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Conceptual model of post-war restoration of agricultural land with integration of bioenergy technologies

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Abstract. Russia's full-scale military actions against Ukraine led to large-scale degradation of agricultural land, which was accompanied by mechanical destruction of soil cover, chemical pollution, and loss of productive potential. The lack of an integrated system of post-war reconstruction led to the need to form a comprehensive model of reclamation, combining environmental and economic tools within a single management approach. The purpose of the study was to develop a conceptual model of post-war restoration of agricultural land based on the integration of engineering, chemical, biotechnological, and economic approaches within the circular land use system. Analytical, comparative, and system structural methods, and conceptual modelling were used. As a result of the study, the

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scale of physical degradation of soil cover on de-occupied agricultural land was determined and a conceptual model of their agrobiological restoration using phytoremediation crops was proposed. A multi-level recovery model was formed, which included stages of humanitarian demining, technical preparation of the territory, pollution assessment, mechanical reclamation, chemical detoxification, biotechnological regeneration, and long-term phytoremediation with the integration of bioenergy technologies. The expediency of a 15-year phytoremediation cycle in the structure of reclamation with a gradual transition to an economically viable land use system was substantiated. A circular model of biomass processing was proposed, which provides for energy valorisation of phytomass and the return of stabilised products to the soil, ensuring partial or complete self-sufficiency of the recovery process. The practical viability of the model was demonstrated using the example of damaged agricultural land in the Snihurivka urban territorial community of Mykolaiv Oblast, where the bioenergy component was shown to generate a stable cash flow for partial compensation of engineering reclamation costs. The proposed model can be adapted to various types of belligerent agricultural landscapes and creates prerequisites for the development of financially stable reclamation mechanisms. It has the potential for practical application in Ukraine and other countries affected by military operations, and can become the basis for the development of national policies in the field of land restoration and sustainable development of the agricultural sector

Keywords: agrolandscapes; bioenergy crops; circular economy; ecological stabilisation; soil reclamation; phytoremediation; land detoxification

Introduction

Russia's full-scale invasion of Ukraine in 2022 caused a large-scale degradation of land resources. The fighting caused systemic damage to the ground cover: physical destruction as a result of explosions and compaction by equipment was combined with chemical contamination by ammunition detonation products, fuel and lubricants, and remnants of weapons. The high resistance of toxicants in soils has created risks of long-term withdrawal of land from agricultural circulation and has created long-term environmental and socio-economic consequences. Analysis of scientific sources showed that the war led to mechanical damage and prolonged chemical contamination of the soil, which, according to M. Gulich *et al.* (2024), may have a significant impact on ecosystem functions and food system security. T. Chaika & I. Korotkova (2023) noted that without systemic reproduction measures, degraded lands can lose their productive potential for a long period of time. This made it necessary to develop an integrated algorithm for post-war restoration of belligerent landscapes, which combined technical, chemical, and biotechnological tools.

The initial stage of post-war reconstruction provided for a comprehensive identification of the scale and spatial structure of soil cover damage. O. Bonchkovskyi *et al.* (2025) noted that the use of remote sensing data on the Earth's surface helped to quickly identify areas of mechanical disturbance and potential pollution, but stressed the need for further geochemical analysis to assess the risks of toxicant migration in the soil profile. Developing this approach, O. Drebot & O. Korol (2025) noted that the restoration of affected landscapes should be based on the integration of satellite monitoring with an assessment of the state of hydrological systems and biodiversity. The next logical step was to develop decontamination and remediation strategies. V. Samokhvalova (2024) proposed an algorithm that covered consecutive stages – from previous studies and environmental risk assessment to the implementation of measures to reduce pollutant concentrations. O. Mudrak *et al*. (2025) proved that the restoration of belligerently transformed landscapes required the harmonisation of ecosystem system management tools with reclamation and bioremediation measures. Effective implementation of the proposed recovery strategies requires a strong resource base. N. Didenko (2024) suggested that the implementation of comprehensive recovery strategies is impossible without long-term planning, the introduction of advanced technologies, and the attraction of significant financial resources. In turn, V. Naumchuk (2024) noted that the success of phytoremediation and other methods of soil restoration depended on a harmonious combination of environmental, social and economic aspects, in particular through the creation of public-private partnerships that could ensure stable financing of such projects. Special attention should be paid to the transition to adaptive management, which has become necessary for continuous monitoring and correction of recovery strategies. M. Melnykovych *et al*. (2026) identified several strategic ways of post-war reconstruction, among which the key was the use of digital tools to ensure the climate sustainability of landscapes, and the support of ecosystem services, which will contribute to the long-term restoration of land functions.

The final phases of soil restoration should combine environmental feasibility with economic efficiency. As noted by N. Martynova & T. Kolombar (2025), one of the promising areas was the use of phytoextraction involving fast-growing crops, which helped to simultaneously detoxify land and obtain biomass for renewable energy production. The analysis of scientific sources showed that, despite the presence of thorough research of individual technological and managerial decisions, there is no integrated conceptual model in the scientific discourse that would systematically combine the stages of primary damage diagnostics, engineering and chemical reclamation, biotechnological restoration, and the development of bioenergy clusters into a single logically completed system of post-war agricultural land reclamation. The purpose of the study was to substantiate the scientific and methodological foundations of post-war restoration of agricultural land damaged as a result of military operations, and to develop a conceptual model that would ensure ecological stabilisation of the soil cover and the development of an economically viable land use system. To achieve this goal, the following research objectives were defined: 1) to analyse contemporary scientific approaches and practices for restoring soils that have been exposed to military influence; 2) to develop an integrated model that combines engineering, chemical, and biotechnological reclamation measures; 3) to substantiate the economic feasibility of the model and assess its potential for self-financing through the integration of the bioenergy component. The scientific originality of the study was the development of an integrated approach to the post-war restoration of agricultural land, combining phytoremediation, bioenergy use of contaminated biomass, and the principles of circular economics to ensure economically sustainable reclamation of belligerent soils.

Materials and Methods

The study was conducted in 2025 using a systematic and interdisciplinary approach to the development of a conceptual model of post-war restoration of agricultural land damaged by military operations. Geographical coverage provided for the generalisation of international experience in the reclamation of territories affected by military influence (Bosnia and Herzegovina, Lebanon), and the analysis of contemporary practices of phytoremediation and environmental restoration in the EU countries based on scientific publications of C. Lievens *et al.* (2008), J. Vangronsveld *et al.* (2009) and N. Witters *et al.* (2012). The research drew on data from V. Samokhvalova (2024), who developed algorithms for selecting soil reclamation methods, determining the dosage of soil improvers and monitoring soil degradation under military and anthropogenic influences, and

O. Bonchkovskyi *et al.* (2025), which characterised physical disturbances and contamination of the soil cover in north-eastern Ukraine as a result of military operations and laid the basis for morphometric and geochemical assessment of belligerent agricultural landscapes. In addition, official documents of international organisations and other authors on the post-war restoration of agricultural territories were investigated. In particular, W. Verheye *et al.* (2007) discussed algorithms for surveying damaged land and spatial planning for restoration, whilst UNDP (2011) described practices relating to humanitarian demining and the return of agricultural land to productive use in the context of post-conflict recovery. The FAO report (2025) provided an assessment of the scale of degradation of agricultural landscapes and recommendations for the transition from operational mine clearance to integrated environmental reproduction strategies. These documents became an important methodological basis for substantiating the sequence of stages of the conceptual model and consideration of international experience in the development of approaches to the post-war restoration of agricultural land. In addition, analytical, comparative, and system structural methods were used to generalise international experience in land restoration, compare technological solutions for reclamation, and determine their relationships within an integrated model. The conceptual modelling method was used to develop a scheme for combining technical reclamation, chemical detoxification, phytoremediation, and bioenergy processing of biomass. The study considered the provisions of International Mine Action Standards (IMAS 01.10, 2003), UNMAS (n.d.) recommendations. Data from the NATO standards STANAG 2143 and STANAG 2449 presented in EOD publications – overview (n.d.), which regulated the requirements for the safety of cleaning up territories and assessing environmental risks in contaminated areas.

