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Scenario modeling of grain production potential in conditions of military risk: the case of Ukraine

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This paper examines the transformation of Ukraine's grain sector under the conditions of the full-scale war and its implications for global food security. Using annual data from 2000 to 2023, we forecast grain production potential for 2025–2026 carrying out ARIMA models (a non-seasonal specification within the SARIMA family). To support interpretation under heightened uncertainty, the results are discussed through three military-risk scenarios -low, medium, and high—that differ in the severity of constraints on agricultural operations and export logistics. The study finds that even under the high-risk scenario, Ukraine retains the capacity to supply over 5% of global grain exports. We argue that the key determinants of sector resilience include technological modernization, institutional support, and logistical adaptation. Additionally, an integrated scenario matrix is developed to link strategic priorities, implementation levers, and financing sources for grain-sector modernization. Four vectors for strengthening long-term resilience are identified: economic, technological, institutional, and European integration. The findings suggest that a coordinated, multi-vector strategy can help offset wartime losses and support Ukraine's integration into the European market with higher value added and greater resistance to external shocks.

KEYWORDS
agricultural sector, food security, grain production, scenario analysis, Ukraine, war crisis

1 Introduction

The Russian military aggression against Ukraine has triggered a multifaceted crisis, one of the most acute manifestations of which is the threat to global food security. Prior to 2022, Ukraine accounted for up to 12% of global wheat and corn exports, while its share in barley supplies exceeded 16% (Potori and Molnar, 2024). Indeed, over the past two decades, Ukraine has become as a key player in the global markets for grains, oilseeds, and their derivatives exporting 20 million tonnes of wheat—which represents approximately10% of the global market share. The blockade of Black Sea ports, the destruction of grain storage infrastructure, and the partial mining of agricultural land caused a 32% reduction in total grain harvest in 2022, disrupting established supply chains, particularly for countries in the Middle East, North Africa, and Sub-Saharan Africa. In this context, assessing the current state and forecasting the potential of Ukrainian grain production is critically important not only for the national economy but also for international food policy coordinated by humanitarian institutions, including the Food and Agriculture Organization of the United Nations (FAO), the World Food Programme (WFP), and the International Food Policy Institute (IFPRI).

To contextualize the scenario assumptions and the interpretation of baseline forecasts, we draw on recent assessments by leading international organizations that document structural shifts in global grain markets and the transmission of wartime shocks. The OECD–FAO Agricultural Outlook 2024–2033 projects that global demand for grains will increase by 12% by 2032, while yield growth is expected to slow down (OECD–FAO Agricultural Outlook 2024–2033). According to the IFPRI Global Food Security Update (2023), the FAO Global Food Price Index remains 17% above the pre-crisis level, with a substantial portion of recent grain-price pressures linked to the war in Ukraine (FSIN and GNAFC, 2025). AMIS Market Monitor No. 109 highlights regional supply tensions and trade re-routing effects resulting from constraints in Black Sea export routes and increased reliance on alternative corridors (AMIS, 2023). In turn, USDA WASDE Report Q1 (2024) reports a decline in global ending grain stocks to a multi-year low of 591 million tons, reinforcing the relevance of Ukraine's production and export capacity for global food security.

The objective of this study is to assess Ukraine's grain production potential in 2025–2026 using a non-seasonal ARIMA framework and to interpret the resulting baseline trajectories under alternative wartime risk conditions. To achieve this goal, a number of tasks were set, including the development of an integrated statistical database for the period 2000–2023, the construction and verification of ARIMA models (a non-seasonal specification within the SARIMA family) for key indicators and an assessment of their implications for total harvest, exports, and foreign exchange earnings, exports, and foreign exchange earnings, as well as a comparative analysis of the authors' forecasts with estimates from international organizations. The information base of the study was formed using official statistical sources (i.e., FAOSTAT; USDA; World Bank Pink Sheet; Ministry of Agrarian Policy of Ukraine, Ukrzaliznytsia (UZ), and the Ukrainian Sea Ports Authority).

Agriculture plays a crucial role in maintaining the sustainability of natural resources and protecting biodiversity, especially in the face of climate change issues. Additionally, agricultural production and trade must adapt and expand to meet the rising food demands in both developed and developing nations (Balogh and Jámbor, 2020; Chmieliński et al., 2018). At the national level, academic schools, research institutions, and analytical centers have been actively studying a wide range of issues related to the functioning of the agricultural sector under wartime conditions during 2022–2024. For example, For example, recent research by Malakhail et al. (2023) shows that food inflation in North American countries reached its peak primarily due to two major factors: the COVID-19 pandemic and the Russia–Ukraine war, with several pandemic-related disruptions significantly contributing to this increase. Several pandemic-related disruptions significantly contributed to this rise in inflation. Overall, three main research directions can be distinguished: assessing the losses of production potential and logistical infrastructure (Hrynchak et al., 2023), modeling scenarios for the recovery of sown areas and total grain harvest (Nykolyuk et al., 2022), and analyzing the macroeconomic consequences for gross domestic product, foreign trade, and regional economies (Andriushchenko et al., 2020).

