integrating it with the assessment of the effectiveness of specific agrotechnical and biological measures in different agricultural landscapes. Additionally, the study by Tsuchiya et al. [66] highlighted the role of an interdisciplinary approach in assessing soil degradation and implementing rehabilitation measures, confirming the consistency of the new study with current trends: a comprehensive combination of agrotechnical, biological and nature-oriented methods ensures the effective restoration of land productivity and the stabilization of ecosystems.

Summarizing the analysis, it is possible to note that studies in the field of degraded land restoration demonstrate a high variability of approaches, while highlighting several common patterns. The effectiveness of recultivation measures largely depends on the complexity of methods, the integration of physicochemical and biological measures, as well as adaptation to local agricultural landscapes, climatic conditions and the type of soil degradation. A comparison of the presented study with the work of other scientists showed that most authors addressed the need to combine technical, biological and nature-oriented solutions, however, the newer study expands this approach by assessing the effectiveness of measures comprehensively, incorporating both local environmental features and the scale of degradation.

Conclusions

1. The study quantified the fertility of soil degraded by military operations and assessed the effectiveness of various technological approaches to soil restoration. The study determined that soil initial parameters deviated significantly from the

optimal values: the humus content was only 2.1 % compared to 3.4 % in the control areas, total nitrogen was 0.12 % compared to the norm of 0.20 ÷ 0.25 %, mobile phosphorus was 58 mg/kg against the optimal 90 ÷ 120 mg/kg, exchangeable potassium was 82 mg/kg against 130 ÷ 180 mg/kg. Physical properties also indicated deterioration in agrophysical condition: density was 1.46 g/cm³ (with an acceptable range of 1.20 ÷ 1.30 g/cm³) and water permeability decreased to 5.8 mm/hour, which is below the minimum threshold of 8.0 mm/hour.

2. The assessment of dynamics under different intervention options revealed differences in the pace and scale of recovery. Under the conditions of minimal intervention (ploughing and mineral fertilization N60P60K60), humus content increased from 2.10 % to 2.30 %, which corresponds to only a 12 % increase. The integral fertility index increased slightly from 32 to 36 points. With biological remediation (green manure, organic fertilizers and microbial preparations), a humus growth reached 2.80 % and relative recovery was 55 %, with the soil fertility restoration index (Irestor) increasing from 28 % in the first season to 55 % in the second and third season. The highest effect was achieved by comprehensive restoration, where, due to the combination of biological and ameliorative measures, the humus content rose to 3.20 %, which corresponds to 84 % restoration, and the integral assessment increased from 53 to 84 points.
3. Thus, the results confirmed that the isolated use of mineral fertilizers is ineffective for degraded soil. In contrast, biological approaches ensured noticeable recovery of key indicators after just three seasons, and a comprehensive combination of agrotechnical, organic and ameliorative measures facilitated the achievement of benchmark fertility parameters. The limitation of the study is the focus on physicochemical parameters without the consideration of soil biota, which requires further research. A promising direction is the assessment of the long-term effect of technologies on the productivity of fruit and vegetable crops, as well as the improvement of combined remediation models considering the climatic risks of the region.

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ODTWARZANIE PRODUKCJI WARZYW I OWOCÓW NA GRUNTACH DOTKNIĘTYCH DZIAŁANIAMI WOJENNYMI W POŁUDNIOWEJ UKRAINIE

Streszczenie

Wprowadzenie. Działania wojenne w południowej Ukrainie spowodowały poważną degradację gleb rolniczych, prowadząc do obniżenia ich żyzności, zaburzenia struktury, zanieczyszczenia oraz wzrostu zasolenia. Zmiany te zagrażają zrównoważonemu rozwojowi produkcji warzyw i owoców oraz bezpieczeństwu żywnościowemu regionu. Dotychczasowe badania podkreślają potrzebę stosowania zintegrowanych podejść do rekultywacji, jednak nadal brakuje eksperymentalnie zweryfikowanych, kompleksowych metod łączących działania biologiczne, agrotechniczne i melioracyjne. Celem pracy była ocena procesów degradacji gleb oraz porównanie skuteczności trzech strategii ich odtwarzania – minimalnej interwencji, rekultywacji biologicznej oraz kompleksowej rekultywacji – w rzeczywistych warunkach gospodarstw rolnych w obwodach chersońskim, mikołajowskim i zaporoskim.

Wyniki i wnioski. Wstępna analiza gleb wykazała istotny spadek ich żyzności: zawartość próchnicy obniżyła się do 2,1 % (w porównaniu z 3,4 % w próbach kontrolnych), azotu do 0,12 %, fosforu do 58 mg/kg, a potasu do 82 mg/kg, przy jednoczesnym wzroście zagęszczenia gleby i spadku jej przepuszczalności wodnej. Spośród badanych metod minimalna interwencja przyniosła ograniczone efekty (wzrost próchnicy do 2,3 %; efekt odtworzenia ≈ 12 %). Rekultywacja biologiczna zapewniła umiarkowaną poprawę (próchnica do 2,8 %; efekt ≈ 55 %), co potwierdza znaczenie materii organicznej i aktywności mikroorganizmów. Najwyższą skuteczność wykazała kompleksowa rekultywacja, łącząca działania biologiczne, chemiczne i fizyczne, która zwiększyła zawartość próchnicy do 3,2 % i osiągnęła 84 % efektu odtworzenia. Podejście to istotnie poprawiło również bilans składników pokarmowych, zmniejszyło zasolenie oraz przywróciło strukturę gleby. Wyniki potwierdzają, że stosowanie wyłącznie nawożenia mineralnego jest niewystarczające w przypadku gleb zdegradowanych, natomiast zintegrowane technologie zapewniają szybszą i bardziej stabilną regenerację. Badanie podkreśla znaczenie lokalnie dostosowanych, wielokomponentowych strategii rekultywacji jako podstawy powojennej odbudowy rolnictwa oraz długoterminowej produktywności gleb.

Słowa kluczowe: Zabiegi agrotechniczne, rekultywacja biologiczna, żyzność, próchnica, efekt zintegrowany, degradacja gleb