

Prospects for overcoming the systemic crisis in agriculture: Focus on Ukraine

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Abstract

The current state of Ukraine's agricultural sector is characterized by the deepening of a systemic crisis driven by the cumulative impact of military, economic, environmental, and social factors, as well as climate change. War-related destabilizing factors, including the temporary occupation of territories, landmine contamination of agricultural lands, destruction of infrastructure and irrigation systems, chemical and mechanical soil contamination, disruption of logistics chains, and shortages of financial, human, and material resources, have significantly intensified environmental challenges. The consequences include mechanical and chemical soil degradation, land erosion, severe disruption of regional water balances, biodiversity loss, and declining resilience of both agroecosystems and natural ecosystems. The study substantiates the crucial role of environmental and conservation principles in the recovery and development of the agricultural sector under conditions of war and global challenges. Overcoming the systemic crisis in agriculture requires a radical paradigm shift - from extractive, resource-depleting farming toward an environmentally oriented model of sustainable development. Alongside mitigating the environmental consequences of war, priority should be given to the transition toward sustainable agricultural practices, the implementation of digital technologies, and adaptation to international standards, particularly those of the European Union.

Keywords: *Systemic crisis, Agricultural production, Nature management, Sustainable development, European Green Deal, Degradation of natural resources, Global challenges, Environmental risks, Transformation of agricultural production models.*

Introduction

The full-scale war has caused extensive destruction of infrastructure, reduction of cultivated areas, labor shortages, logistical disruptions, and rising production costs, resulting in substantial direct and indirect losses in Ukraine's agricultural sector. According to recent estimates, direct agricultural damages amount to approximately USD 10–12 billion, while indirect losses (including lost revenues, reduced value added, and additional operating costs) reached USD 70–82 billion by late 2025 to early 2026. Destroyed infrastructure has been valued at more than USD 37 billion (KSE, 2025; World Bank, 2024). Agricultural production declined significantly: in particular, 25% of farms reported redu-

ced output in 2022 (Kotykova et al., 2025). Grain exports decreased by 11–15% during 2023–2024, while exports of major crops in 2025 remained approximately 35% below pre-war levels. These disruptions led to reductions in overall production and profitability and generated global food security consequences through rising food prices and supply chain instability. For comparison, during the first six years of the Syrian war (2011–2016), the agricultural sector suffered losses estimated at approximately USD 16 billion, equivalent to nearly one-third of the country's GDP in 2016 (Kotykova et al., 2025). Cultivated land decreased by 30%, irrigated land by up to 50%, while wheat production declined by half. Syria transformed from a

net food exporter into a net importer, resulting in a prolonged food crisis affecting more than 60% of the population. In Yemen, prolonged military conflict combined with climate stressors caused massive destruction of farms, landmine contamination, and the collapse of irrigation systems. Consequently, widespread famine, forced displacement, and a shift toward non-food crops (particularly qat) further intensified water scarcity and reduced food self-sufficiency (ICRC, 2022). At the same time, Ukraine's agricultural sector has demonstrated considerable resilience through rapid adaptation, including the development of alternative export routes (Danube ports and overland corridors) and the implementation of technological solutions. Unlike the near-total collapse of the agricultural sectors observed in Syria and Yemen, Ukraine has avoided systemic destruction of the industry, although its long-term sustainability remains under severe pressure (Kotykova et al., 2025; Nehrey and Finger, 2024). At the same time, the full-scale war in Ukraine has significantly intensified mechanical, chemical, and biological soil degradation. Major manifestations include soil compaction caused by heavy military equipment, contamination by heavy metals (HM), alterations in the soil microbiome, and the accumulation of toxic explosive compounds (Solokha et al., 2024; 2023; Dmytrenko et al., 2024). The destruction of the Kakhovka Hydroelectric Power Plant resulted in the loss of irrigation across approximately 584–600 thousand hectares of agricultural land, increasing the risk of desertification. In addition, more than 30% of protected natural areas have been damaged due to physical degradation, fires, and pollution. These impacts are expected to be long-term because of extensive landmine contamination and persistent toxic pollution (Leal Filho et al., 2024; Solokha et al., 2024). Similar long-term environmental consequences were previously documented following persistent contamination of coastal zones and soils in the Persian Gulf region. Simultaneously with increasing land degradation, rapid global population growth continues to intensify pressure on food systems and natural resources. According to current estimates, the global population reached approximately 8.2 billion people in 2025 and is projected to increase to 9.6–9.8 billion by 2050, requiring a 30–70% increase in food production depending on consumption and income scenarios (FAO, 2025). However, rapid population growth, particularly in Sub-Saharan Africa, combined with climate change and land degradation, poses serious risks to agroecosystem sustainability and global food security.

Rising food demand stimulates agricultural expansion, which is responsible for nearly 90% of global deforestation (FAO, 2024). More than half of global forest loss is associated with conversion to cropland, while almost 40% is linked to livestock grazing. These trends emphasize the urgent need to transition toward intensive yet environmentally sustainable agriculture capable of simultaneously increasing productivity while conserving soils, biodiversity, and water resources. Under the conditions of unprecedented contemporary global challenges, food resources are increasingly transforming from conventional commodities into strategic instruments of international stability and geopolitical security. In this context, Ukraine's role extends far beyond regional leadership: despite full-scale military aggression, the country continues to serve as a guarantor of global food security. Prior to the war, Ukraine's agricultural sector annually provided food for approximately 400 million people worldwide (WFP, 2025). Even in 2025, despite substantial losses, Ukraine remained one of the leading actors on the global agricultural market. During the 2025/2026 MY, the country ranked among the top 1–3 global exporters of sunflower products and rapeseed, ranked fourth in corn exports, and occupied fifth to sixth positions in wheat, barley, and soybean exports (CSIS, 2026; USDA, 2025). In 2025, the agricultural sector accounted for 56.1% of Ukraine's total exports (exceeding USD 22.5 billion), demonstrating not only the resilience of the industry but also its strategic importance for both the national economy and global markets (OECD, 2025). Despite a decline in grain exports compared with the pre-war period (approximately 35% for major crops in 2025), Ukraine continues to fulfill its role as a reliable supplier, particularly for countries in Africa, the Middle East, and Asia. The aim of this study was to identify the principal drivers of the systemic crisis in Ukrainian agriculture and to substantiate pathways for transforming the agricultural sector toward an innovative environmentally oriented development model.

