

СЕКЦІЯ 1. ЕКОНОМІЧНИЙ РОЗВИТОК ТЕРИТОРІАЛЬНИХ ГРОМАД ЯК СКЛАДОВА НАЦІОНАЛЬНОЇ БЕЗПЕКИ УКРАЇНИ

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ECONOMIC ASPECTS OF SOIL RESTORATION MODELING IN WAR- AFFECTED TERRITORIAL COMMUNITIES

Under conditions of the full-scale war in Ukraine, soil cover degradation over large areas has acquired a systemic character, which necessitates the development of scientifically grounded approaches to its restoration [1]. In this context, modeling of reclamation processes becomes particularly relevant as a tool for predicting the effectiveness of restoration measures, optimizing resource use, and forming long-term strategies for sustainable land use, taking into account their economic feasibility. Soil degradation in war-affected regions not only represents an environmental challenge but also directly threatens the economic sustainability of territorial communities and the stability of food security systems.

The aim of this study is to model the processes of restoration of agricultural soils damaged as a result of military actions, considering the stage-wise transformation of the physical, chemical, and biological properties of the soil cover, as well as the integration of ecological and economic components of restoration, including the assessment of their impact on local economic resilience and food security.

The methodological basis of the study is a systems approach to the assessment of degraded soils, which involves the sequential implementation of a set of measures ranging from initial site assessment to the application of biotechnological and phytoremediation technologies. The proposed model comprises six interrelated stages: restoration of anthropogenically damaged soils, assessment of contamination levels, mechanical reclamation, chemical amelioration, biotechnological restoration of soil fertility, and long-term phytoremediation with elements of bioenergy utilization of biomass [2].

At the initial stage, the key priority is to ensure site safety through humanitarian demining and the elimination of mechanical damage to the soil cover. This creates the necessary preconditions for subsequent agrotechnical measures and prevents secondary contamination. The next stage involves detailed soil diagnostics, including the determination of toxicant content, which enables the identification of the most affected zones and the differentiation of reclamation approaches.

Mechanical reclamation is aimed at restoring soil structure, normalizing bulk density, water permeability, and aeration through land leveling and the reconstruction of the fertile topsoil layer. Chemical amelioration involves the immobilization of toxicants using sorbents and soil amendments, thereby reducing the bioavailability of

heavy metals and organic pollutants. The biotechnological stage is focused on restoring soil microbiological activity, increasing its water-holding capacity, and stimulating plant growth under stress conditions.

A distinctive feature of the proposed model is the integration of long-term phytoremediation with elements of the circular economy [3]. The use of extractor and stabilizer plant species in combination with bioenergy crops enables not only the gradual remediation of soils but also ensures the economic feasibility of restoration through energy production and carbon sequestration. This approach forms a “Soil-to-Energy” model that integrates ecological rehabilitation with the restoration of the productive function of land [4]. Such an approach contributes to the diversification of local economies, supports energy independence of rural communities, and creates additional income streams from degraded lands.

To formalize soil restoration processes, an integral soil recovery index (R_s) is proposed, which incorporates physical, chemical, and biological soil indicators, as well as their weighted significance within the structure of reclamation measures:

$$R_s = w_1P + w_2C + w_3B + w_4E,$$

where P represents physical indicators (bulk density, structure, water permeability); C denotes chemical indicators (pH, toxicant content, cation exchange capacity); B refers to biological indicators (microbiome, enzymatic activity); E represents economic indicators (restoration costs, expected yield recovery, land use efficiency, and potential economic return); and w_i are weighting coefficients.

The proposed index makes it possible to integrate the results of individual reclamation stages into a unified quantitative scale, thereby enabling the assessment of soil recovery dynamics and the formalization of the selection of effective restoration technologies. The inclusion of an economic component further enhances its applicability for decision-making at the community level by linking soil recovery processes with economic outcomes.

The dynamics of the integral index R_s reflect the stage-wise nature of soil restoration. At the initial stages (demining and technical preparation), improvements are primarily observed in physical properties; at the stage of chemical amelioration, a reduction in toxicity levels and stabilization of the soil environment occur; whereas the greatest increase in R_s is associated with biotechnological restoration and phytoremediation, which ensure microbiome regeneration and long-term enhancement of soil fertility. The generalized trajectory of index variation is nonlinear and reflects a transition from rapid physical changes to more inert biological processes. This nonlinear recovery trajectory also reflects differences in the economic return of restoration measures, with early-stage interventions yielding rapid functional improvements, while biological recovery ensures long-term economic sustainability.

The obtained generalizations indicate that the effectiveness of soil restoration is determined by adherence to the sequence of stages and the adaptation of technologies to the level of damage and specific agroclimatic conditions. The proposed approach accounts for different temporal horizons of recovery: during the de-occupation phase, priority is given to humanitarian demining and primary soil assessment, whereas the full-scale restoration of soil fertility is implemented under conditions of a stabilized security environment. The integrated application of mechanical, chemical, and

biological methods ensures the restoration of soil structure, reduction of toxicity, regeneration of the microbiome, and gradual recovery of soil fertility.

The practical significance of the study lies in the possibility of applying the proposed model as a tool for planning restoration activities in affected regions, assessing their economic efficiency, and developing state programs for land reclamation in the post-war period. The proposed framework addresses contemporary challenges in the restoration of war-affected agrolandscapes and can be integrated into sustainable development strategies of the agricultural sector of Ukraine. It supports the economic recovery of territorial communities by restoring the productive capacity of agricultural land, reducing long-term environmental risks, and improving the stability of local agri-food systems. It also contributes to strengthening national food security by ensuring the gradual reintegration of degraded lands into agricultural production.

References

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