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The impact of operating leverage and financial elasticity on the budgeting of variable costs in grain production

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▸ **Abstract.** The sustainability of financial strategies in agricultural enterprises depended on accurate forecasting of production parameters and associated credit risks under volatile market conditions. This study aimed to assess the technological response of grain production to changes in resource supply and to integrate the results into liquidity forecasting and negative interest rate risk assessment. The estimated quadratic production function adequately captured the nonlinear response of wheat yield to variable inputs, confirming diminishing marginal returns. The model demonstrated satisfactory statistical performance ($R^2 = 0.606$, adjusted $R^2 = 0.409$) and was statistically significant ($F = 3.073$, $p = 0.027$). The identified technological optimum corresponded to a maximum predicted yield of 55.1 c/ha, achieved at fertiliser and seed expenditures of approximately 5.3 and 0.85 thousand UAH/ha, respectively. When value-based indicators were applied, the optimum shifted toward profit maximisation. The maximum marginal profit reached 9.32 thousand UAH/ha at slightly lower input levels, with a corresponding yield of 53.8 c/ha, while the maximum net profit equalled 5.46 thousand UAH/ha after accounting for fixed costs. The operating leverage analysis revealed pronounced nonlinearity of financial sensitivity. Extremely high DOL values (up to 9.99) occurred in underfunded production regimes, where net profit approaches zero, indicating critical operational instability, whereas a stable DOL range of 1.1-1.6 corresponded to moderate input levels. Scenario analysis of credit conditions (±20% interest rate variation) indicated asymmetric interest rate risk. The highest financial elasticity of net profit ($E \approx 0.10$) was observed in low-input, loss-making regimes, while near the technological optimum elasticity approaches zero, indicating relative financial resilience. The results confirmed that integrating production modelling with financial sensitivity indicators improved liquidity forecasting and credit planning in grain production

▸ **Keywords:** parabolic production function; resource optimisation; marginal profit; liquidity; interest rate risk; financial planning

▸ Introduction

The relevance of this study was determined by the growing need to improve cost management in grain production as a critical condition for ensuring the financial stability of agricultural enterprises under increasing market volatility. Agricultural producers operated in a highly uncertain environment characterised by seasonality of cash flows, biological constraints, climate risks, price volatility for both inputs and outputs, and limited access to financial resources. These factors significantly increased financial risks and complicated managerial decision-making in budgeting, liquidity planning, and debt servicing, especially in economies exposed to macroeconomic instability. Scientists K. Abid *et al.* (2024) demonstrated that excessive financial leverage negatively affected firm performance, particularly in emerging markets, where enterprises faced higher sensitivity to macroeconomic shocks. Similar conclusions were reached by J.D. Odhiambo *et al.* (2025), who emphasised that optimal leverage levels were essential for balancing profitability and financial resilience. A.A. Hegde *et al.* (2022) further showed that firms with higher financial flexibility demonstrated more adaptive leverage dynamics, enabling them to better withstand revenue fluctuations and financial stress. S. Byoun (2021) argued that financial flexibility played a strategic role in corporate financial decisions, allowing enterprises to mitigate

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liquidity constraints and maintain solvency during adverse economic conditions.

In the context of agricultural enterprises, these relationships became more complex due to sector-specific features. R. Bachynsky (2022) substantiated the principles of managing economic stability of agricultural enterprises, highlighting that traditional financial models often underestimated production risk, seasonality, and biological uncertainty. I. Svynous *et al.* (2021) analysed accounting and analytical aspects of cost management in agriculture and confirmed that ineffective cost control significantly amplified financial instability, especially under volatile price conditions. O. Lotysh & A. Kardash (2021), analysing global grain markets, identified strong price cyclicality and exposure to geopolitical and climatic shocks, which further complicated revenue forecasting and cost planning for grain producers. The interaction between operating leverage, production capacity, and financial distress had also been examined in empirical studies. R. Maronrong *et al.* (2022) confirmed that high operating leverage combined with financial leverage substantially increased the probability of financial distress, particularly in sectors characterised by volatile demand and cost structures. These findings were directly applicable to grain production, where high fixed costs, long production cycles, and dependence on natural conditions intensified financial vulnerability.

Ukrainian scholars had significantly contributed to the understanding of financial risk management in agribusiness. O. Tomilin *et al.* (2023) conducted a comprehensive empirical analysis of financial risk management practices in Ukrainian agricultural enterprises, identifying key vulnerabilities related to liquidity shortages, excessive short-term borrowing, and inadequate integration of production and financial planning. Their results demonstrated that most enterprises relied on fragmented budgeting practices, which limited their ability to forecast financial stress and respond proactively to adverse market changes. The authors emphasised the necessity of implementing integrated financial planning models that incorporated production risks, cost variability, and credit constraints. O. Tomilin & Ya. Oleksashenko (2025) explored agricultural insurance as a stabilisation mechanism for farm finances, providing empirical evidence that insurance instruments significantly reduced income volatility and enhance financial sustainability. Scientist's analysis showed that farms utilising insurance coverage exhibited higher liquidity ratios, lower probability of insolvency, and greater access to external financing. Importantly, the authors argued that insurance mechanisms should be embedded into broader financial management frameworks, linking risk transfer instruments with cost planning, budgeting, and capital structure decisions. This approach reinforced the need for integrated financial models that accounted for both production and financial risks in agricultural enterprises.