Materials and Methods

The study of the current state of Ukraine's agricultural sector and the identification of the drivers of the systemic crisis were conducted using a comprehensive interdisciplinary approach that integrated general scientific, specialized environmental, agroecological, and economic-statistical methods. This approach enabled a systematic analysis of contemporary challenges, including soil degradation, climate change, environmental

pollution, biodiversity loss, and intensive agricultural practices, as well as the substantiation of prospects for the sustainable development of the agricultural sector based on ecological principles and rational natural resource management. The theoretical framework of the research was grounded in the fundamental principles of general and applied ecology, agroecology, soil science, and landscape ecology, as well as the concept of sustainable development, including the Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). A dialectical method of cognition was applied to analyze the unity and interaction of opposing processes within the “human agricultural production environment” system, while a systems approach was employed to examine the agricultural sphere as a complex, open, and dynamic socio-ecological system.

Results and Discussion

Structure of the systemic crisis

The systemic crisis of Ukraine’s agricultural production, with a focus on ecology and natural resource management, represents a multifactorial destabilization of the sector in which military impacts and their destructive consequences are superimposed on an outdated extensive model of agricultural production and climate-related challenges. This crisis affects the fundamental components of agroecosystems, including soil cover, biodiversity, and biogeochemical cycles, thereby necessitating a profound structural transformation (Fig. 1). Contemporary studies emphasize the synergistic interaction among the major drivers of the

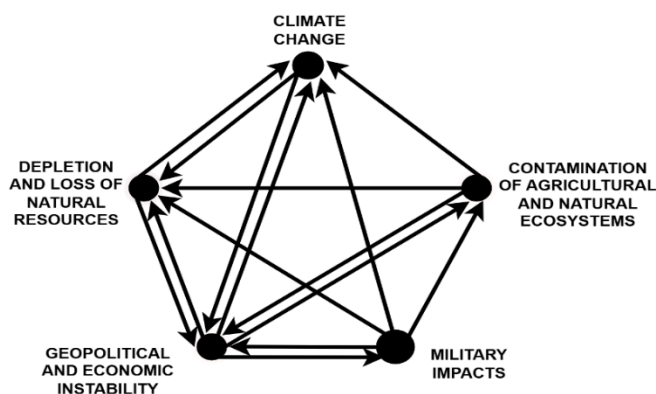


Figure 1. Conceptual model of the systemic crisis of agricultural production in Ukraine in the context of environmental security and sustainable natural resource management

crisis, including technogenic pressure, technological mismatch, operational disruptions, monocultural practices, and financial constraints (Kraamwinkel et al., 2021; Li et al., 2025; Moscona and Sastry, 2025; Demyanyuk et al., 2026). In Ukraine, the problem has become particularly acute. The extremely high degree of land plowing (more than 57% of the territory under arable land), long-term intensive exploitation of chernozem soils, and the dominance of monoculture systems have resulted in the loss of up to 30% of soil organic matter over the past 130 years. Approximately 20% of agricultural land has already undergone substantial degradation, while the remaining areas are considered to be at high risk. Since 2022, the full-scale invasion by the Russian Federation has dramatically intensified degradation processes through mechanical soil disturbance, chemical contamination with HM (Pb, Cd, Cu, Zn) and explosive compounds, as well as the long-term withdrawal of land from agricultural use due to mine contamination (Solokha et al., 2024; 2023). The global dimension of this problem is alarming not only for Ukraine. According to expert estimates, soil degradation already directly affects the well-being of at least 3.2 billion people worldwide. By 2050, up to 90% of the world’s soils may become degraded. Soil degradation has increasingly been proposed as a tenth planetary boundary because it is closely interconnected with already transgressed boundaries, including climate change, biodiversity loss, and disruptions of nitrogen and phosphorus cycles, while simultaneously generating strong positive feedback mechanisms: erosion → loss of soil organic carbon (SOC) → intensification of climate extremes → further erosion (Kraamwinkel et al., 2021). Particularly vulnerable in this context are chernozems, which are among the most fertile soils on Earth. Although they occupy only 5.6% of the global soil cover (approximately 725 million ha), they contain 8.2% of the world’s SOC reserves (around 56 billion tons of C) and support a substantial share of global wheat, maize, soybean, and sunflower production (FAO, 2022; Li et al., 2025). A systematic analysis of 1,290 scientific publications demonstrated that the dominant degradation processes affecting chernozems are erosion and the depletion of fertility and soil organic matter. Anthropogenic pressure has been identified as the principal driver of degradation across all major black-soil regions, from Northeast China to the East European Plain and the Pampas. Intensive tillage, disrupted crop rotations, excessive agrochemical application, monocultures, and mechanical compaction accelerate water and wind erosion, contribute to SOC