Panfilova et al. (2025) present notable research into the sectoral characteristics of the Ukrainian grain market during the war and its prospects after its end. Researchers emphasize the strategic importance of implementing circular economy principles in Ukraine's agricultural sector, especially in the context of globalization challenges and military threats. The authors emphasize that the war has led to a significant reduction in cultivated areas, a decline in livestock numbers, destruction of infrastructure, and a decline in export potential, directly affecting the productivity and profitability of agricultural enterprises. These results are directly relevant to scenario modeling of grain production, as they allow for a range of factors to be taken into account, from a reduction in the resource base to logistical constraints (Shebanin et al., 2024). Similar conclusions are reported by Mykhailova et al. (2023), Zavadska et al. (2025), Tananaiko et al. (2023), and Bazaluk et al. (2022), who emphasize that wartime disruptions—ranging from reduced sown areas and lower yields to infrastructure damage and export/logistics constraints—translate into losses in production potential. Indeed, Neik et al. (2023) argue that the global food system has become too dependent on a small number of crops, regions, and supply chains, and the Russia–Ukraine crisis exposed how fragile that system is. Xue et al. (2025) argue that agri-food supply chains are fragile because they are highly interconnected and optimized for efficiency. As a result, disruptions—whether economic, environmental, or political—can spread quickly across the system. Their main point is that food insecurity depends not just on production, but on how risks propagate through supply chains, so resilience requires managing these systemic vulnerabilities. Focusing on this, Mkumbukiy et al. (2025) examine how to make agri-food systems more resilient to geopolitical tensions. They argue that food security depends on systems that can withstand and adapt to disruptions like conflicts and trade shocks. Samoilenko et al. (2024) examine how war conditions affect the international logistics of agricultural products. They show that war disrupts transport routes, infrastructure, and supply chains, making food movement slower, more costly, and less reliable, so logistics systems must adapt with alternative routes and more flexible coordination. For example, another recent research on Ethiopia conflicts points out that wars disrupt farming activities, reduce crop production, and damage infrastructure, such as irrigation systems or storage facilities, while also limiting access to markets and inputs, all of which threaten food security and livelihoods (Gejea and Tolesa, 2024).

Recent advances in grain yield forecasting highpoint machine learning (ML) as a pivotal methodological shift driven by the necessity to better embody nonlinear and interacting agro-climatic processes (Shawon et al., 2025; Shahhosseini et al., 2021). Early conceptual work by Lobell and Burke (2010) demonstrated that flexible, data-driven models could improve yield predictions under climate variability by relaxing assumptions of linearity inherent in traditional regression approaches. Their findings laid the foundation for broader adoption of ML techniques in climate–agriculture research. Subsequent empirical studies systematically evaluated the performance of ML algorithms in operational forecasting contexts. Jeong et al. (2016) showed that ensemble methods, particularly Random Forest, consistently outperform linear models in regional crop yield prediction due to their robustness to multicollinearity, noise, and heterogeneous inputs. Neural network–based approaches further expanded the modeling capacity of ML in agriculture. Khaki and Wang (2019) demonstrated that artificial neural networks could effectively learn high-dimensional relationships between weather variables and crop yields, achieving superior predictive accuracy when sufficient training data are available. However, their work also highlighted key limitations, including reduced interpretability and sensitivity to hyperparameter selection. A comprehensive synthesis by Xi et al. (2021) underscored that despite their predictive strength, ML models face challenges related to data quality, transparency, and generalizability. Collectively, these studies converge on the conclusion that ML methods are most effective when integrated with domain knowledge and used alongside process-based crop models, particularly for decision support and policy-relevant grain production forecasting. Becker-Reshef et al. (2010) develop a regression-based model using MODIS satellite data (Moderate Resolution Imaging Spectroradiometer, which is a satellite sensor aboard NASA's Terra and Aqua satellites) to forecast winter wheat yields in Kansas and Ukraine. Their approach enables large-scale, early-season yield estimation with strong predictive performance. Regarding the contrast mechanistic and data-driven forecasting methods, Van Ittersum et al. (2003) describe Wageningen crop models using weather, soil, and management inputs with physiological data, on the other hand Van Klompenburg et al. (2020) review ML approaches for yield prediction, highlighting high accuracy from nonlinear, multi-source data but limited interpretability. Naylor et al. (2007) analyze the impacts of climate variability and change on Indonesian rice production, showing significant yield risks from temperature and rainfall fluctuations. The work emphasizes the need for adaptive strategies to maintain food security under changing climate conditions. Joshi et al. (2024) present deep transfer learning methods that combine climate records and satellite time-series data to predict crop yields by capturing spatio-temporal patterns, improving accuracy over traditional machine learning models. Wang et al. (2022) show that integrating machine learning and deep learning with satellite time-series improves classification accuracy across diverse crops. Table 1 presents a comprehensive synthesis of the principal methodologies applied in grain production forecasting, specifying the types of input data employed, their methodological advantages, and inherent limitations, as documented in the extant literature.

The remainder of the paper is organized as follows. The next section describes the data and methodology. The subsequent section presents the empirical results and forecasts. The final section discusses the findings, limitations, and scenario implications.

2 Methodology

The information base of the study was formed using official statistical sources, including FAOSTAT (Production_Crops section); USDA (WASDE and PSD Reports; WASDE, 2024); World Bank Pink Sheet (FOB prices); as well as operational data from the Ministry of Agrarian Policy of Ukraine, Ukrzaliznytsia (UZ), and the Ukrainian Sea Ports Authority (USPA). Primary data series were compiled from official statistical sources (FAOSTAT, USDA, FAO GIEWS) for the period 2000–2023. The estimation sample ends in 2023 because a finalized and fully harmonized annual data for 2024"was not consistently available across the sources used at the time of manuscript preparation. All the data were converted into common units of measurement (million tons, tons per hectare, USD per ton).