The conceptual model was developed as a consistent system of interrelated stages of land restoration, which included humanitarian demining, technical reclamation, chemical soil stabilisation, phytoremediation, and the use of biomass in bioenergy technologies in accordance with the principles of the circular economy ("Soil-to-Energy"). To substantiate the economic feasibility of the recovery model proposed in the study, a set of economic methods and approaches was applied. The cost calculation was used to determine the amount of financial resources required for the implementation of each technological stage of reclamation – from humanitarian demining to agrochemical land reclamation. The revenue approach was used to assess the economic potential of the bioenergy component of the model by determining the projected revenues from the sale of biofuels and by-products of its processing. Profit and profitability were calculated based on a comparison of gross income with operating expenses for growing crops and processing biomass, which allowed estimating net cash flow and the payback period for capital investments. These approaches provided verification of the financial stability of the conceptual model and its ability to gradually self-sufficiency. Morphometric analysis of explosive craters was performed using Google Earth data for a 122-hectare field in the Snihurivka urban territorial community (UTC) of the Mykolaiv Oblast. Identification of zones of mechanical disturbance of the soil cover was carried out by visual interpretation of images, measurement of morphometric parameters of craters – using the ImageJ programme (USA). The approximate depth of craters was estimated from the empirical ratio between the diameter and depth of explosive craters ($H \approx 0.4$ D) proposed in the study by J.P. Hupy & R.J. Schaetzl (2006). Based on the obtained parameters, the area of the mechanically disturbed surface and the approximate volume of displaced soil were determined. Statistical processing and visualisation of the results were performed in Python.

Results and Discussion

The developed conceptual model of post-war restoration of agricultural land was verified based on initial data of territories that were subjected to intense mechanical and anthropogenic impacts as a result of military operations in the south of Ukraine. The analysis of real conditions of soil cover destruction allowed structuring the reclamation process in the form of a consistent multi-level system that integrated engineering, chemical, biotechnological, and economic recovery tools. The proposed architecture of the model (Table 1) reflects the logic of the transition from primary stabilisation of the territory to long-term phytoremediation and the development of a bioenergy component, which ensured partial economic self-sufficiency of recovery measures.

Table 1. *Stages of implementation of the conceptual model of post-war restoration of agricultural soils*

Stage	Main activities	Goal and expected results
Initial stabilisation of the territory	Humanitarian demining; clearing the territory of man-made residues; levelling the surface	Ensuring the safe condition of the territory and preparing the soil cover for reclamation works
Environmental diagnostics of soils	Soil sampling; laboratory determination of heavy metals, radionuclides, and anthropogenic pollutants	Determining pollution levels and spatial structure
Mechanical reclamation	Filling craters with soil; surface planning; deep loosening of compacted areas	Restoration of topography and agrophysical properties of the soil
Chemical detoxification	Liming; application of sorbents (zeolites, activated carbon); introduction of phosphate meliorants	Immobilisation of toxicants and reduction of their bioavailability
Biological recovery	Application of organic meliorants; microbial inoculation; restoration of the soil microbiome	Increasing biological activity and soil fertility
Phytoremediation and bioenergy use of biomass	Cultivation of remediant plants and bioenergy crops; processing of biomass on the principle of "Soil-to-Energy"	Soil purification and development of economic self-sufficiency of reclamation

Source: based on P. Soudek *et al*. (2014), T. Steliga & D. Kluk (2021), N. Didenko (2024), O. Bonchkovskyi *et al.* (2025)

The initial and most critical stage of restoration was ensuring the safety of the territory and eliminating the consequences of direct mechanical destruction of the soil cover. At this stage, a set of measures for humanitarian demining and technical preparation of the territory was implemented. Humanitarian demining was carried out using advanced technologies for remote detection of explosive objects. The use of sapper drones equipped with magnetometers for detecting metal objects and thermal imagers for detecting thermal anomalies in the ground has allowed increasing the safety and efficiency of mine clearance compared to conventional methods. All mine clearance operations were carried out exclusively by certified operators in accordance with the International Mine Action Standards (IMAS 01.10, 2003) and UNMAS recommendations (n.d.), and national security protocols (Law of Ukraine No. 2642-VIII, 2018). When planning and executing the work, the technical requirements of NATO standards STANAG 2143 (AJP-3.15) and 2449 (AEODP-10) (EOD publications – overview, n.d.). A prerequisite for the transition to the next stages of reclamation was obtaining an official certification on the safety of the territory, which confirmed the absence of explosive objects and allowed further agricultural work.

Technical preparation of the territory and elimination of the remains of fortifications included several consecutive operations. The first step was a diagnostic scan of the territory with multispectral drones, which allowed detecting hidden remnants of military structures, metal accumulations, and other objects that are not noticeable during visual inspection of the surface. Multispectral scanning provided comprehensive information about the state of the surface and subsurface layer of the soil, which became important for planning further reclamation activities

(Qiu *et al*., 2023). Mechanised cleaning of large remnants of machinery, concrete fragments, and metal structures was carried out using specialised stone harvesting machines and heavy equipment (US Army Corps of Engineers, 2015). This operation helped to clear the territory of massive objects that could not be removed manually, and which prevented further agrotechnical operations, created a long-term environmental risk. Special attention was paid to the removal of concrete residues of fortifications, since they not only created physical obstacles, but could also be a source of secondary contamination of the soil with alkaline compounds. Magnetic separation of the upper soil layer was carried out using specialised trawls to extract small metal fragments and shrapnel. The method was based on the physical separation of metal-containing particles in a magnetic field. Its effectiveness in cleaning contaminated soils has been demonstrated in experimental studies by B. Caballero-Mejía *et al*. (2025). As noted by S.D. Young (2012), small metal fragments remaining in the soil were gradually oxidised in the soil solution, which could lead to the release of mobile forms of heavy metals. Such processes created prerequisites for long-term secondary soil contamination. In addition, the presence of a significant proportion of large solid fragments in the arable layer changed the physical properties of the soil and could affect the efficiency of its cultivation.

The final operation of the first stage of reclamation was the dismantling and planning alignment of lines of trenches, dugouts, and other military engineering structures. The development of defensive fortifications was accompanied by significant mechanical disturbances of the soil cover and transformation of the microrelief, which changed the natural structure of surface runoff, reduced the infiltration capacity of the soil, and disrupted the local water balance. The deformation of microtopography caused spatial unevenness of hydrological processes, which could manifest itself in the form of local waterlogging, stagnation of water or, conversely, excessive drainage of individual areas, which was confirmed in the study by D. Caviedes-Voullième *et al*. (2021) on the role of microrelief in surface runoff generation and moisture redistribution. Restoration of natural or agronomically optimised terrain by surface planning has become a necessary prerequisite for stabilising the hydrological regime, ensuring uniform distribution of moisture and nutrients, and forming homogeneous conditions for further agricultural use of the territory.