losses of 20–50% compared with natural conditions, reduce the thickness of the humus horizon, and significantly diminish ecosystem services. In many regions, these processes are approaching tipping points beyond which ecological and economic recovery becomes extremely difficult (Li et al., 2025; Kraamwinkel et al., 2021). Another important structural component of the crisis is technological backwardness and the inconsistency of agricultural technologies with environmental principles. Outdated or poorly adapted technologies create a substantial technological gap and intensify environmental pressure. Research by Moscona and Sastry (2025) demonstrates that the majority of agricultural innovations, including new crop varieties and hybrids, are developed primarily for the ecological conditions of highly industrialized countries with temperate climates. Such ecological mismatch reduces the probability of successful technological adoption by 44% at median levels of environmental divergence and explains approximately 15–20% of interregional differences in agricultural productivity. In Ukraine, legacy agricultural systems remain highly resource-intensive and poorly adapted to contemporary climatic challenges, thereby further intensifying technogenic pressure and the degradation of natural resources. Violations of technological regulations act as a powerful catalyst of cumulative degradation. Excessive application of pesticides and fertilizers, neglect of crop rotations, lack of crop diversification, and inadequate waste management generate synergistic effects with other crisis factors, leading to toxicant accumulation, soil structure degradation, suppression of soil microbiota, eutrophication of water bodies, and accelerated progression toward ecological tipping points (Kraamwinkel et al., 2021; Li et al., 2025). In Ukraine, water erosion affects approximately 13.4 million ha, including 10.6 million ha of arable land, covering nearly 15–22% of the national territory. Overall erosion processes (water and wind erosion combined) negatively affect more than 40% of agricultural land. Annual humus losses in chernozem soils range from 0.5 to 0.9 t ha⁻¹, while over recent decades the content of organic matter in the plow layer has declined by 15–40% (Stupak, 2016; FAO, 2022; Pozniak et al., 2019). A striking example is the Steppe zone, where the combination of sunflower and maize monocultures with excessive nitrogen fertilization causes nitrate leaching, groundwater contamination, soil acidification, reduced biological activity, and biodiversity decline. A historical precedent illustrating the vulnerability of mo-

nocultural systems is the Irish Potato Famine (1845–1852), which was triggered by potato mono-culture and the spread of late blight disease (Li et al., 2025). In contrast, the transition toward poly-culture systems and regenerative agriculture practices – including cover crops, minimum or zero tillage, agro-forestry, and diversified crop rotations – demonstrates considerable potential for restoring resilience. Meta-analyses and global modeling studies indicate that the implementation of such practices can increase crop productivity by 14–27%, depending on the region and combination of practices, while simultaneously enhancing drought resistance, improving economic profitability, and restoring ecosystem services. Diversified agricultural systems exhibit significantly greater resilience to climate-related stressors compared with monocultures (Houngkpatin et al., 2026). Chronic financial constraints represent the final element that closes the cycle of the systemic crisis. Limited financial resources substantially restrict access to modern precision agriculture technologies, restorative land management practices, soil monitoring systems, and green technologies. Under conditions of high technogenic pressure and wartime risks in Ukraine, financial shortages force agricultural producers to rely on short-term extensive practices, including intensive agrochemical use and minimal investment in soil conservation measures, which further aggravates environmental degradation. Existing studies demonstrate a high potential return on investment (ROI) from regenerative practices and slow-release fertilizers; however, their implementation requires substantial initial capital, the development of MRV systems (Monitoring, Reporting, Verification), and effective green finance policies together with targeted governmental support (World Bank, 2024). The drivers of the systemic crisis do not operate in isolation but instead form interconnected synergistic positive feedback loops that substantially reinforce one another, accelerate soil degradation, and reduce the overall resilience of agroecosystems (Fig. 2). Such interactions lead to the crossing of critical thresholds (tipping points), beyond which the recovery of fundamental ecosystem functions becomes extremely difficult and resource-intensive. Effective crisis mitigation is only possible through a systemic transformation aimed at simultaneously breaking multiple links within these reinforcing loops via the implementation of agroecological diversification, regenerative practices, precision agriculture, and green financing instruments.

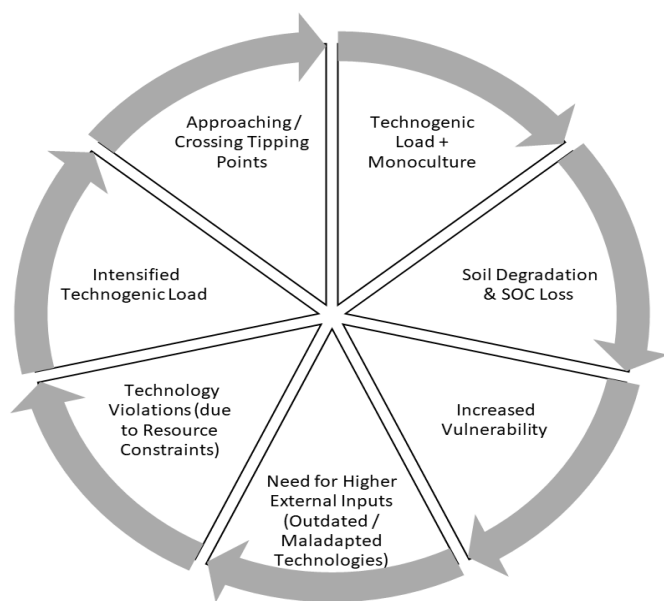


Figure 2. Synergistic feedback loops driving the systemic crisis in Ukrainian agroecosystems

Environmental drivers of the crisis and pathways to its mitigation

In the current context, environmental research and natural resource conservation in Ukraine's agricultural sector represent not merely a scientific direction but a matter of survival, economic resilience, and national security. This is a system-forming factor that determines the efficiency, safety, and competitiveness of the agricultural sector, and consequently the economic stability of the state. At present, the deepening and expansion of environmental research in agriculture constitute the foundation for post-war recovery, adaptation to climate change, and long-term economic stability. Investment in this area today ensures the preservation of natural resources, enhanced productivity and resilience of agroecosystems, and strengthened positions of Ukraine in the global market in the future. First and foremost, it is necessary to emphasize the scale of challenges facing not only Ukraine but the world as a whole. It is estimated that the war has damaged approximately 1.91 million hectares of agricultural land, while total environmental losses exceed €85–108 billion. Projected nutrient deficits by 2030 (1.7 million tons of N, 2.8 million tons of P, 2.1 million tons of K) threaten irreversible soil fertility loss and declining productivity of key crops (Medinets et al., 2025). These processes are superimposed on global trends of land degradation and climate instability, making environmentally oriented research not only a scientific priority but also a cornerstone of recovery un-