Data consistency and harmonization (2000–2023). To ensure comparability over time, the core forecasting series were compiled at the national annual level from internationally harmonized statistical sources (FAOSTAT, USDA, FAO GIEWS), which reduces distortions that may arise from regional reporting breaks and administrative-border changes. Where multiple sources reported overlapping values, we relied on consistent definitions and units and used cross-source checks to confirm the direction and magnitude of year-to-year changes. Regional and operational information (e.g., from the Ministry of Agrarian Policy of Ukraine, UZ, and USPA) is used to contextualize wartime constraints and interpret scenarios rather than to construct the national estimation series. Any remaining discontinuities, definitional updates, or reporting gaps are treated transparently as limitations of the available data and are discussed in the limitations section. Overall, this approach prioritizes a stable, reproducible national time series suitable for annual forecasting while acknowledging the presence of wartime measurement constraints.

Before modeling, all time series were tested for stationarity: for total grain harvest, the unit root hypothesis could not be rejected (ADF: $\tau = -1.87$; $p = 0.34$), and stationarity was achieved after first differencing ($\tau = -4.21$; $p < 0.01$). Because the empirical analysis uses annual data, intra-annual seasonality is not modeled; therefore, a non-seasonal ARIMA specification was applied This specification choice follows standard time-series forecasting guidance (Hyndman and Athanasopoulos, 2021; Nau, 2023). Table 2 presents the specification

TABLE 1 Methods and data used in grain production forecasting: strengths, limitations, and key sources.

Methods	Data	Strengths	Limitations	Key sources
Statistical models	Historical yield, weather	Simple, transparent	Poor with nonlinear effects	Naylor et al. (2007)
Crop growth models	Weather, soil, management	Physiological realism	Data- and calibration-intensive	van Ittersum et al. (2003)
Remote sensing	NDVI (Normalized Difference Vegetation Inde), EVI (Enhanced Vegetation Index), SAR (Synthetic Aperture Radar)	Large-scale, early forecasts	Cloud/sensor issues	Becker-Reshef et al. (2010)
Machine learning	Weather + satellite + soil	High accuracy, flexible	Limited interpretability	van Klompenburg et al. (2020)
Deep learning	Time-series satellite and climate	Captures spatio-temporal patterns	High data & compute needs	Joshi et al. (2024)
Hybrid approaches	Deep learning + Machine Learning + time-series satellite data	Robust, improved accuracy	Complex implementation	Wang et al. (2022)

Source: compiled by the authors based on the cited sources.

TABLE 2 Parameters of the forecast models.

Indicator	Model	MA(1)	MA(2)	Drift	σ^2	AIC	MAPE % (2019–2021)
Gross output	ARIMA(0,1,2)	−0.77	+0.37	–	63.85	132.6	8.56
Export	ARIMA(0,1,0) + drift	–	–	+2.20	62	143.1	6.78
FOB price	ARIMA(0,1,1)	−0.13	–	–	142	202.8	6.36
Yield	ARIMA(0,1,1)	−0.34	–	–	0.107	28.8	8.43

Source: Author's own research.

of the ARIMA models used for four key indicators: total grain harvest, exports, FOB price, and yield Model comparison also considered the Akaike information criterion (AIC) as a standard fit–parsimony criterion (Boisbunon et al., 2014). We focus on four indicators—gross grain output, yield, exports, and FOB price—because together they capture (i) supply capacity and productivity (output and yield), (ii) the ability to convert production into realized external demand under logistical constraints (exports), and (iii) the external price environment that shapes revenue potential and incentives for recovery and modernization (FOB price). Other determinants (e.g., land area, investment, labor) are important but are not modeled explicitly in order to keep the forecasting framework transparent and comparable over the full 2000–2023 period using consistently available annual series. ARIMA is employed here as a parsimonious baseline model for annual series, where the primary objective is generating transparent, replicable benchmark trajectories under heightened uncertainty. More structural approaches would require additional consistently measured covariates and stronger identifying assumptions, which are beyond the scope of this study. Accordingly, we interpret ARIMA projections as baseline paths that support the subsequent scenario discussion rather than as precise point predictions.

Scenario modeling is used to interpret baseline ARIMA projections under different levels of military risk. We distinguish three scenarios (low, medium, high) that differ in the severity of constraints on land access, inputs, infrastructure, and export logistics. These scenarios are not estimated as separate statistical models; they complement the quantitative baselines by making assumptions explicit and linking them to policy and modernization levers (Table 3).

3 Results

The key analytical findings from the aforementioned international and national studies serve as an important foundation for scenario forecasting. In particular, the logistical factor is identified as one of the most sensitive elements in the post-war export model. According to estimates by the Kyiv School of Economics, expanding port capacity by 10 million tons could potentially add up to 2% to gross domestic product (KSE, 2023). At the same time, infrastructure losses, including the destruction of 6.5 million tons of grain storage capacity, have turned storage into a bottleneck in the value chain, increasing operating costs by USD 12–17 per ton. Mine hazard limit the area of agricultural land available for use and effectively sets the upper boundary of the pessimistic development scenario. Against the backdrop of reduced access to traditional production resources, the importance of technological modernization is increasing. In particular, the introduction of precision farming in selected pilot farms has resulted in a 7% increase in yields and a 12% reduction in fertilizer costs (FAO, 2022a). In the context of the post-war restructuring of the agricultural economy, combining technological solutions with new institutional mechanisms aimed at increasing value added in agricultural production becomes particularly important. On the one hand, modernization through the implementation of precision farming technologies, sensor-based monitoring, automated resource management, and the use of satellite data (including through the Copernicus program and AgTech platforms) lays the foundation for sustainable productivity growth under resource constraints. The concept of Agriculture 4.0, which involves the integration of digital tools into all stages of the production cycle, makes it possible to achieve yield increases of 5–9% and reduce fertilizer, fuel, and crop protection costs by 10–15% (FAO, 2022b; Wyman, 2018). On the other hand, the shift from raw material exports to a model with a developed processing sector—flour milling, oil extraction, feed, and biotechnology industries—creates the potential for additional foreign currency earnings of over USD 2.5 billion annually, even under conditions of partial recovery of pre-war production.