The second stage of soil cover reclamation was devoted to a comprehensive diagnosis of its condition and quantitative determination of the levels of contamination with various toxicants formed as a result of explosive and man-made impacts in the war zone. The study by M. Solokha *et al*. (2024) reported that military operations were accompanied by the accumulation of heavy metals, explosive components, detonation products, and fuel and lubricants in the soil, which made it necessary to systematically monitor and assess their spatial distribution. In addition, the authors noted that high concentrations of pollutants were observed in the epicentres of explosive impacts, where due to the localised accumulation of toxic components, their levels could exceed the background values. At this stage, systematic soil sampling was carried out, considering typical classification zones of pollution (crater zones and adjacent massifs). The use of standardised sampling methods guaranteed the representativeness of the sample for further laboratory analysis. Similar approaches have also been used in practical soil sampling protocols proposed by the US Army Corps of Engineers (2015). The density of sampling points varied depending on the size of the damaged area and the nature of pollution, but at least one sample per 100 m^2 within crater zones and one sample per 500 m^2 in buffer zones were recommended for a representative assessment of spatial heterogeneity, which provided a reasonable basis for quantifying pollution and subsequent reclamation measures.

According to the approach of S.D.Young (2012), laboratory analysis of the collected samples involved determining the concentrations of heavy metals, including lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni), and mercury (Hg), which are typical components of anthropogenic loading on soils under conditions of wartime impact. The assessment was carried out both by the gross content of metals and by their mobile (bioavailable) forms, since it was the latter that determined the level of environmental danger and the potential ability of plants to accumulate. X. Cao *et al.* (2003) found that mobile forms of Pb, Cd, Zn, and other metals were characterised by higher phytotoxicity compared to their stabilised compounds, which made it necessary to control them in agroecosystems. The determination of mobile forms was carried out by extraction with an acetate-ammonium buffer solution with a pH of 4.8, which allowed assessing the potential availability of metals for the root system of plants and the real level of soil toxicity.

The radiological survey of the territory included measuring the exposure dose rate of gamma radiation using field dosimeters-radiometers and laboratory determination of the specific activity of radionuclides in the soil, in particular Caesium-137 (^{137}Cs) and Strontium-90 (^{90}Sr). According to M. Solokha *et al.* (2024), the need for radiological monitoring was conditioned by the possibility of radioactive contamination due to the use of certain types of ammunition or conducting combat operations in territories with a previous anthropogenic load. Radionuclides ^{137}Cs and ^{90}Sr are characterised by the ability to be fixed in the soil profile and potentially included in biogeochemical cycles, which created a risk of their entry into plant products. P. Broomandi *et al.* (2020) noted that comprehensive radiological monitoring helped to identify areas of increased radiation danger in a timely manner and determine the feasibility of restrictions on further agricultural use of land. The analysis of chemical contaminants included the determination of residues of explosive compounds (TNT, RDX, HMX), their detonation products (nitrates, nitrites), and components of fuels and lubricants, in particular polycyclic aromatic hydrocarbons and petroleum products. These compounds became characteristic of areas of active military operations and were characterised by high toxicity to the soil microbiota, invertebrates, and plants. Their accumulation significantly slowed down the processes of natural self-regulation and biological restoration of soils. The accumulation of nitro compounds and petroleum products in the topsoil can lead to disruptions in microbial activity, changes in redox conditions, and alterations in the nutrient cycle (Gulich *et al.*, 2024). The results of analytical studies served as a scientific basis for developing targeted recommendations for choosing optimal methods of reclamation of a particular site, including phytoremediation, agrochemical, or engineering measures. Simultaneously, the detailed documented state of pollution of territories was of important legal importance, since it formed the evidence base for assessing environmental damage and justifying compensation claims in accordance with the principles of international environmental law and compensation for environmental damage.

The third stage was aimed at restoring the physical structure and spatial configuration of the soil cover, disturbed as a result of explosive impacts and the movement of heavy military equipment. Detonation of ammunition and mechanical loading caused the destruction of the aggregate structure, compaction, mixing of horizons and the development of crater forms of microrelief, which significantly changed the physical properties of soils. T.L. Chow *et al.* (2007) found that the choice of mechanical reclamation methods and the intensity of their application were determined by the mechanical composition of the soil and the degree of its compaction, since the ratio of sandy, dusty and clay fractions directly affected the restoration of water permeability and structural state. The return of ejected soil to craters has become a major mechanical reclamation operation. During the explosion, significant amounts of soil mass were removed from the epicentre of the detonation and formed peripheral mounds, while less fertile deep horizons were exposed at the bottom of the crater. The discarded top layer retained most of the organic matter and nutrients compared to the exposed subsurface layers, which substantiated the feasibility of its return to the place of its original occurrence. Surface planning and restoration of the microrelief created prerequisites for the development of a productive arable layer and stabilisation of the water regime. As noted by T.L. Chow *et al.* (2007), a mandatory element of this process was the preliminary cleaning of the soil mass from large debris, metal fragments, and foreign inclusions that affected the agrophysical properties of the soil and could complicate the further use of land.

The import of fertile chernozem from ecologically safe territories became a necessary measure in areas of greatest destruction, where the volume losses of soil mass could not be compensated only by the return of discarded material. The development of a clean starting layer with a thickness of 20-30 cm provided conditions for primary rooting of plants and reduced the risk of contact of the root system with increased concentrations of pollutants in crater zones. Imported soil must meet the agrochemical characteristics of zonal soil types, have an optimal content of humus and nutrients and do not contain quarantine weeds, pathogens or pests, which corresponded to the principles of environmentally safe reclamation. For areas that were significantly compacted due to the movement of heavy military equipment, deep loosening of 35-50 cm was applied using diesel units or heavy cultivators. The military load led to the destruction of the soil structure, an increase in volume mass, a decrease in porosity and water permeability, which negatively affected aeration and the availability of nutrients for plants. Violation of the physical parameters of the soil was directly associated with a decrease in the productivity of agrocoenoses, which was confirmed in the studies by T.L. Chow *et al.* (2007) on the impact of compaction on the water regime and crop development. Restoration of the optimal density and structure of arable and sub-arable layers has become a necessary prerequisite for effective phytoremediation and stabilisation of agrophysical properties of the soil at subsequent stages of recovery.

The fourth stage of recovery was crucial for reducing the toxicity of contaminated soils and minimising the risk of toxicants entering plant products. Unlike mechanical removal of pollutants, chemical reclamation was aimed at changing their chemical state and converting them to sedentary or bound forms by regulating the physical and chemical parameters of the soil environment. Liming using calcium carbonate ($CaCO_3$) has become the basic operation of chemical reclamation of acidic and slightly acidic soils that have been acidified under the influence of detonation products. According to M. Solokha *et al.* (2024), nitrogen and sulphur oxides were formed during the explosion, which formed nitric and sulphuric acids under moist conditions, causing a decrease in the pH of the soil solution. According to V. Samokhvalova (2024), the application of lime in doses of 3-8 t/ha, depending on the degree of acidification, provided neutralisation of acidity and created favourable conditions for the development of plants and soil biota. Increasing the pH also significantly affected the behaviour of heavy metals, contributing to their transition to poorly soluble hydroxide and carbonate compounds. As shown by S.D. Young (2012), the motility of Pb, Cd, and Zn was sharply reduced under conditions of neutral and slightly alkaline reaction of the medium, which minimised their bioavailability to plants.

Sorption soil purification was carried out by introducing highly porous materials with a developed specific surface area that can immobilise organic and inorganic toxicants. As noted by P. Broomandi *et al.* (2020), the use of activated carbon at doses of 5-10 t/ha provided effective adsorption of fuel and lubricants and detonation products, in particular polycyclic aromatic hydrocarbons and nitroaromatic compounds, which have become typical for combat areas. The sorption mechanism included physical retention of molecules in micropores and chemical interaction with functional groups on the surface of the sorbent, which reduced the concentration of organic toxicants in the soil solution and limited their migration to plants. The use of activated carbon has significantly reduced the bioavailability of organic pollutants already in the first growing season. Natural zeolites (clinoptilolite, mordenite) were used in doses of 10-15 t/ha to bind mobile forms of heavy metals and stabilise the physical and chemical properties of the soil. The framework structure of zeolites with a developed channel system provided a high capacity of cation exchange, which caused selective absorption of cations Pb^{2+}, Cd^{2+}, Zn^{2+} and other metals from the soil solution and their fixation in the mineral lattice. In addition to the detoxification effect, zeolites improved the water and physical characteristics of the soil, increasing its moisture capacity and buffering, which became an important factor in stabilising agroecosystems at the initial stages of recovery.