der the “*building back better resilience*” paradigm (Moldavan et al., 2023). Climate instability is increasingly manifesting its impact on Ukraine's agricultural sector. Droughts, extreme temperatures, dust storms, and uneven precipitation distribution are radically transforming traditional farming systems, significantly increasing the risks of yield losses and production instability. In recent years, Ukraine has experienced a growing frequency and intensity of extreme weather events. In particular, 2024 and 2025 were characterized by recurrent droughts, especially in the southern, central, and northeastern regions. According to the Ukrainian Hydrometeorological Center, the average annual air temperature in 2025 exceeded the long-term norm by 1.2°C, while precipitation during the first 11 months reached only 80% of the norm (and only 50% in some southern and central regions). The second consecutive drought (following the destruction of the Kakhovka Reservoir) led to a significant decline in yields of both winter and spring crops in the Steppe zone (CES, 2025). It is estimated that droughts in 2015, 2018, and 2020 caused wheat yield reductions in southern Ukraine ranging from 7–53%, maize from 16–40%, sunflower from 17–26%, and soybean from 26–30% compared to relatively favorable years. For instance, in 2020 wheat yields declined by 53% in Odesa region and by 24% in Mykolaiv region (KSE, 2024). Future projections indicate an increasing risk trend: under climate change scenarios (RCP 4.5–8.5), the frequency of heatwaves, aridification periods, and drought probability is expected to rise, particularly in southeastern regions where major grain and oilseed production areas are concentrated. Precipitation variability is characterized by alternating heavy rainfall events and prolonged dry spells, disrupting soil water balance, complicating field operations, and intensifying pest and disease pressure (Mostoviyak and Demyanyuk, 2020). In addition to droughts, the frequency of dust storms (dry winds) is increasing, enhancing wind erosion and leading to further loss of fertile topsoil (Tarariko et al., 2025). Some estimates indicate that climatic factors already cause annual economic losses in Ukraine's agricultural sector equivalent to approximately 0.6% of agricultural GDP (about USD 2 billion annually over the last 20 years prior to the full-scale war). A growing body of research highlights the depletion and loss of natural resources in Ukraine's agricultural sector (Symochko et al., 2024). Intensive resource exploitation, combined with significant biodiversity loss, leads to long-term reductions in soil productivity and ecosystem service

provision. The situation became particularly critical following the destruction of the Kakhovka Reservoir in June 2023. This disaster deprived hundreds of thousands of hectares of agricultural land in southern regions of stable irrigation sources. According to the Ministry of Economy, Environment, and Agriculture of Ukraine, approximately 584,000 hectares of arable land were left without irrigation, previously producing around 4 million tons of grain and oilseed crops (about 4% of national production). In Kherson region, 94% of irrigation systems were destroyed, in Zaporizhzhia 74%, and in Dnipropetrovsk 30% (Shumilova et al., 2025). As a consequence, soil degradation has accelerated, with increased risks of salinization and declining groundwater levels. In many areas, a shift from surface irrigation to intensive groundwater extraction is observed, creating additional risks of aquifer depletion (PRIF, 2026). Environmental research in this area is urgently needed for rational water resource management and the implementation of water-saving technologies, particularly precision irrigation, which can reduce water use by 20–50% compared to conventional methods (Lakhiar et al., 2024); for identifying alternative irrigation sources, including restoration and modernization of existing systems, construction of new wells, the use of treated wastewater, and the introduction of institutional water-user governance mechanisms (Markova et al., 2024); as well as for preventing secondary soil salinization and further soil degradation. Environmental pollution represents one of the most acute and complex challenges for Ukraine's agricultural sector. Excessive and unjustified use of agrochemicals, including counterfeit and low-quality plant protection products and fertilizers, industrial emissions, and the consequences of military activities are generating new and often synergistic environmental risks that threaten soil fertility, water quality, biodiversity, and food safety. Prior to the war, excessive use of pesticides and mineral fertilizers already led to residue accumulation in soils and water bodies, as well as contamination of crop products (Mazur and Matuselych, 2023). The share of counterfeit plant protection products on the Ukrainian market is traditionally estimated at 20–25%, resulting not only in reduced crop protection efficiency but also in additional chemical pollution of soils, surface and groundwater, and risks to non-target organisms (including bees) (Budziak and Budziak, 2025). Counterfeit products often contain higher levels of toxic impurities that degrade slowly and migrate through environmental compartments. The full-scale

war has significantly intensified these risks. Military actions have caused soil contamination with HM, residues of explosive substances, and combustion by-products. In conflict-affected areas, HM concentrations often exceed maximum permissible levels by several times. For example, in northern and eastern regions (Chernihiv, Sumy, Kharkiv oblasts), elevated levels of Pb, Zn, and Cd have been recorded, posing long-term threats to agricultural land use and the entry of toxicants into trophic chains (Solokha et al., 2023; 2024). The destruction of industrial and agricultural infrastructure, as well as agrochemical and fuel storage facilities due to military operations, leads to localized and regional environmental disasters. Combined with excessive agrochemical use, this creates a cumulative effect that accelerates soil degradation, reduces microbial activity, and diminishes biodiversity, while also deteriorating agricultural product quality. Limited financial resources, high investment risks, and overall global economic and political instability significantly hinder the implementation of necessary innovations such as precision agriculture, biological plant protection products, pollution monitoring systems, and soil restoration technologies. At the same time, the demand for such innovations is increasing exponentially, as without systemic solutions to pollution, the long-term sustainability and competitiveness of Ukraine's agricultural sector are at risk. The highly complex contemporary conditions, combining the challenges of war, accelerated climate change, limited natural resources, and Ukraine's European integration process, create unique opportunities for a fundamentally new development trajectory in agricultural science and the sector as a whole. Ukrainian agricultural production requires transformation. There is a growing demand for resource-efficient, climate-adapted, and environmentally safe technologies, as well as for products meeting high international environmental standards. Producers are increasingly aligning with European requirements, particularly those defined by the European Green Deal, which has become a strategic framework for sustainable agricultural development. Compliance with the principles of the European Green Deal (European Commission, 2019) opens new opportunities for Ukrainian agriculture in terms of access to EU markets, increased added value, and strengthened competitiveness. At the same time, this requires substantial restructuring of technological processes (European Commission, 2020), implementation of digital solutions, precision farming, circular resource-use models, and a significant strengthening of

the environmental dimension of production (European Commission, 2020). In this context, science–business interaction becomes strategically important, as it ensures technology transfer, innovation implementation, and enhanced sectoral competitiveness. At the global level, this defines a paradigm shift – from an extensive

production model characterized by excessive exploitation of natural resources and the principle of “profit above all” to a sustainable ecological model based on natural laws and ecological principles, integrating environmental management, economic profitability, and social responsibility (Table 1).