Another important parameter is the "war premium" in logistics, which amounts to USD 16–22 per ton in ports under FOB delivery terms. Despite the gradual recovery of export tonnage, this factor drives the downward trend in foreign exchange revenues. This phenomenon was incorporated into the construction of pricing models in the relevant part of the study (Latifundist, 2022). Thus, Ukrainian analytical sources not only detail the scale of losses but also provide quantitative elasticity parameters, which were integrated into the econometric model and the system of recommendations developed within this analysis.

The study combines statistical and econometric methods to assess Ukraine's grain production potential under wartime risk. Logistics constraints are reflected in scenario assumptions through export capacity limits and corridor availability, which affect the feasible export volumes and the interpretation of production potential under military risk. Reported diagnostics include MA terms, drift (where applicable), residual variance (σ^2), AIC, and MAPE for the 2019–2021 test period.

The results indicate an acceptable level of forecast accuracy across the specifications. The FOB price model exhibits the lowest error (MAPE $\approx$ 6.36%), whereas the yield model is more variable (MAPE $\approx$ 8.43%). Overall, the validation on the 2019–2021 period supports using these projections as baseline inputs for the scenario analysis.

Among the main limitations of the study are potential structural breaks due to the escalation of the war, the limited quarterly detail of logistics data, and the assumption of a linear relationship between cultivated area and production volume.

To illustrate sensitivity to the full-scale invasion as a structural break, we conducted a robustness check. We re-estimated the ARIMA model on the pre-invasion subsample (2000–2021) and generated an out-of-sample forecast for 2022–2023. The backtest error was

TABLE 3 Scenario matrix of modernization effects on Ukraine's grain sector (2026).

Strategic goal	Tactical guidelines	Implementation tools (type/status)	Key risks and conditions
1. Increase in value added	Expand processing share from 18 to 25%	• "eRobota" program (*state/active since 2022*) • Technopark grant programs (*state/approved*) • SME investments in processing (*private/in progress*)	Volatility of energy prices, need for long-term financing
2. Technological efficiency	Scale up precision farming; AgTech; satellite monitoring	• Horizon Europe (*international/open to Ukraine since 2023*) • AgTech platforms (*private/partially active*) • Copernicus/Digital Europe (*international/approved*)	Weather risks, limited access to equipment, digitalization inequality
3. Financial resilience	Wartime insurance, agro-bonds, financial guarantees	• Agro-bonds (*private/under design with IMF/WB*) • Agricultural insurance system (*state/pilot phase*) • WB/IMF guarantees (*international/under negotiation*)	Geopolitical instability, regulatory gaps in insurance
4. EU integration and market access	Harmonization with CAP, ACAA, SPS; open access to EU market	• Ukraine Facility (*international/active since 2024*) • ACAA Regulation (*state/in harmonization process*) • Horizon Europe/SPS Support (*international/active*)	Regulatory inertia, technical unpreparedness of businesses for certification

Compiled by the authors.

MAE = 16.5 mln t and MAPE = 26.9%, which confirms that the wartime shock substantially disrupts the historical trajectory. Therefore, the projections should be interpreted as baseline paths rather than point-accurate predictions. We also compared 2025–2026 projections from the pre-invasion specification with the full-sample model (2000–2023): the pre-invasion model implies a higher path (84.57–86.70 mln t), while including 2022–2023 yields a more conservative baseline (73.63–70.33 mln t). A brief implementation note and summary output are provided in Appendix A.

The relevance of the results is driven by the large-scale wartime disruptions of 2022–2023, which significantly transformed both the internal structure of Ukraine's grain sector and the global supply–demand balance. On the one hand, the reduction of sown areas and destruction of elevator infrastructure exacerbated supply constraints at the national level; on the other, sharp price fluctuations and logistical barriers prompted the reorientation of export flows toward alternative routes through the Danube, Poland, and the Baltic region.

In 2023, the structure of Ukraine's sown areas shifted toward higher-margin crops. According to official data from the Ministry of Agrarian Policy and Food of Ukraine, wheat accounted for about 53% of all grain crops, corn for 39%, and barley for 8%. This transformation represents a rational response by agricultural producers to the new configuration of wartime risks, rising resource costs, and the complexity of logistics operations.

At the global level, 2023 was marked by a decline in the ratio of global grain stocks to annual consumption to 19.8%—the lowest value in the past decade. Under these conditions, Ukraine supplied over 55 million tons of grain exports, which accounts for more than 7% of global grain trade. This positions Ukraine as a stabilizing force in key markets of North Africa, the Middle East (MENA), and Sub-Saharan Africa (SSA), where food security remains vulnerable to external shocks (FAO-AMIS, 2024; USDA, 2024; FAO-GIEWS, 2024). Despite the war, the structural adaptation of Ukraine's agricultural sector — taking into account market, logistical, and climatic challenges — is transforming it from merely a recipient of aid into one of the guarantors of global food stability.

To substantiate the scenario assumptions and refine the domestic grain supply model, baseline production indicators for the last pre-war decade were analyzed, with a focus on changes caused by the full-scale war. The table below summarizes the dynamics of sown areas, gross output, and yields of *Ukraine's* main grain crops in 2015–2023 (Table 4).