Despite extensive research, existing studies often treat cost management, financial leverage, and risk management as separate analytical domains. Corporate finance literature focused on industrial and service firms, where production functions exhibited relatively stable input-output relationships. In contrast, agricultural production was characterised by nonlinear responses to inputs, biological constraints, and significant exposure to exogenous shocks, which fundamentally altered the transmission mechanisms between cost structures, operating leverage, and financial performance. The interaction between nonlinear production functions, cost intensity, and financial sensitivity remained insufficiently integrated into unified budgeting and risk assessment frameworks for agriculture. The aim of this study was to develop an adaptive cost management model for grain production that optimised resource allocation, while minimising financial risks under conditions of economic instability. The objectives of the research were: 1) to analyse cost management approaches specific to grain production; 2) to adapt operating leverage and financial sensitivity indicators to agricultural conditions; 3) to develop a scenario-based budgeting framework integrating nonlinear production functions with financial risk indicators. The scientific novelty of the research lain in constructing an integrated analytical framework that combined production economics and financial risk management, thereby enhancing the financial stability and resilience of grain-producing enterprises in volatile market environments.

▸ Materials and Methods

The methodological approach to integrating operating leverage and financial elasticity into the budgeting of agricultural enterprise costs was based on combining production and financial logic of analysis. The study focused specifically on grain production, allowing for a detailed assessment of the interplay between input allocation, yield response, and financial sensitivity. The research was conducted in several consecutive stages to ensure reproducibility of results by other researchers.

Production basis of analysis

The foundation of the study was the law of diminishing returns, typical for agricultural production: the increase in yield from additional expenditures on specific resources decreases after reaching a certain level of their use. To formalise this relationship, a parabolic specification of the production function was applied:

$$Y(X_k) = \beta_0 + \beta_1 X_k + \beta_2 X_k^2, \beta_2 < 0, \quad (1)$$

where Y – yield, c/ha; X_k – expenditures on the respective resource, thousand UAH/ha; β_0, β_1, β_2 – parameters of the production function.

In multi-factor production, the model expanded to the form:

$$Y = f(X_1, X_2, ..., X_n), \quad (2)$$

where Y – wheat yield, c/ha, X_n – variable costs by specific category, for example.

In the multi-factor analysis of wheat production, the production function included the following variable costs: X_1 – expenditures on fertilisers per hectare, thousand UAH; X_2 – expenditures on seeds per hectare, thousand UAH; X_3 – expenditures on contractor services per hectare, thousand UAH; X_4 – expenditures on fuel and lubricants per hectare, thousand UAH; X_5 – expenditures on labour per hectare, thousand UAH; X_6 – other material costs per hectare, thousand UAH and others.

Transition to financial indicators

Based on the production function, revenue from product sales was determined as:

$$TR(X) = P \cdot Y(X), \quad (3)$$

where $TR(X)$ – total revenue; P – price per unit of output; $Y(X)$ – yield function.

Marginal profit:

$$MP(X) = TR(X) - VC(X), \quad (4)$$

where $MP(X)$ – marginal profit per hectare, thousand UAH; $VC(X)$ – variable costs.

In the analysis of marginal profit per hectare in wheat production, the variable costs were defined as follows: X_1 – expenditures on fertilisers, thousand UAH/ha; X_2 – expenditures on seeds, thousand UAH/ha; X_3 – expenditures on contractor services, thousand UAH/ha; X_4 – expenditures on fuel and lubricants, thousand UAH/ha; X_5 – expenditures on labour, thousand UAH/ha; X_6 – other material costs, thousand UAH/ha and others. Net profit:

$$NP(X) = MP(X) - FC - INT(X) - TAX, \quad (5)$$

where $NP(X)$ – net profit per hectare, thousand UAH; FC – fixed costs; $INT(X)$ – interest expenses; TAX – taxes.

Credit servicing costs:

$$INT(X) = VC(X) \cdot \frac{r(X)}{2}, \quad (6)$$

where $INT(X)$ – interest expenses; $VC(X)$ – variable costs; $r(X)$ – average weighted credit rate.

It was assumed that own financing sources covered at least 50% of total resource needs, while credit covered a maximum of half of variable costs.

Operating leverage (DOL)

To evaluate the efficiency of budgeting variable costs, the degree of operating leverage was used:

$$DOL(X) = \frac{dNP(X)/dX}{dTR(X)/dX}, \quad (7)$$

where $DOL(X)$ – degree of operating leverage; $NP(X)$ – net profit; $TR(X)$ – total revenue.