Table 1 Transformation of agricultural production models

Indicator	Extensive model (Past)	Sustainable ecological model (Future)
Resource use	Maximum exploitation of soil and water resources	Optimization, resource conservation, closed cycles
Technologies	Analog solutions, excessive use of chemical fertilizers and pesticides, monoculture	Smart technologies, precision agriculture, digitalization
Market focus	Orientation exclusively on volume	Quality, safety, EU eco-standards
Risk management	Reactive response to losses	Scientific forecasting, flexible business models

Model of natural resource use

The current model of natural resource use in Ukraine’s agricultural sector remains predominantly extensive–intensive (conventionally intensive), characterized by high anthropogenic pressure on agroecosystems. It is manifested in excessive ploughing of land (68–70% of the national land fund, of which more than 78% is arable land), the dominance of monocropping systems (wheat, maize, and sunflower), intensive application of agrochemicals, and conventional tillage practices. These

factors have led to the progressive degradation of chernozem soils. Water erosion affects approximately 13.4 million hectares of agricultural land, including 10.6 million hectares of arable land. Overall land degradation has impacted more than 40% of agricultural areas (Table 2). The SOC content in chernozems has decreased by 15–40% compared to the natural (virgin) state, while annual humus losses in the arable layer amount to 0.5–0.9 t/ha (FAO, 2022; Li et al., 2025; Baliuk et al., 2023).

Table 2. Comparative analysis of extensive–intensive and regenerative farming systems

Indicator	Extensive-intensive model	Ecologically oriented (regenerative) model	Sources
Approach to soil	Resource exploitation	Restoration and enhancement of natural capital	FAO (2022); Li et al. (2025)
Tillage	Intensive tillage	Minimal/zero tillage	Baliuk et al. (2023)
Crop structure	Monoculture	Diversification + cover crops	Houunkpatin et al. (2026)
Technogenic load (inputs)	High	30–76% reduction in the long term	Houunkpatin et al. (2026)
Change SOC / humus	Loss of 0.5–0.9 t/ha annually	Conservation and enhance-ment (+0.3–1% in 3–5 years)	He et al. (2026); Baliuk et al. (2023)
Resilience to climate stresses	Low	Significantly higher (better water retention capacity)	Houunkpatin et al. (2026)
Yield (long-term)	Reduction due to degradation	Stable or higher (+7–27% depending on practice)	Houunkpatin et al. (2026)
Cost efficiency	Dependence on external inputs	Cost reduction + new sources of income (carbon credits)	World Bank; HeavyFinance (2024–2025)
Risk of tipping points	High	Significantly reduced	Kraamwinkel et al. (2021)

Model of natural resource use

The alternative paradigm of natural resource use is grounded in the principles of regenerative agriculture and agroecology. Unlike the conventional intensive model, it is aimed not only at maintaining the current state of soils but also at actively restoring and enhancing their ecosystem functions, strengthening biodiversity, increasing carbon sequestration, and improving the climate resilience of agroecosystems. The transition to such a model supports not only the restoration of chernozem fertility but also the formation of resilient agroecosystems capable of withstanding climate change, droughts, and biotic stresses. Empirical evidence demonstrates that the systematic implementation of regenerative practices significantly enhances production resilience and reduces external dependence on agrochemicals (Hounkpatin et al., 2026; FAO, 2022). This approach integrates monitoring as a critical component of agricultural resource assessment, using advanced tools such as remote sensing, satellite data, un-

manned aerial vehicles (UAVs), sensor networks, and artificial intelligence algorithms (Tarariko et al., 2025). It also includes essential technological blocks such as restoration technologies – scientifically grounded approaches for the remediation of damaged and mined soils – and adaptation strategies, including the development of climate-resilient and ecologically plastic crop varieties, the use of predictive climate models, and related tools. Innovation-oriented solutions include the development and implementation of precision agriculture systems and advanced water management technologies. Figure 3 shows a conceptual transition model of the Ukrainian agricultural sector from a crisis-affected state characterized by systemic vulnerabilities, environmental degradation, infrastructural destruction, and low value-added production toward a target ecosystem defined by resilience, climate-smart agricultural practices, innovation-driven growth, and full integration into global markets in alignment with the Sustainable Development Goals.

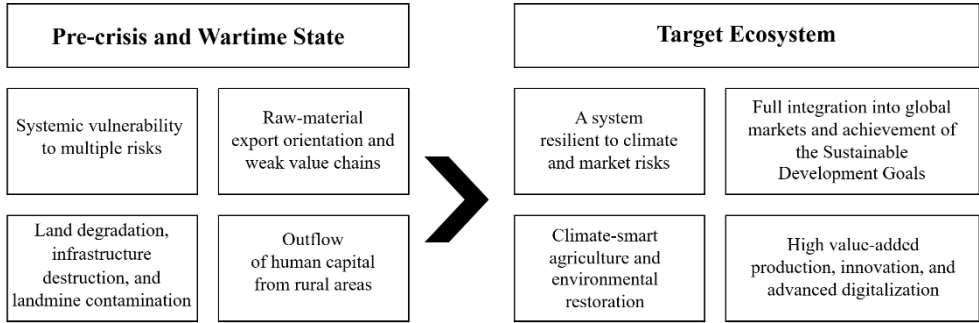


Figure 3
Target resilience model of the Ukrainian agricultural sector

Among the key strategic priorities for the post-war development of Ukraine’s agricultural sector, two main directions can be identified: (i) restoration of natural resources, primarily soils, and (ii) transformation of agricultural production based on innovative environmentally oriented technologies. The first direction is associated with large-scale land losses resulting from military activities. Contemporary international practice demonstrates the effectiveness of land reclamation and remediation based on ecosystem-based restoration and Nature-Based Solutions (NBS) (Alkorta and Garbisu, 2021). These approaches rely on the use of hyperaccumulator plants in symbiosis with rhizosphere microorganisms to extract and stabilize HM in soils (Thomas et al., 2021). The efficiency of these processes significantly increases when plants are combined with functional microbial consortia that enhance soil biogeochemical cycling (Raffa et al., 2021). An important complementary approach is the use of organo-mineral amendments and biochar, which stabilize SOC and im-