An aggregated analysis shows that in 2023, the area under grain crops remained significantly lower (by 34%) than the pre-war peak of 2021. The largest declines were recorded for corn (−970 thousand ha) and barley (−190 thousand ha). Nevertheless, yields remained at a relatively high level, supported by favorable agroclimatic conditions and targeted technological modernization. The average yield in 2023 reached 5.12 t/ha — only 0.28 t/ha lower than the record year of 2021. Gross output decreased by 7.6 million tons (−9%), with corn accounting for more than half of the harvest. Thus, the sector demonstrated adaptability to exogenous shocks through shifts in crop structure, improved technological efficiency, and strategic use of logistical windows.

The results allow us to highlight three key analytical conclusions.

First, the reduction of sown areas by one-third resulted in only a 7% loss in gross output, indicating the relative resilience of the grain sector under crisis conditions.

Second, the stable yield level compensated for the decline in cultivated areas, reflecting a technological effect driven by the modernization of production processes, particularly the adoption of elements of precision agriculture.

TABLE 4 Summary dynamics of sown areas, gross output, and yields of grain crops in Ukraine, 2015–2023.

Indicator	Crop	Year					
		2015	2019	2021	2022	2023	Change (2023–2021)
Sown area, thousand ha	Wheat	6,340	6,735	6,300	5,800	5,820	−480
	Corn	4,110	5,145	5,100	4,800	4,130	−970
	Barley	2,060	1,350	1,200	1,100	1,010	−190
	Total grains	14,641	15,292	15,948	10,700	10,500	−5,448
Gross output, thousand t	Wheat	26,529	28,314	32,184	20,745	22,240	−9,944
	Corn	23,946	35,880	42,080	27,335	28,560	−13,520
	Barley	8,294	8,911	10,092	5,320	4,870	−5,222
	Total grains	60,400	65,800	86,000	65,000	58,400	−27,600
Yield, t/ha	Wheat	4.18	4.2	5.11	3.58	3.82	−1.29
	Corn	5.83	6.97	8.25	5.69	6.92	−1.33
	Barley	4.03	6.6	8.41	4.84	4.82	−3.59
	Total grains	4.7	5.52	6.7	4.56	5.08	−1.62

Source: FAOSTAT; USDA; WASDE (World Agricultural Supply and Demand Estimates); Ministry of Agrarian Policy and Food of Ukraine – Operational statistics on sown areas and crop yields: annual reports (2021–2023); State Statistics Service of Ukraine – Form No. 29-agriculture (annual agricultural production statistics). Model estimation uses annual data for 2000–2023; the 2015–2023 window is shown for compact presentation of recent dynamics prior to the full-scale invasion (2015–2021) and the subsequent wartime period (2022–2023).

Third, there was a structural shift toward corn, which has a higher export potential; this, in turn, placed additional pressure on logistical infrastructure, as the FOB export price for this crop is sensitive to transshipment costs and the geographical distribution of supplies.

Following the quantitative assessment of gross production, the next step is to determine the distribution of the harvested crop between domestic consumption and exports. The balance formula—production + imports − consumption − exports = change in stocks—makes it possible to assess the extent to which the actual 2023 volumes met domestic food and feed demand, as well as the size of the reserve available at the beginning of 2024. This balance-based perspective is crucial for subsequent scenario analysis, as it defines the opening stocks, export opportunities, and the foreign exchange context in which forecasts for the next periods will be implemented (Table 5).

TABLE 5 Grain balance of Ukraine in 2023 (million tons).

Indicator	Value	Δ vs. 2022, %	Share of production, %
Opening stocks (S_o)	32.35	−23.4	55.4
Production (P)	58.4	−10.2	100
Imports (I)	0.85	7.6	1.5
Supply ($P + I + S_o$)	91.6	−13.9	156.9
Domestic consumption (C)	21.5	−3.8	36.8
Of which: feed	13.2	−5.2	22.6
Seed and losses	2.05	1.2	3.5
Exports (E)	55	14.1	94.2
Closing stocks (S_e)	15.1	−53.3	25.8
Self-sufficiency ratio (P/C)	2.72	-	-

USDA WASDE Report Q1, 2024; Ministry of Agrarian Policy and Food of Ukraine – Operational information on sowing and harvesting campaigns, 2023; Author's calculations based on a consolidated database from FAOSTAT, USDA, and UCAB (using the balance formula: $P + I - C - E = \Delta S$).

In 2023, the total grain supply in Ukraine, including opening stocks, amounted to 91.6 million tons. Of this volume, 55 million tons—or 94% of gross production—was exported. Domestic consumption decreased by 3.8% due to a decline in livestock numbers, reduced processing activity, and demographic factors. As a result, closing stocks totaled 15.1 million tons, more than 17 million tons less than at the start of 2023, when carry-over reserves were estimated at 32.35 million tons. This indicates active use of previous years' reserves to sustain export activity.