The introduction of phosphorite flour in doses of 3-5 t/ha provided chemical immobilisation of heavy metals, primarily lead and cadmium, by converting them into hard-to-dissolve phosphate compounds. X. Cao *et al.* (2003) noted that the stabilisation mechanism is associated with the development of poorly soluble minerals such as pyromorphite ($Pb_5(PO_4)_3Cl$) and other lead phosphates with extremely low solubility, which dramatically reduced the migration capacity of the metal in the soil solution. This approach, according to P. Broomandi *et al.* (2020), has become particularly effective for soils with a high Pb content, characteristic of areas of intense shelling. An additional advantage of phosphorite flour was the improvement of the phosphorous regime of the soil and the restoration of elemental balance in areas that have not been used in agricultural production for a long time. The use of bentonite clays as a natural sorbent with a high cationic exchange capacity contributed to the fixation of heavy metal cations and reduced their bioavailability. The layered structure of bentonites with an expandable interpackage space provided effective absorption of Pb^{2+}, Cd^{2+}, and Zn^{2+} cations and their retention in the mineral structure. Increasing the sorption capacity of the soil helped to stabilise its buffer properties and reduce the toxic load on plants, which corresponded to approaches to chemical reclamation of land disturbed as a result of military operations. In addition to the detoxification effect, bentonite materials improved the water retention capacity and structural condition of the soil, increasing its resistance to fluctuations in acidity and pollutant concentrations.

The fifth stage of the conceptual model was aimed at restoring the biological activity of the soil by regenerating its microbiome and improving its agrophysical properties. Biological degradation of soils in war zones was manifested by a decrease in microbial biomass, a violation of enzymatic activity, and a decrease in the content of organic matter. Therefore, a differentiated approach was applied, in which the composition of land reclamation plants was adapted to the soil and climatic conditions of a particular territory. To stabilise the water regime and activate biological processes in degraded soils at the initial stages of recovery, it was advisable to use a set of materials and biological measures aimed at increasing the water retention capacity, improving the structural state and forming a stable microbial environment. Depending on the hydrothermal conditions and physical properties of the soil, synthetic hydrogels, organo-mineral sorbents, porous natural minerals and microbiological inoculants can be used, the main characteristics of which are given in Table 2.

Table 2. *Technological measures to stabilise the water and biological state of belligerent soils*

Material/technological reception	Terms of use	Application dose	Functional role
Potassium polyacrylates and polyacrylamides	Arid regions, light soils	20-40 kg/ha	High water retention capacity; development of a hydrogel structure with gradual release of moisture

***Table 2.** Continued*

Material/technological reception	Terms of use	Application dose	Functional role
Biochar	Arid regions, light soils; areas with sufficient moisture	10-20 t/ha(dry conditions); 15-25 t/ha (sufficient moisture)	Improvement of soil structure; increase of water retention capacity; development of microenvironments for soil microorganisms; deposition of stable organic carbon
Basalt tuff	Arid regions, light soils	5-20 t/ha	Improvement of the structural state of the soil; development of a microporous environment for microflora; source of trace elements; improvement of buffer properties of the soil system
Microbiological inoculation (plant growth promoting rhizobacteria, PGPR)	Areas with sufficient moisture	1-2 l/ha, titre ≥10^8-10^9 CFU/ml	Activation of mineralisation of organic residues; improvement of nitrogen and phosphorus nutrition; development of a stable soil microbiome

Source: based on W.J. Rawls *et al*. (2003), J.K. Vessey (2003), J. Lehmann & S. Joseph (2015), L. Reczek *et al*. (2020)

The presented complex of materials and biological measures provided simultaneous stabilisation of the water regime, improvement of the structural state and activation of microbiological processes in the soil, which created prerequisites for further stages of phytoremediation and agro-ecological restoration of degraded territories. The sixth stage of the conceptual model provided for the implementation of a long-term strategy for cleaning the soil from residual concentrations of heavy metals with the parallel development of an economically feasible land use model. The use of phytoremediation in combination with bioenergy production helped to integrate environmental and economic goals of restoration of territories, transforming the reclamation process into a self-supporting bioenergy project. A 15-year crop rotation cycle using specially selected crops was recommended, aimed at gradually reducing the concentration of pollutants in the soil and simultaneously obtaining biomass for energy or technical needs (Martynova & Kolombar, 2025). The choice of such a planning horizon has become scientifically based and is conditioned by the need to go through three consecutive phases of reclamation: stabilisation (1-5 years) – for intensive phytoremediation and neutralisation of toxicants; regeneration (6-10 years) – for restoring the soil structure and accumulation of organic matter due to perennial grasses; adaptation (11-15 years) – for the transition to productive crop rotation and achieving full payback of costs. M.-C. Leewis *et al.* (2024) noted that this duration correlates with the international practice of restoring belligerent landscapes, where the period of complete soil rehabilitation after massive impact was at least 10-12 years.

The selection of phytoremediation crops was carried out according to the functional principle, considering the natural and climatic zone, the mechanical composition of the soil, the nature and intensity of pollution. Field crops with different biological and morphofunctional characteristics could perform the functions of phytoextraction, phytostabilisation, or structural and reclamation restoration of the soil. The efficiency of using industrial and energy crops on metal-contaminated lands was demonstrated in the studies by T. Vamerali *et al.* (2010) and M. Flajšman *et al.* (2023). Within the framework of the conceptual model, three main functional groups of crops were identified, which were used sequentially or in combination, depending on the degree of site degradation. Plant crops used in phytoremediation systems could perform the functions of both phytoextraction and phytostabilisation and structural restoration of the soil. The choice of crops was determined by their morphofunctional characteristics, their ability to accumulate metals or form significant biomass, and their adaptability to degraded soil conditions. The main crops used in such schemes are shown in Table 3.

Table 3. *Phytoremediation crops for the restoration of belligerent soils*

Crop	Main function	Biological features	Practical significance
Cannabis sativa L.	Phytoextraction	High biomass, developed root system, ability to accumulate Cd, Pb, Zn	Extraction of metals from the soil; use of fibre for technical needs
Helianthus annuus L.	Phytoextraction	Significant aboveground biomass, ability to accumulate Pb and Cd	Use in phytoextraction schemes; technical or energy use of oil
Brassica juncea L.	Phytoextraction	Fast growth, short growing season, high metal accumulation capacity	Use as an intermediate crop in phytoremediation crop rotations
Melilotus albus, M. officinalis	Phytostabilisation/ sideration	Nitrogen fixation (80-150 kg N/ha), powerful root system	Improving soil structure and increasing microbiological activity
Carthamus tinctorius L.	Structure development	Drought resistance, deep root system (up to 2-3 m)	Cultivation on degraded soils of the steppe zone
Sorghum bicolor L.	Phytostabilisation/ biomass	C4-photosynthesis, high productivity, drought tolerance	Obtaining biomass for bioenergy

Source: based on T. Vamerali *et al.* (2010), P. Soudek *et al*. (2014), T. Steliga & D. Kluk (2021), M. Flajšman *et al.* (2023)

In addition to the ecological function of soil purification and stabilisation, the use of plant crops in phytoremediation systems can provide biomass for energy or technical needs, which formed the economic basis of the reclamation process (Table 4). This integration of environmental and economic functions has become important for ensuring the financial sustainability of long-term reclamation projects, as conventional land reclamation programmes require significant external investment without guaranteed returns. The cultivation of bioenergy crops on contaminated land helped to obtain marketable products even at a time when the use of the territory for the production of food or fodder crops became unacceptable for environmental reasons. The combination of phytoremediation with the production of biomass for renewable energy can significantly increase the economic attractiveness of such projects and reduce their payback period. Thus, the bioenergy component acted not only as a source of income, but also as a mechanism that motivated land users to long-term compliance with phytoremediation crop rotation.