prove structural and functional soil properties (Chiampo and Zacchini, 2021). In the context of soil restoration, international assessments indicate that total costs may reach USD 20 billion, representing approximately 15% of Ukraine’s pre-war GDP (Didenko, 2024). Overall recovery needs for the agricultural sector are estimated at USD 56.1 billion (World Bank, 2024). The second strategic direction involves the implementation of innovative sustainable farming technologies aligned with EU policies, particularly the European Green Deal and the Farm to Fork Strategy (European Commission, 2020). For example, precision agriculture can reduce input use by 15–25% and increase yields by 10–20% through optimized agroecosystem management (Zhang and Kovacs, 2012). Climate-smart agriculture focuses on reducing greenhouse gas emissions and enhancing soil carbon sequestration capacity. According to FAO estimates, sustainable soil management practices can sequester 2–5 t CO₂-eq·ha⁻¹ annually, depending on

soil type and management system (Sweetha, et al., 2025). No-till and reduced tillage systems combined with cover crops can reduce CO₂ emissions by 20–30% and increase soil organic matter in the topsoil horizon (Lal, 2020). Organic agriculture excludes synthetic fertilizers and pesticides while promoting soil fertility and biodiversity conservation. According to EU Regulation (EU) 2018/848, such systems are based on ecological balance, closed biogeochemical cycles, and minimal external inputs (European Commission, 2018). Organic farming systems can increase soil organic carbon by 0.1–0.3 t C·ha⁻¹·year⁻¹ and enhance soil biodiversity by 20–50% compared to intensive systems (Lori et al., 2017). These approaches are fully aligned with EU targets, which include a 50% reduction in pesticide use and at least a 20% reduction in mineral fertilizers by 2030 (World Bank, 2023) In this context, value crea-

tion agricultural production increasingly depends on ecological certification and compliance with sustainability standards. For Ukraine, international integration and compliance with international standards in the field of agriculture is not only a requirement of the time, but also a strategic condition for integration into the global agricultural market (Fig. 4). The implementation of organic and low-carbon farming systems provides access to premium EU market segments, where environmental performance, traceability, and sustainability compliance are highly valued. Organic products in the EU are sold at prices 20–60% higher than conventional products, and the European organic food market exceeds €45 billion with steadily growing demand (Willer et al., 2024). Accordingly, the transition to organic and low-carbon production offers significant economic advantages for export-oriented farms in Ukraine.

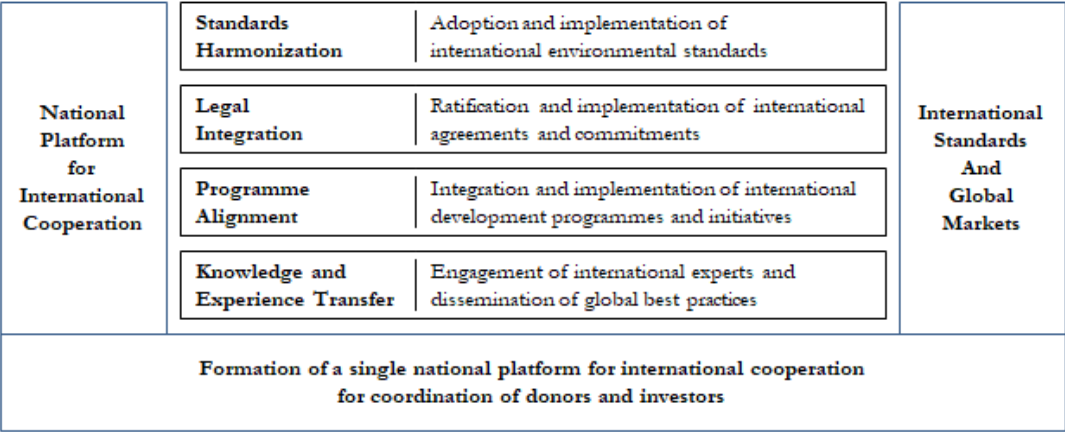


Figure 4
International integration as a catalyst for agricultural sector growth in Ukraine

Figure 4 illustrates the role of international integration as a catalyst for the sustainable development and modernization of the agricultural sector. The framework emphasizes the importance of aligning national policies and practices with international standards, strengthening legal and institutional integration, implementing international programmes, facilitating knowledge transfer, and establishing a national coordination platform. Together, these measures enhance access to global markets, attract international investment, and support the achievement of sustainable development objectives. Furthermore, compliance with international standards enables participation in carbon financing mechanisms. Under voluntary carbon markets, agricultural producers can receive compensation for soil carbon sequestration. According to the World Bank, carbon credit prices range from USD 10 to 50 per t CO₂-eq, potentially generating additional income of USD 50–250 per hectare per year depending on im-

plemented practices (World Bank, 2023). However, participation in such mechanisms requires the implementation of MRV systems aligned with international standards (Verra, 2022). Thus, the development of organic and low-carbon agriculture in Ukraine is not only environmentally justified but also economically viable, contributing to integration into the European agricultural space, increasing product competitiveness, and attracting investment for agroeco-system restoration. Such approaches are consistent with the principles of sustainable development and are linked to the implementation of the SDGs (Fig. 5). Another promising direction is the implementation of Agricultural Technology (AgTech), which includes modern digital and innovative solutions aimed at improving production efficiency, optimizing resource use, and ensuring environmental sustainability. AgTech encompasses precision farming technologies, automated monitoring systems for soil and crop conditions,