The calculated self-sufficiency ratio of 2.72 confirms that, even under conditions of limited domestic demand, Ukraine remained a resilient net exporter. Key factors behind exports exceeding expected volumes included the expansion of the Danube logistics corridor (up to 10.8 million tons/year) and the introduction of state subsidies for agricultural railway tariffs at a rate of 25%. Considering these factors, the following section presents a medium-term forecast for the grain sector. The forecast for 2024 to 2026 was generated using a verified ARIMA (0, 1, 2) model calibrated on historical data from 2000 to 2023. The baseline ARIMA trajectory is interpreted under medium-risk wartime assumptions, including stabilization of the front line without further territorial losses, gradual demining of productive land, preservation of current logistics infrastructure, and limited but steady investment in fertilizers and machinery. According to the modeling results, the baseline forecast for 2026 projects gross grain output at 69.9 million tons. Figure 1, in fan chart format, presents the forecast values with the baseline trajectory and 80 and 95% confidence intervals. The uncertainty range reaches ±8.4 million tons, widening in 2025–2026 due to the influence of climatic risks and potential wartime escalation. A fan chart visualizes forecast uncertainty by

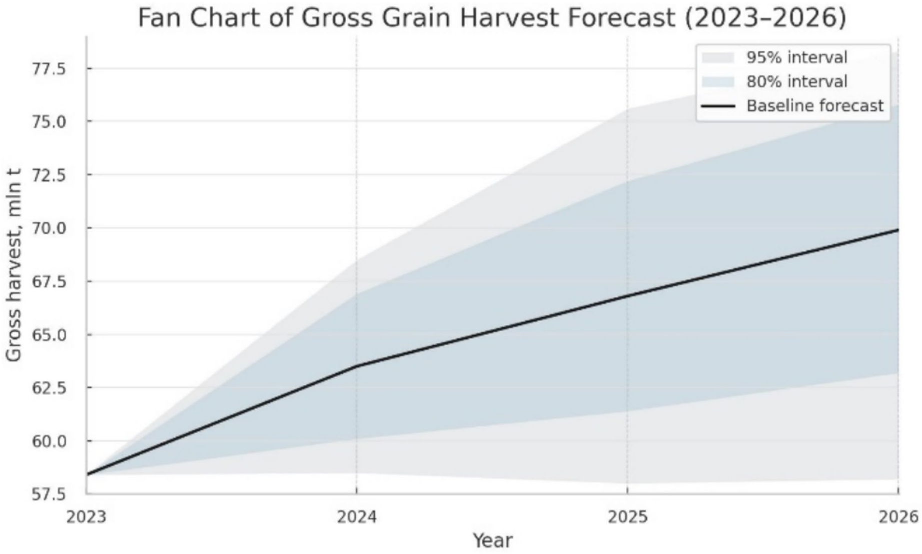

FIGURE 1
Projected values of Ukraine's gross grain output (with baseline trajectory and confidence intervals) for 2025–2026. USDA PSD Online and WASDE Reports (2023–2024), FAOSTAT, (2024), and Ministry of Agrarian Policy and Food of Ukraine (2024).

showing prediction intervals that widen over the forecast horizon (darker bands indicate ranges with higher probability).

According to Figure 1, the gradual widening of the uncertainty cone indicates rising exogenous risks after 2025. This is driven by both climatic factors (ENSO and associated agrometeorological shocks) and potential wartime escalation. Even within the lower bound of the 95% confidence interval (≈ 61 million tons in 2026). Ukraine is projected to maintain a substantial net export surplus of more than 35 million tons, equivalent to 5–6% of the global grain market. An additional validity check for the model is provided by comparing the author's forecasts with the consensus estimates of FAO AMIS and USDA WASDE (Table 6).

TABLE 6 Consensus forecasts of Ukraine's gross grain output, 2024–2026 (million tons).

Year	USDA WASDE	FAO AMIS	ARIMA baseline (medium-risk assumptions)	Δ % vs. USDA
2024	61.0	60.4	63.4	+3.9
2025	63.5	62.1	66.7	+5.0
2026	64.8	63.0	69.9	+7.9

AMIS (2024); FAO (2024); USDA (2025). USDA WASDE and FAO AMIS values represent agency outlooks available at the time of manuscript preparation, while the ARIMA column reports the authors' model-based baseline trajectory. These estimates should not be interpreted as ex post observed outcomes or as a no-war counterfactual.

In all years, the ARIMA baseline projects higher gross output volumes (by 3.9–7.9%), driven by the inclusion of a technological dividend (+7%) in yield due to precision farming, according to World Bank (2023) and the logistical expansion through the Danube corridor (up to 35 million tons/year) (UNCTAD, 2023), which are not fully accounted for in the forecasts of international agencies. In this context, a key task is to determine the implementation logic of the forecasting results through systematic modernization of the grain sector, taking into account structural changes and foreign economic priorities. A conceptual transformation model for the sector is proposed, based on four functional vectors aligned with the principles of sustainability, EU integration synergy, and institutional strengthening (European Commission, 2024; European Commission, 2023). This approach makes it possible to integrate scenario-based calculations with realistic mechanisms for their implementation. The first component is the economic block, which envisions a gradual transition from raw material exports to domestic processing. Relevant measures — such as tax incentives for equipment and state grants for deep-processing projects — generate a value-added multiplier (World Bank, 2023). The second component is the technological vector, focused on scaling up precision farming, utilizing satellite monitoring (Copernicus), and optimizing logistics chains. This enables a 7% increase in yields and a 12% reduction in fertilizer use per hectare, while minimizing technological losses and enhancing resilience to climate risks. Key instruments include dedicated programs, support for AgTech platforms, and co-financing through technology parks and industry accelerators. The third component is the institutional block, which involves deregulation, expanded access to financial resources, and the systematic implementation of wartime insurance. The main tools are the establishment of agro-financial guarantees, the issuance of agro-bonds, and the development of risk insurance—particularly through a state agricultural risk management program. Under the optimal scenario, coverage could reach 70% of cultivated land, reducing investment risk and stimulating sector capitalization by an additional USD 1.5 billion annually (IMF and World Bank, 2023). The fourth vector is the EU integration component, which envisages alignment with EU policies—in particular, the European Commission (2024). Common Agricultural Policy (CAP), implementation of ACAA requirements and SPS standards, as well as opening access to the EU internal market (Horizon Europe, 2024). This creates synergies with technical regulation, ensures compliance with trade norms, and provides access to co-financing mechanisms. These measures are embedded in both the Ukraine Facility policy and the Agreement on the Common Customs Area.