Table 4. *Bioenergy crops for economic support of reclamation*

Crop	Type of bioenergy products	Performance	Usage features
Brassica napus L.	Biodiesel	2.5-4.0 t/ha of seeds	Oil is used for the production of biodiesel; metals mainly accumulate in the vegetative organs
Miscanthus × ×*giganteus*	Solid biofuels	15-25 t/ha of dry biomass	Perennial crop with a plantation life of 15-20 years
Panicum virgatum L.	Biofuels/bioenergy biomass	10-20 t/ha of dry biomass	Tolerance to degraded soils and high efficiency of moisture use

Source: based on G. Knothe (2010), P. Soudek *et al.* (2014), N. Martynova & T. Kolombar (2025)

Thus, the cultivation of phytoremediation and bioenergy crops created a resource basis for further processing of biomass, which allowed integrating the ecological and energy functions of restoring territories. On this basis, a circular model of the use of biomass from reclaimed land ("Soil-to-Energy") can be implemented. The model will be based on the principles of a closed cycle, according to which all products and secondary processing flows were returned to the system or transformed into marketable products, which corresponded to the concept of a circular economy by M. Geissdoerfer *et al.* (2017). The biomass of remediant plants was collected in optimal terms, which ensured maximum accumulation of pollutants and the highest yield of target products. For oilseeds (*Brassica napus*, *Helianthus annuus*, *Carthamus tinctorius*), seeds were collected in the full ripeness phase, while the remaining plant mass could be used for mulching or energy processing. For green extractors (*Cannabis sativa*, *Brassica juncea*), all aboveground biomass was removed. Perennial energy crops (*Miscanthus × giganteus*, *Panicum virgatum*) were mowed after the complete drying of the aboveground part and the migration of nutrients to the rhizomes (late autumn – early spring), which reduced the nitrogen content of biomass and improved its fuel characteristics.

The production of biodiesel from oilseeds can be carried out using compact modular plants of small and medium capacity, which allowed organising processing directly at the level of farms or regional centres. G. Knothe (2010) pointed out that the process scheme was based on the transesterification reaction of vegetable oil triglycerides with methanol in the presence of an alkaline catalyst (NaOH or KOH) to form fatty acid methyl esters and glycerol as a byproduct. The yield of biodiesel under optimal conditions was about 96-98% by weight of oil, which corresponded to about 950-980 kg of fuel per 1 tonne of oil. The resulting fuel can be used to meet the farm's own energy needs or sold in accordance with the requirements of the EN standard 14214:2012+A2:2019 (2019). Raw glycerine after purification can be used in the chemical industry or other technical areas. Thermal processing of contaminated biomass (oilseed straw, extractor stalks, meal) was advisable by pyrolysis – thermal decomposition of organic matter without oxygen access at temperatures of 400-600°C (Bridgwater, 2012). As a result, a gaseous fraction (CO, H_2, CH_4), a liquid phase (bioolium), and a solid residue (biochar) were formed. The typical yield of biochar was 20-35% by weight of dry raw materials, depending on the temperature regime. The return of resources to the soil was carried out by introducing biochar obtained from relatively pure biomass (in particular, rhizomes of perennial grasses, characterised by limited transportation of heavy metals to the aboveground part). J. Lehmann & S. Joseph (2015) noted that periodic application of biochar in moderate doses (5-10 t/ha) contributed to the gradual restoration of fertility and stabilisation of the ecological state of reclaimed land. Detoxification and final removal of pollutants from the biological cycle was achieved through controlled disposal of the ash residue formed during pyrolysis of contaminated biomass. A.V. Bridgwater (2012) showed that during pyrolysis, inorganic components, including heavy metals, were concentrated in the solid residue. Such ash is not suitable for agricultural use, but it can be used in solid building materials technologies. B. Chen *et al.* (2024) noted that the fixation of heavy metals in a cement or alkali-activated matrix provided a significant reduction in their mobility and leaching risk, which is confirmed for ash products in the production of foam concrete and other cement-concrete mixtures. An alternative route was to stabilise highly polluted ash, followed by controlled disposal in accordance with hazardous waste management requirements.

The economic efficiency of implementing the proposed conceptual model was formed due to diversified sources of income and synergy between the ecological and production functions of land. Revenues were generated through the production of biodiesel from oilseeds and solid biofuels from perennial energy grasses, and through potential involvement in potential carbon incentive mechanisms. Economic verification of the bioenergy component of the model was carried out based on the V. Mesel-Veseliak (2015) approach, according to which winter rapeseed became the most productive link in crop rotation. Calculations were made using the method of cost balance of products of its deep processing, updated in accordance with market prices at the beginning of 2026. This scenario approach helped to assess the marginal economic potential of the system. With an average seed yield of 3.0 t/ha and a technological yield of methyl esters of

400 kg/t, about 1,364 litres of biofuel were obtained from one hectare of reclaimed land. At the current market price of 46 UAH/l, revenue from the sale of the main energy product amounted to 62.7 thousand UAH/ha. However, the key factor in the economic sustainability of the model was the valorisation of by-products. Obtaining 1,650 kg/ha of high-protein cake (market value ~20 UAH/kg) and 204 kg/ha of technical glycerol (market value ~60 UAH/kg) generated additional income in the amount of 45.2 thousand UAH/ha. Thus, the total gross income from 1 ha reached UAH 108.0 thousand. Even with high operating costs for cultivation and processing (which were estimated at approximately 45-50 thousand UAH/ha), the model generated an estimated net profit of 58.0 thousand UAH/ha. This confirmed the conclusions that deep processing of raw materials has become an alternative to improving the efficiency of agricultural production. Production of solid biofuels (pellets) from perennial energy crops (*Miscanthus* × *giganteus*, *Panicum virgatum*) was estimated using the energy equivalents method, which involved comparing the calorific value of biomass with the cost of substituted natural gas. With a dry biomass yield of 15-25 t/ha, the gross solid fuel yield provided the replacement of 7-12 thousand m^3 of natural gas per hectare (Gutsalenko & Fabiyanska, 2013). In monetary terms, with the average market price of fuel pellets of 6,500-8,000 UAH/t, this formed a gross income of 97.5-187.5 thousand UAH/ha annually. Even excluding the costs of harvesting, logistics and pelletising (which accounted for up to 40-50% of the cost of the final product), the net economic effect exceeded the indicators of conventional grain production on degraded land, ensuring stable profitability for 15-20 years of operation of the plantation without the need for annual tillage.