Economic Dimension	Environmental Dimension	Social Dimension
Modernization of the production base and enhancement of investment attractiveness	Implementation of sustainable land and water management practices, restoration of degraded land, and conservation of biodiversity	Job creation and development of social infrastructure
Development of export capacity and agricultural value chains	Climate change adaptation and reduction of anthropogenic environmental pressures	Improvement of the quality of life of the rural population
Support for small and medium-sized agricultural enterprises	Development of organic and climate-smart agriculture	Support for youth and women, human capital development, and labor force reintegration

Figure 5
Contribution of agricultural sector transformation to the achievement of the Sustainable Development Goals

sensors, UAVs, satellite data, big data analytics, and artificial intelligence components (Wolfert et al., 2017). Recent studies confirm that the integration of digital technologies into agriculture significantly improves agroecosystem management. Remote sensing and UAV-based monitoring enable high-precision, real-time assessment of crop and soil conditions (Tsouros et al., 2019). Sensor networks and IoT technologies provide detailed data on soil moisture, nutrient content, and physicochemical parameters, which are essential for informed decision-making (Jawad et al., 2017). The implementation of AgTech enables real-time agroecosystem control, yield forecasting, and resource optimization. Machine learning and artificial intelligence algorithms improve yield prediction accuracy by 10–25% and reduce input costs by 15–30% (Kamilaris and Prenafeta-Boldú, 2018). Moreover, variable-rate application of fertilizers and plant protection products based on geospatial data reduces environmental pressure and nutrient losses (Cai et al., 2025). For scientific research, AgTech is a critical tool for high-resolution data collection, long-term monitoring, and modelling of soil and biological system dynamics. The integration of big data with ecological models enables more robust agroecosystem management and improved forecasting under climate change conditions (Wolfert et al., 2017). These directions define a new agricultural development paradigm – innovative, ecologically balanced, and economically efficient. The shift toward climate-oriented agriculture, digitalization of the agricultural sector, and integration into the European scientific and

tural science. The current situation in Ukraine is paradoxical: on the one hand, substantial losses and risks; on the other, unique opportunities for sectoral renewal aligned with modern global requirements. The results of the analysis confirm that the systemic crisis in Ukraine’s agricultural production is highly complex and multifactorial. Anthropogenic pressure, outdated technologies, systematic violations of agronomic practices, monocropping systems, and chronic financial constraints generate persistent synergistic positive feedback loops. These loops drive progressive degradation of chernozem soils, substantial losses of SOC, and a systemic decline in agroecosystem resilience. A comparison between the current extensive–intensive model of natural resource use and the alternative eco-oriented regenerative model clearly demonstrates the need for deep structural transformation. International experience from the implementation of the European Green Deal (2019) and the Farm to Fork Strategy (2020) provides important lessons for Ukraine. EU countries have shown that systemic agricultural crises can be effectively mitigated through comprehensive public policies aimed at reducing environmental pressure, diversifying production systems, and restoring soil ecosystem functions. The Netherlands and Denmark are among the most successful examples, where the integration of precision agriculture and regenerative practices has significantly reduced nitrogen and pesticide inputs without critical productivity losses (Schreefel et al., 2022). At the same time, experiences from France, Germany, and Eastern European coun-

tries (Poland, Hungary) demonstrate that ambitious environmental targets without adequate transitional financial support may generate significant socio-economic resistance (Kolasiński and Wigier, 2026; Pawłowski et al., 2024). A key lesson is that successful transition requires not only regulatory frameworks but also effective economic instruments such as green finance, payments for ecosystem services (carbon farming, biodiversity credits), MRV systems, and targeted support for small and medium-sized producers. Empirical evidence shows that regenerative practices can increase yields by 7–27% in the long term while simultaneously restoring soil organic carbon and enhancing climate resilience (Hounkpatin et al., 2026; Hawes et al., 2025). For Ukraine, integrating the principles of the European Green Deal into post-war agricultural recovery is strategically justified. However, direct transfer of EU approaches without adaptation to national specificities (high share of chernozems, war impacts, land-use structure) may be counterproductive. A tailored national model is required, combining gra-

dual reduction of anthropogenic pressure with simultaneous soil restoration, promotion of agroecological diversification, large-scale implementation of precision agriculture, and development of effective financial mechanisms supporting the transition. The Figure 6 presents a conceptual framework for overcoming the systemic crisis of the agricultural sector based on six interrelated dimensions: institutional transformation, economic recovery and competitiveness, environmental sustainability and climate adaptation, human capital and rural development, risk management and resilience building, and post-war recovery and reconstruction. The integrated implementation of these directions is aimed at creating a competitive, environmentally sustainable, and socially inclusive agricultural sector capable of supporting the achievement of long-term Sustainable Development Goals. This division is well aligned with the three components of sustainable development and at the same time takes into account the current challenges of Ukraine's agricultural sector.