The integrated scenario matrix (Table 3) summarizes the modernization logic and connects it to the three military-risk scenarios (low, medium, high) used to interpret the forecast trajectories. The table is structured around strategic goals, tactical implementation guidelines, implementation tools, and the key risks and conditions required to achieve the expected outcomes. It is intended as a modernization and policy matrix aligned with the risk scenarios; it complements the quantitative baselines (Table 6) by making assumptions and feasible levers explicit, rather than serving as a standalone statistical scenario model.

Thus, the long-term resilience of Ukraine's grain sector cannot rely solely on the extensive restoration of sown areas or the automatic return to pre-war production levels. Structural transformation of the agricultural sector requires a comprehensive approach that combines economic incentives, technological renewal, institutional reform, and alignment with European standards. This multi-vector logic is reflected in the integrated scenario matrix (Table 3), which serves as a tool for systematic planning and strategic management. It structures modernization efforts by strategic goals and tactical guidelines and complements them with implementation mechanisms, as well as potential risks and enabling conditions.

The implementation of such structural changes is impossible without the creation of a new financing architecture—in particular, the launch of agro-bonds, the scaling up of wartime agricultural insurance, the provision of state guarantees for investment projects, and access to international support instruments (Horizon Europe, Ukraine Facility, grant components of the EBRD and IFC). Attracting private capital also requires a transparent regulatory framework, predictable taxation conditions, and streamlined access to finance. Ultimately, combining innovative technologies with a modern institutional framework will not only ensure production stability but also reposition Ukraine in the global agrifood chain—from a raw material supplier to an integrated player with a high share of value added and innovation potential.

At the same time, deregulation, procedural transparency, and anti-corruption tools remain key prerequisites for the implementation of these measures. The EU integration vector establishes the regulatory framework for harmonizing standards (including compliance with CAP, ACAA, and SPS requirements), facilitating access to the EU internal market and participation in multiannual support programs (Horizon Europe, Ukraine Facility). Harmonization of Ukrainian agricultural legislation with EU law will not only create new export opportunities but also improve food quality, the environmental sustainability of production, and market transparency.

In this way, the integration of investment, technological, institutional, and regulatory instruments, synchronized within the framework of the scenario matrix, forms the foundation for an adaptive, innovative, and resource-efficient agricultural policy. Such a holistic approach makes it possible not only to offset the consequences of wartime destruction but also to bring the grain sector to a qualitatively new level of competitiveness in the global food chain—reducing vulnerability to external shocks, strengthening export potential, and creating preconditions for food security.

4 Discussion

The results of scenario forecasting demonstrate the adaptability of Ukraine's grain sector under wartime risk conditions. Despite a nearly one-third reduction in sown areas, gross output in 2023 declined by only 9%, which can be explained by the preservation of high yields at 5.12 t/ha. Under the baseline scenario, gross output in 2026 could reach 69.9 million tons, which is 3.9–7.9% higher than current forecasts by international organizations. This dynamic is attributed to the positive effects of the implementation of precision farming practices, automation of agricultural processes, and the expansion of logistics routes—particularly toward the Danube region. Indeed, it is argued that the key determinants of the sector's resilience include technological modernization (precision farming, AgTech, satellite monitoring), institutional support (agrobonds, war-risk insurance, international guarantees), and logistical adaptation (expansion of the Danube corridor). Given the projected production volume, Ukraine retains the potential for an export surplus of more than 35 million tons, equivalent to approximately 6–7% of the global grain market. This confirms the possibility of Ukraine maintaining a stable presence in key export markets even under conditions of high uncertainty.

Based on the scenario modeling results, a structured approach has been developed for the transformation of the grain sector, encompassing economic incentives for deeper processing, technological modernization of production, institutional support to improve access to financial resources, and harmonization with the EU regulatory framework. This integrated approach makes it possible to combine forecast estimates with practical implementation mechanisms, ensuring a gradual transition from the stage of agricultural production recovery to structural modernization and long-term resilience. Certain limitations, as well as a strength, arise from the use of multiple official databases, while future research should aim to incorporate variables related to rural social capital, which appears crucial for agricultural production under conditions of stress and risk associated with war.

The resilience demonstrated by Ukraine's grain sector in the context of ongoing conflict and systemic risk underscores the critical necessity of well-designed, targeted policy interventions to sustain agricultural production under conditions of high uncertainty. Empirical evidence and scenario modeling suggest that strategic investments in advanced agricultural technologies—including precision agriculture, mechanization, and satellite-based crop monitoring—play a dual role: they not only enhance yield stability and resource-use efficiency but also strengthen the sector's capacity to adapt to both short-term shocks and longer-term climatic and geopolitical disruptions. By enabling more precise input application, early detection of crop stress, and real-time monitoring of field conditions, these technological measures reduce production volatility and contribute to more reliable forecasting of agricultural outputs.

Equally important are robust institutional support mechanisms. Financial instruments such as agrobonds, war-risk insurance, and international guarantees can facilitate access to capital, mitigate exposure to unforeseen risks, and incentivize continued investment in productivity-enhancing technologies. Alignment with international trade regulations also enables Ukraine to maintain its competitiveness in global grain markets, ensuring that policy frameworks are conducive to both domestic agricultural development and export-oriented growth. These measures collectively create an enabling environment in which private and public stakeholders can invest with reduced risk, thereby promoting longer-term sectoral stability and resilience.