An additional economic effect could be associated with the deposition of stable organic carbon in the soil in the form of biochar and the replacement of fossil fuels, potentially allowing participation in voluntary carbon markets. A key feature of the proposed model was its ability to gradually self-finance: revenues from the sale of bioenergy products could compensate for operating costs for growing crops, processing biomass and measures to restore soil fertility. The payback period for initial capital investments was determined by the scale of production, logistics costs, and local market conditions and required a separate feasibility study. Thus, the proposed conceptual model provided for the transformation of the ecological burden caused by military soil damage into a long-term bioenergy project with a combination of restoring ecosystem functions and creating a stable source of income for land users and territorial communities. To illustrate the practical application of individual elements of the proposed conceptual model, a model scenario was formed for a belligerent agricultural landscape (experimental field) with an area of 122 hectares in the Mykolaiv Oblast (Snihurivka UTC). Since the full implementation of the model provided for a multi-year cycle of soil restoration and phased implementation of technological solutions, only key elements of the system were practically tested within the framework of this study, which concerned the initial assessment of the state of the territory, the choice of phytoremediation crops and the economic substantiation of the bioenergy component. Morphometric analysis of satellite images helped to identify 98 explosive craters with a total area of 2.81 hectares and an estimated volume of displaced soil of 73.1 thousand m^3 (Fig. 1). Figure 1 shows the field under study, which is located within agricultural land with a characteristic land use structure for the steppe zone. Visual analysis of the image revealed numerous dark spots of rounded shape, which is a typical sign of explosive craters against the background of a uniform surface of an arable field. The spatial distribution of damage was uneven: areas of increased concentration of craters alternated with relatively undamaged areas, which indicated the chaotic nature of artillery and aviation impacts. To accurately identify the boundaries of craters and measure their morphometric parameters, a detailed analysis of fragments of the image with an increased scale was performed (Fig. 2).

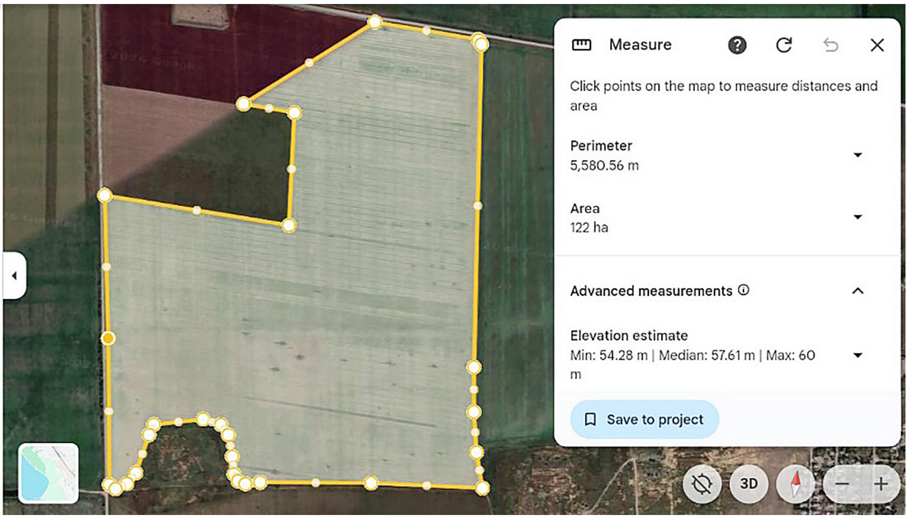

Figure 1. *Satellite image of a 122-hectare experimental field in Snihurivka UTC, Mykolaiv Oblast*
Note: image date – 03.06.2022, plot centre coordinates: 47°05'27"N, 32°46'18"E
Source: Google Earth (2022)

Figure 2. *Fragment of a satellite image of a research field with visually identified explosive craters*
Source: Google Earth (2022)

Analysis of the distribution of craters by diameter showed significant heterogeneity of explosive damage (Fig. 3). Small craters with a diameter of 1.5-3.5 m corresponded mainly to mortar ammunition, while medium-sized craters (3.5-7.0 m) were typical for artillery shells. The vast majority of damage is represented by large-scale craters with a diameter of more than 7 m, which were formed as a result of the use of aviation ammunition or multiple launch rocket systems. The dominance of large craters indicated a high level of mechanical transformation of the soil cover and significant volumes of soil mass movement.

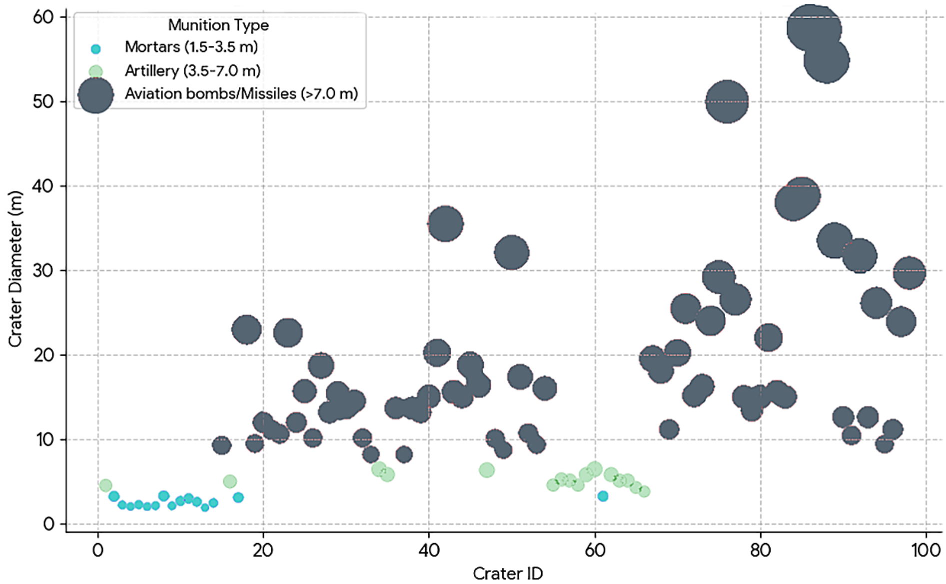

Figure 3. *Morphometric distribution of explosive craters in the experimental field (n = 98)*

Source: compiled by the authors

Based on the results of morphometric analysis of explosive damage to the experimental field, the key parameters of mechanical transformation of the soil cover necessary for the development of a model scenario for the restoration of agricultural land were determined (Table 5). These parameters included the area of direct crater damage, the volume of displaced soil, and the spatial scale of secondary degradation associated with soil mass spread, surface layer compaction, and the development of geochemical areas of pollution. Generalisation of these indicators determined the initial parameters used for calculating the volume of reclamation works and further modelling the scenario of restoring the belligerent agricultural landscape.

Table 5. *Initial parameters for forming a model scenario for restoring the belligerent agricultural landscape in Snihurivka UTC*

Indicator	Value
Area of the experimental field, ha	122
Number of explosive craters	98.0
Direct damage percentage, %	2.3
Total area of craters, ha	2.81
Volume of displaced soil, thousand m³	73.1
Estimated number of metal fragments in the degradation zone, thousand units	262.4
Coefficient of spatial expansion of degradation	5.0
Potential reclamation area, ha	14.1

Source: compiled by the authors

The total volume of displaced soil for 98 explosive craters was calculated from their morphometric parameters, considering the empirical ratio H ≈ 0.4D (Hupy & Schaetzl, 2006). Small craters (diameter 1.5-3.5 m, n = 15) had an average area of 5.04 m² and an average depth of 1 m, which corresponded to the volume of one crater of 1.68 m^3 and a total volume of 25.2 m^3. Medium-sized craters (diameter 3.5-7.0 m, n = 16) were characterised by an average area of 21.61 m^2 and a depth of 2.1 m; the volume of one crater was 15.13 m^3, and the total – 242.0 m^3. Large craters (diameter over 7.0 m, n = 67) had an average area of 412.95 m^2 and a depth of 7.9 m, which formed the volume of one crater of 1,087.44 m^3 and the dominant total volume of 72,858.5 m^3. The coefficient of spatial expansion of degradation was assumed to be 5, which corresponded to the upper limit of the theoretically estimated range of contamination propagation beyond the immediate blast zone. This choice is conditioned by the significant dominance of craters formed by large-calibre ammunition (more than 60% of the total number). According to research by G. Certini *et al.* (2013), the area of secondary pollution can exceed the area of direct crater damage by 3-5 times.