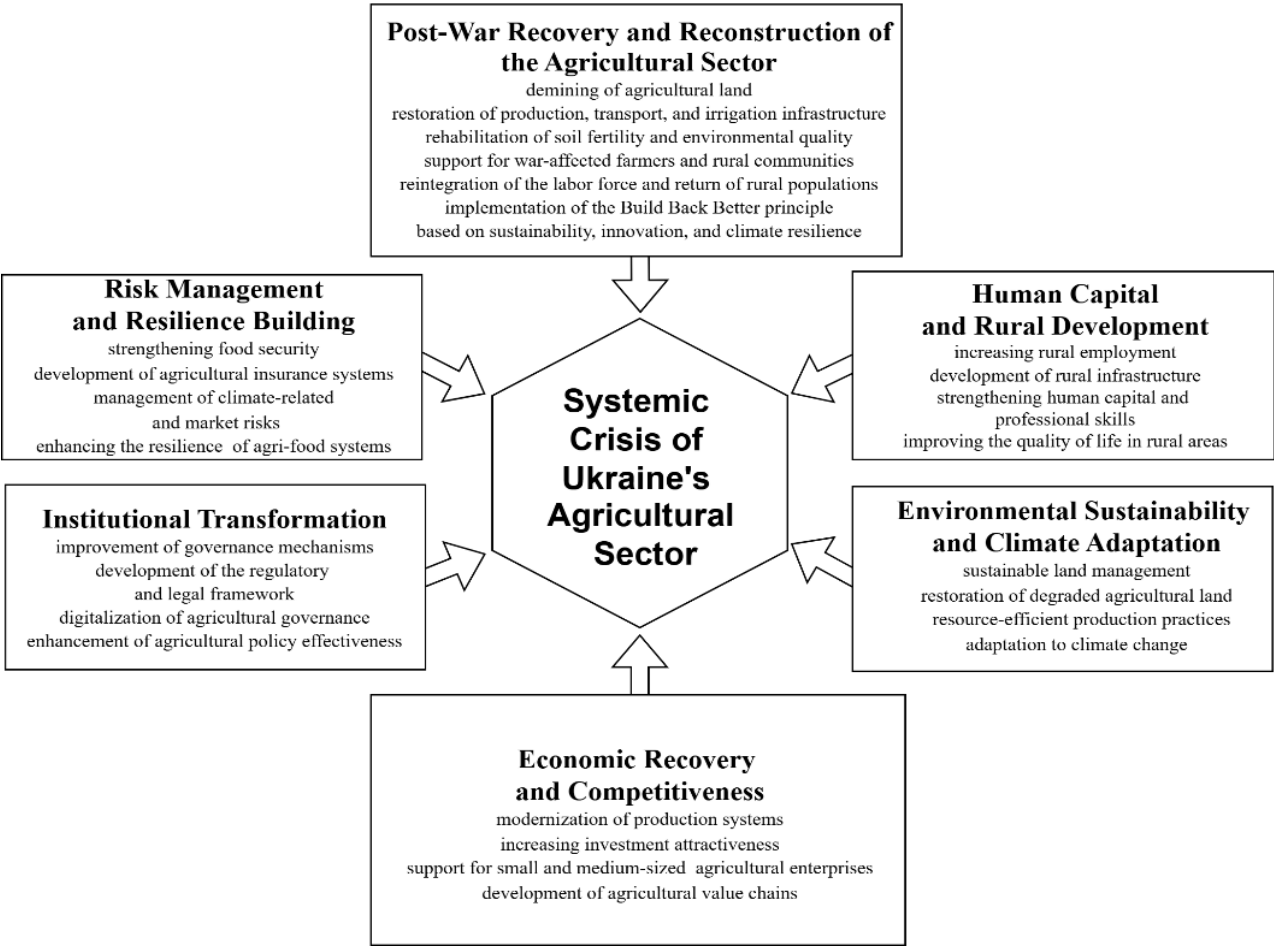


Figure 6 Conceptual framework for overcoming the systemic crisis of the agricultural sector through sustainable development and post-war reconstruction

For agricultural producers, current transformations imply not only new opportunities but also significantly higher environmental and market requirements. The key trend is the shift toward sustainable production systems, where organic and low-carbon agriculture, reduced chemical input use, and soil conservation determine access to European and global markets. Under EU policy, particularly the Farm to Fork Strategy, targets include a 50% reduction in pesticide use and a 20% reduction in mineral fertilizers by 2030 (European Commission, 2020a). In conditions of rising input costs and market volatility, operational efficiency becomes a critical competitiveness factor. Precision agriculture technologies reduce production costs by 15–25% and increase yields by 10–20% (Cai et al., 2025). An additional adaptation strategy involves diversification of cropping systems, particularly the transition to more drought- and stress-resilient crops and varieties. According to IPCC assessments, such adaptations can reduce yield loss risks by 20–30% (IPCC, 2019). Overcoming the systemic crisis in Ukrainian agricultural production is possible only through a comprehensive transformation of the natural resource use model – from an extensive–intensive system to an eco-oriented regenerative one. The European Green Deal demonstrates that such transformation is technically feasible, environmentally necessary, and economically promising, provided it is adapted to national conditions and supported by strong state policies and integration of science, technology, and business.

Conclusions

Overcoming the current crisis is impossible without a fundamental paradigm shift in the use and conservation of agricultural resources. The transformation of Ukraine's agricultural science and production systems requires scientifically grounded ecological solutions aimed at transitioning from a resource- and energy-intensive extensive model toward an innovation-oriented, high-tech, and environmentally balanced system. The results of the analysis indicate that the key driver of these transformations is the integration of scientific research, digital technologies, and environmentally oriented approaches. In this context, agricultural science performs not only the function of knowledge generation but also serves as a practical instrument for transforming production systems through the implementation of AgTech solutions, precision agriculture models, low-carbon technologies, and ecosystem-based approaches to land resource ma-

agement. The environmental component of agricultural development is acquiring particular strategic importance and is gradually becoming the core of the sector's future development. Rational natural resource management, restoration of soil resources, and reduction of anthropogenic environmental pressure determine the long-term sustainability of the agricultural sector and its capacity to adapt to climatic and market challenges. In this regard, the greening of agricultural production should not be viewed as a constraint but rather as a prerequisite for maintaining global competitiveness. The obtained results suggest that Ukraine's agricultural sector is entering a qualitatively new stage of development, in which competitive advantages will be determined not by production scale alone but by innovation capacity, resource-use efficiency, and compliance with international environmental standards. The greatest benefits will accrue to those agricultural stakeholders capable of early adaptation to emerging technological and environmental requirements. Consequently, the combination of scientifically grounded approaches, digital transformation, and ecological modernization creates the foundation for the transition of Ukraine's agricultural sector toward a sustainable, innovation-driven, and globally integrated development model. In the long-term perspective, ecology and rational natural resource management will determine the trajectory of recovery, operational efficiency, and international competitiveness of Ukraine's agricultural sector.

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