In addition to technological and institutional measures, logistical enhancements represent a critical component of the sector's adaptive capacity. The expansion of alternative export corridors, particularly through the Danube and other strategically significant routes, ensures the continuity of international grain trade even under constraints imposed by conflict or infrastructure disruptions. Such measures highlight the interplay between agricultural policy and transport infrastructure planning, demonstrating that resilience is contingent not only on production efficiency but also on the ability to maintain uninterrupted access to export markets.

Integrating scenario and forecast-based insights into concrete implementation strategies allows for a structured transition from immediate post-crisis recovery to comprehensive structural modernization. This approach facilitates the coordination of economic incentives, technological adoption, and institutional support in a manner that promotes long-term sustainability. Moreover, future research should increasingly incorporate variables related to rural social capital, including community networks, knowledge-sharing practices, and cooperative structures, which have been shown to significantly influence agricultural productivity and risk mitigation in conditions of stress. Accounting for such socio-institutional dimensions will enable the development of more nuanced, evidence-based policy interventions that reinforce the adaptive capacity of the agricultural sector, ensuring both food security and economic stability under complex, high-risk scenarios.

5 Conclusion

This study provides a transparent baseline assessment of Ukraine's grain production potential under wartime conditions, using annual data for 2000–2023 and non-seasonal ARIMA forecasting for 2025–2026. The results indicate that Ukraine retains a meaningful role in global grain supply even under adverse conditions, while the forecast trajectories should be interpreted as baselines rather than precise point predictions given the structural break associated with the full-scale invasion. We show that sector resilience is shaped by a combination of productivity dynamics, export feasibility under logistical constraints, and the external price environment. To support practical interpretation, the findings are framed through three military-risk scenarios (low, medium, high) and complement the quantitative baselines with an integrated modernization matrix that links assumptions to feasible implementation levers. From a policy perspective, the analysis underscores the critical importance of pursuing targeted technological modernization, ensuring predictable and effective institutional support, and maintaining sustained logistics adaptation as mutually reinforcing priorities. Technological modernization can enhance productivity, improve resource efficiency, and reduce vulnerability to supply chain disruptions, for example through precision farming, sensor-based monitoring, and satellite-assisted crop management. Predictable institutional support—including clear regulatory frameworks, timely access to subsidies or credit, and coordinated risk management strategies—provides the stability necessary for farmers and agribusinesses to invest in long-term improvements. Sustained logistics adaptation, such as diversifying export corridors, upgrading port capacity, and strengthening inland transport networks, is essential to maintain trade flows under wartime constraints and minimize the economic impact of supply bottlenecks. Alignment with European standards and mechanisms can further accelerate recovery by facilitating access to high-value markets, attracting investment in modern agritech and processing infrastructure, and fostering integration into value-added agricultural chains. Together, these policy measures create a synergistic effect, enhancing sector resilience, supporting economic recovery, and positioning Ukraine as a more stable and reliable contributor to global food security. The main limitations relate to wartime data constraints, the use of annual series (which do not capture within-year dynamics), and the reliance on a parsimonious baseline forecasting framework.

Future research can extend this work by integrating additional determinants (e.g., land use, investment, labor), exploring alternative models that explicitly accommodate regime changes, and examining regional heterogeneity as consistent subnational data become available.

Data availability statement

Publicly available datasets were analyzed in this study. These data are available from FAOSTAT (https://www.fao.org/faostat/en/#data/QCL), USDA PSD Online (https://apps.fas.usda.gov/psdonline/app/index.html), USDA WASDE reports (https://www.usda.gov/about-usda/general-information/staff-offices/office-chief-economist/commodity-markets/wasde-report), FAO GIEWS Ukraine Country Brief (https://www.fao.org/giews/countrybrief/country.jsp?code=UKR), the World Bank Commodity Markets resources (https://www.worldbank.org/en/research/commodity-markets), Ukrzaliznytsia (https://www.uz.gov.ua/en/), and the Ukrainian Sea Ports Authority (https://www.uspa.gov.ua/en/homepage-en). Operational statistics from the Ministry of Agrarian Policy and Food of Ukraine were also used (https://minagro.gov.ua/ye-roslynnytstvo).

Author contributions

YZ: Conceptualization, Writing – original draft. IO: Investigation, Writing – original draft. MF: Writing – review & editing. YO: Methodology, Writing – original draft. KO: Data curation, Writing – original draft. LL: Formal analysis, Writing – original draft.

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In memoriam

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Appendix A

Robustness check (ARIMA).

The robustness check re-estimated the ARIMA model on the pre-invasion subsample (2000–2021) and produced an out-of-sample forecast for 2022–2023. We then compared 2025–2026 projections from the pre-invasion specification with those from the full-sample specification (2000–2023). This exercise re-selects the ARIMA order on the restricted subsample to test sensitivity to the wartime structural break. The estimation was implemented in Python using statsmodels (ARIMA(1,0,3), selected by AIC within a limited grid). The console output below summarizes the key results.

Selected order (pre-invasion): (1, 0, 3).

Backtest 2022–2023 MAE: 16.5 mln t.

Backtest 2022–2023 MAPE: 26.9%.

Selected order (full-sample): (1, 0, 3).

Forecast 2025–2026 (full-sample):

2025 73.63

2026 70.33

Forecast 2025–2026 (pre-invasion model):

2025 84.57

2026 86.70