The number of metal fragments in Table 5 was estimated based on empirical data on the fragmentation of ammunition according to their typical tactical and technical characteristics, considering GICHD (2014): mortar shells (~1,600 fragments), artillery shells (~2,400) and large-calibre ammunition (~3,000) per hit. According to calculations, the total number of fragments (~262.4 thousand) corresponded to the average density of approximately 18.6 thousand metal fragments per 1 ha within the degradation zone of 14.1 hectares. To assess the practical implementation of restoration measures, an approximate calculation of the cost of reclamation of damaged areas of the agricultural landscape was performed. The cost structure included the main technological operations necessary to restore the productivity of the soil cover. Considering the possible local acidification of the soil environment due to explosive processes and accumulation of detonation products, liming was included in the list of recovery measures as one of the basic methods of chemical land reclamation. The introduction of limestone materials is aimed at stabilising the reaction of the soil solution and reducing the potential mobility of toxic elements in the zone of explosive damage. The approximate cost structure for the implementation of a set of recovery measures is shown in Table 6.

Table 6. *Economic assessment of the implementation of measures to restore the belligerent agricultural landscape in Snihurivka UTC*

Recovery stage	Expenses, thousand UAH
Humanitarian demining	159.6
Laboratory analysis of soil contamination	59.0
Mechanical reclamation	5,960.0
Replacing the top layer of chernozem	47,530.0
Liming	331.4
Total	54,040.0

Source: compiled by the authors

The total cost of implementing a set of restoration measures for the experimental field amounted to UAH 54.04 million, and the largest share of costs (~88%) was formed by the replacement of the upper soil layer, which is conditioned by a significant amount of displaced and degraded soil mass. In terms of unit area, this amounts to an average of 443.0 thousand UAH/ha for the entire experimental field area, which is more than 11 times higher than the average market value of agricultural land in the region. In order to restore the fertility of the belligerent agricultural landscape, a model of phytoremediation was developed for 15 years with crop rotation, in which crops with different functional properties alternated. This structure made it possible to maintain continuous phytoremediation pressure on contaminated soil and at the same time avoid allelopathic fatigue of the soil environment. Crop rotation combines three main functional groups of crops: phytostabilisation (safflower), biological reclamation (sweet clover) and phytoextraction (sorghum). The biomass of all crops was used exclusively for energy purposes through the production of solid biofuels. Considering the proposed structure of phytoremediation crop rotation and the planned bioenergy use of biomass, a generalised estimated calculation of technical and economic parameters of the project is given to illustrate the economic feasibility of implementing the model (Table 7).

Table 7. *Calculated parameters of the phytoremediation project and economic indicators of its implementation*

Indicator	Value
Project duration, years	15
Restoration area, ha	122.0
Average biomass productivity, t/ha per year	7.4
Total biomass production, t/ha	111.0
Annual volume of biomass for processing, t	900
Calorific value of biomass, MJ/kg	16.5-17.2
Briquetting line capacity, kg/h	350-500
Capital investment in equipment, thousand UAH: ➤ briquetting press; ➤ chopper/drying complex; ➤ installation and electrical work	1,558.8 779.4 623.5 155.9
Biomass processing costs, UAH/t	2,703
Wholesale price of fuel briquettes, UAH/t	6,700
Net cash flow from 1 ha, thousand UAH	262.1
Total profit, thousand UAH, including from: ➤ safflower; ➤ sweet clover (productive years); ➤ sorghum	31,974.4 7,739.9 8,790.8 15,443.7
Average annual profit, thousand UAH	2,131.6
Payback period of the briquetting line, years	0.8
Estimated period of compensation for reclamation costs, years	28

Note: calculations are indicative in nature and are given to illustrate the economic feasibility of the proposed recovery model

Source: compiled by the authors

The generalised results of calculations showed that the use of phytoremediation crop rotation with subsequent energy utilisation of biomass allows not only to ensuring ecological detoxification of the soil, but also forming a stable financial flow that partially compensates for the cost of restoring the damaged agricultural landscape. Scientific approaches to assessing the consequences of military influence on the soil cover of Ukraine, presented in the papers by S. Baliuk *et al.* (2024), focused mainly on quantitative fixation of degradation processes, determination of the scale of losses, and normative monetary assessment of damage. Such studies formed the necessary legal and analytical basis for compensation mechanisms and strategic planning, but they were mainly aimed at fixing and classifying damage and to a lesser extent covered issues of long-term restoration of agricultural landscapes and economic reclamation mechanisms. In this regard, it was appropriate to refer to the international experience of restoring territories affected by armed conflicts. International experience in restoring land damaged as a result of armed conflicts has shown that security, engineering and humanitarian approaches have dominated in most cases. As noted by G. Certini *et al.* (2013), military operations led to complex degradation of the soil cover, which included mechanical disruption of the profile, accumulation of metal fragments, and chemical contamination by detonation products. As noted by W. Verheye *et al.* (2007), in Bosnia and Herzegovina after the war, priority was focused on land inventory, mine-contaminated sites, spatial planning, and the gradual return of land to economic use. Similar approaches were implemented in modern humanitarian demining programmes, where the main focus was on the security of territories and restoring the possibility of their use (Osmolovska & Bilyk, 2024). Simultaneously, ecological remediation of soils and mechanisms of economic self-sufficiency in most such programmes were not a central element.

A similar logic could be traced in Lebanon, where post-war reconstruction developed through mine action systems: clearing areas of explosive remnants of war, marking dangerous zones, informing the population about risks, and supporting a return to safe land use. According to UNDP (2011), this approach had a distinct humanitarian and socio-economic impact, particularly for agricultural areas in southern Lebanon, but it also focused primarily on territory security rather than multi-year integrated soil reclamation. The FAO report (2025) confirmed the fact that the current escalation of the conflict in Lebanon has led to systemic degradation of agricultural landscapes due to the mass destruction of perennial plantings and woodlands, which required a transition from operational mine clearance to integrated environmental reproduction strategies. In addition, biological approaches to the restoration of polluted land have been actively developed in the scientific literature. Research by J. Vangronsveld *et al.* (2009) showed that phytoremediation can be an effective tool for stabilising and removing heavy metals from soils, especially in cases of artificial pollution. Simultaneously, the EU and the UK have accumulated considerable experience in using energy crops in phytoremediation systems. As shown by N. Witters *et al.* (2012), based on field studies in Belgium and the Netherlands, combining phytoremediation with energy production or other forms of biomass use may increase the economic viability of such projects. Research by C. Lievens *et al.* (2008), conducted on materials from metal-contaminated areas of Belgium, also confirmed the possibility of using biomass from remediation crops for energy or technical needs. Most of these approaches were implemented as local technological solutions for metal-contaminated or industrially disturbed territories and did not form a comprehensive system of post-war restoration of agricultural landscapes. This led to the need for integrated models that combined security, environmental and economic tools for land reclamation within a single management approach.

The presented analysis showed that most of the international programmes were focused on safe cleaning of territories or local technological rehabilitation. The economic component, as a rule, was not integrated into the system of long-term land restoration. The proposed model was distinguished by a combination of engineering, agrochemical, biotechnological, and energy tools within a single circular land use system, which allowed combining ecological reclamation with the development of an economically viable mechanism for restoring agricultural landscapes. International phytoremediation studies have focused on the effectiveness of individual biotechnological tools. In particular, G.M. Gadd (2004) showed that microorganisms can bind and transform heavy metals through biosorption, biomineralisation, and complexation processes, which contributed to a decrease in their bioavailability in the soil environment. The researcher found that the cell walls of microorganisms rich in functional groups can adsorb metal ions, while the synthesis of exopolysaccharides and siderophores contributed to their binding and conversion to less mobile forms. M. Rajkumar *et al.* (2012) demonstrated that metal-tolerant rhizospheric bacteria, in particular representatives of genera *Bacillus* and *Pseudomonas* (*Bacillus subtilis* and *Pseudomonas fluorescens*), were characterised by high resistance to Pb, Cd, and Zn and could be used as effective phytoremediation agents. Such PGPRs can simultaneously stimulate plant growth and increase the efficiency of soil purification through the synthesis of phytohormones, siderophores and exopolysaccharides, which activated the development of the root system of remediant plants and increased their stress resistance in toxic conditions. Given the suppression of native microflora even at moderate concentrations of heavy metals, inoculation with adapted strains was considered as an appropriate element of restorative measures. A separate area of research was related to the use of sorption materials of organic origin. The combination of phytoremediation followed by thermal processing of biomass was considered as a promising way to safely remove pollutants from the biogeochemical cycle. However, the study mainly considered individual technological or biochemical solutions focused on locally contaminated sites, industrial areas, or waste landfills. They lack a systematic approach to the restoration of large agricultural landscapes that have undergone complex mechanical, chemical and radiological effects as a result of military operations.

Consequently, the conceptual model proposed in the study was distinguished by transformational logic. It combined engineering reclamation, chemical reclamation, biotechnological detoxification, and bioenergy integration into a single 15-year recovery cycle. Mine clearance and physical restoration of the soil profile were considered not as a final stage, but as a starting condition for launching a long-term system of ecological and economic land reintegration. A special difference between the model was the integration of phytoremediation with the bioenergetic component. Unlike classical rehabilitation programmes, which required constant external funding, the proposed approach provided for partial self-financing through the production of biodiesel and solid biofuels. Such a circular "Soil-to-Energy" model ensured the closure of material flows, reducing the environmental burden and creating economic motivation for long-term management of reclaimed land. The results of the practical case demonstrated a structural asymmetry between the scale of primary engineering costs and the potential for further economic returns. The dominance of physical reclamation in the cost structure was confirmed by the conclusions of S. Baliuk *et al.* (2024) on the depth of degradation changes in the soil profile under military influence. This showed that even with efficient bioenergy integration, full reimbursement of engineering costs required a long period of time and a combination of financial mechanisms. Thus, the proposed model in the study did not challenge the previous approaches of other researchers, but expanded them by integrating detoxification, fertility restoration, and economic reintegration technologies into a single long-term system. The transition from the "harm assessment" model to the "ecological and economic transformation" model was a key conceptual contribution of the study.

Conclusions

Thus, the conceptual model of post-war restoration of agricultural land provided a step-by-step process of reclamation, which integrated engineering, chemical, biotechnological, and economic approaches for the restoration of territories after military operations. The use of phytoremediation and bioenergy crops has allowed integrating environmental and economic recovery goals, contributing to sustainable development and reducing the payback period of projects. The study of the de-occupied agricultural landscape in the Snihurivka UTC of the Mykolaiv Oblast revealed a significant level of physical degradation of the soil cover caused by military operations. 98 explosive craters were identified in the 122-hectare research field. The total volume of displaced soil was more than 73.1 thousand m^3, and craters with a diameter of more than 7.0 m, which accounted for 68% of the total number, formed more than 99% of the volume losses. Considering secondary fragmentation and the spread of metal contamination, the zone of functional degradation of the soil cover was estimated at 14.1 hectares, which was approximately five times the area of direct morphological damage. Economic calculations showed that the full range of technical reclamation and agrochemical reclamation required aproximately UAH 54.0 million, which corresponded to the average cost of 443.0 thousand UAH/ha for the entire area of the experimental field. These costs were more than 11 times higher than the average market value of agricultural land in the region, which created a high risk of long-term withdrawal of such territories from agricultural production in the absence of alternative approaches to recovery.

To overcome this imbalance, a conceptual model of agrobiological recovery was proposed, implemented through a 15-year phytoremediation crop rotation using sorghum (*Sorghum bicolor*), safflower (*Carthamus tinctorius*) and sweet clover (*Melilotus* spp.). The combination of phytoextraction of heavy metals, rhizospheric bioaugmentation of microorganisms capable of degradation of organic pollutants, and structural stabilisation of the soil helped to gradually restore the functional suitability of agricultural landscapes in conditions of limited resources. The use of the resulting biomass for the production of solid biofuels has provided potential economic self-sufficiency of phytoremediation measures. The proposed model has become important for planning the restoration of belligerent agricultural landscapes in the steppe regions of Ukraine. The results showed that the integration of biological methods of reclamation with bioenergy use of phytomass can act as an economically justified alternative to traditional high-cost technologies of soil restoration in post-war conditions. The prospect of further research is field verification of the proposed conceptual model on de-occupied agricultural land in various natural and climatic zones of Ukraine.

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Conflict of Interest

None.

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Концептуальна модель повоєнного відновлення сільськогосподарських земель з інтеграцією біоенергетичних технологій

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Анотація. Повномасштабні воєнні дії росії проти України спричинили масштабну деградацію сільськогосподарських земель, що супроводжувалося механічним руйнуванням ґрунтового покриву, хімічним забрудненням і втратою продуктивного потенціалу. Відсутність інтегрованої системи повоєнного відновлення обумовило потребу у формуванні комплексної моделі рекультивації, що поєднувала екологічні й економічні інструменти в межах єдиного управлінського підходу. Метою роботи стала розробка концептуальної моделі повоєнного відновлення сільськогосподарських земель на засадах інтеграції інженерних, хімічних, біотехнологічних та економічних підходів у межах циркулярної системи землекористування. Було використано аналітичний, порівняльний і системно-структурний методи, а також концептуальне моделювання. У результаті дослідження було визначено масштаби фізичної деградації ґрунтового покриву на деокупованих сільськогосподарських угіддях і запропоновано концептуальну модель їх агробіологічного відновлення з використанням фіторемедіаційних культур. Сформовано багаторівневу модель відновлення, що включала етапи гуманітарного розмінування, технічної підготовки території, оцінки забруднення, механічної рекультивації, хімічної детоксикації, біотехнологічної регенерації та довгострокової фіторемедіації з інтеграцією біоенергетичних технологій. Обґрунтовано доцільність 15-річного циклу фіторемедіації в структурі рекультивації з поетапним переходом до економічно життєздатної системи землекористування. Запропоновано циркулярну модель переробки біомаси, що передбачала енергетичну валоризацію фітомаси та повернення стабілізованих продуктів у ґрунт, забезпечуючи часткову або повну самоокупність процесу відновлення. Практичну життєздатність моделі підтверджено на прикладі пошкоджених сільськогосподарських земель у Снігурівській міській територіальні громаді Миколаївської області, де доведено здатність біоенергетичного компоненту генерувати стабільний грошовий потік для часткової компенсації витрат на інженерну рекультивацію. Запропонована модель може бути адаптована до різних типів белігеративних агроландшафтів і створює передумови для формування фінансово стійких механізмів рекультивації. Вона має потенціал для практичного застосування в Україні й інших країнах, що зазнали військових дій, і може стати основою для формування національних політик у сфері відновлення земель і сталого розвитку аграрного сектору

Ключові слова: агроландшафти; біоенергетичні культури; циркулярна економіка; екологічна стабілізація; рекультивація ґрунтів; фіторемедіація; детоксикація земель