In a multi-factor context (e.g., fertilisers (X_1) and seeds (X_2)):

$$DOL(X_1, X_2) = \frac{\frac{\partial NP}{\partial X_1} + \frac{\partial NP}{\partial X_2}}{P \cdot \left(\frac{\partial Y}{\partial X_1} + \frac{\partial Y}{\partial X_2}\right)}, \quad (8)$$

where X_1 – expenditures on fertilisers; X_2 – expenditures on seeds; P – price per unit of output; Y – yield.

In the multi-factor context, the degree of operating leverage (DOL) for wheat production was calculated using expenditures on fertilisers (X_1) and seeds (X_2). The DOL represented the sensitivity of net profit to changes in revenue and was defined as: X_1 – expenditures on fertilisers, thousand UAH/ha; X_2 – expenditures on seeds, thousand UAH/ha; 3,540 – wheat selling price, UAH/t; numerator – sum of marginal effects of expenditures on net profit; denominator – sum of marginal effects on revenue, calculated as the product of yield and price.

Financial elasticity

The second key indicator was the financial elasticity of profit with respect to the credit rate:

$$E_{NP,r}(X) = \frac{\Delta NP(X)/NP(X)}{\Delta r(X)/r(X)}, \quad (9)$$

where $E_{NP,r}(X)$ – financial elasticity of profit with respect to credit rate; $NP(X)$ – net profit; $r(X)$ – credit rate.

The financial elasticity of net profit with respect to expenditures on fertilisers (X_1) and seeds (X_2) reflected the sensitivity of net profit to changes in revenue resulting from variations in these input costs. The variables were defined as follows: $NP(X_1, X_2)$ – net profit function; $r(X_1, X_2) = P \cdot Y(X_1, X_2)$ – revenue depending on yield and price; X_1, X_2 – expenditures on fertilisers and seeds, respectively; $\partial NP/\partial X_i$ – marginal effect of expenditures on net profit; $\partial r/\partial X_i$ – marginal effect of expenditures on revenue. These definitions allowed for consistent computation of operating leverage (DOL) and financial elasticity across different input scenarios. To test stability, scenario analysis was applied with credit rate variation of ±20% from the baseline level.

Integration of indicators into the budgeting process

Operating leverage and financial elasticity form a complementary system of criteria that enabled the transition from static planning to scenario analysis: DOL evaluated the efficiency of the structure of variable costs in monetary terms; determined the resilience of financial results to changes in credit conditions. Their joint application ensured managerial control over the "result-risk" ratio and provided the foundation for constructing scenario-based budgets. For the calculation of operating leverage and financial elasticity, the variables were defined as follows: $NP(X_1, X_2)$ – net profit, thousand UAH/ha; $Y(X_1, X_2)$ – wheat yield, c/ha; X_1, X_2 – expenditures on fertilisers and seeds, respectively; numerator of the first fraction – total marginal effect of expenditures on profit, normalised to its level; denominator of the second fraction – corresponding marginal effect on revenue, ensuring unit consistency.

▸ Results

The analysis of grain production costs and their impact on yield was important for determining the optimal allocation of resources and assessing the associated financial risks. By integrating production modelling with financial indicators such as operating leverage and financial elasticity, it was possible to determine technical efficiency and economic stability. Technological optimisation of resource use, profit behaviour under different cost structures, and the financial stability of grain producers under different market conditions became key components in assessing the response of grain production to changes in resource supply. To empirically formalise these relationships and quantify the nonlinear effects of key production factors on grain yield, a multivariate quadratic regression model was constructed, which was expressed by the following production function:

$$Y = -41.14 + 16.5 \cdot X_1 + 95.7 \cdot X_2 - 1.55 \cdot X_1^2 - 56.2 \cdot X_2^2 - 3.67 \cdot X_3 - 5.76 \cdot X_4 + 13.62 \cdot X_5 + 5.31 \cdot X_6. \quad (10)$$

The quality of equation (10) was assessed as satisfactory: the coefficient of determination equaled ($R^2 = 0.606$), the adjusted ($R^2 = 0.409$), and the F-statistic value of 3.073 with ($p = 0.027$) confirmed the statistical significance of the model as a whole. The standard error of residuals was 7.12, indicating an acceptable level of forecast accuracy. At the same time, despite the moderate explanatory power, the model primarily performed an analytical function – it allowed for quantitative assessment of the impact of individual cost components on production performance and determination of optimal proportions of their use, at which maximum yield was achieved. The estimated parameters confirmed the appropriateness of the parabolic specification: linear coefficients for fertilisers and seeds were positive, while quadratic coefficients were negative, reflecting the law of diminishing returns. Based on this, the local optimum of expenditures was calculated, at which yield reached its maximum. The calculations showed that the optimal values were approximately 5.3 thousand UAH/ha for fertilisers and 0.85 thousand UAH/ha for seeds. At the same time, the local optimum was determined under the condition of fixing other factors at their average levels: expenditures on contractor services – 0.85 thousand UAH/ha, fuel and lubricants – 0.99 thousand UAH/ha, labour – 0.78 thousand UAH/ha, and other material costs – 1.88 thousand UAH/ha. At the point of maximum, the predicted wheat yield was 55.1 c/ha, which confirmed the practical significance of the model and its suitability for optimising production decisions (Fig. 1).

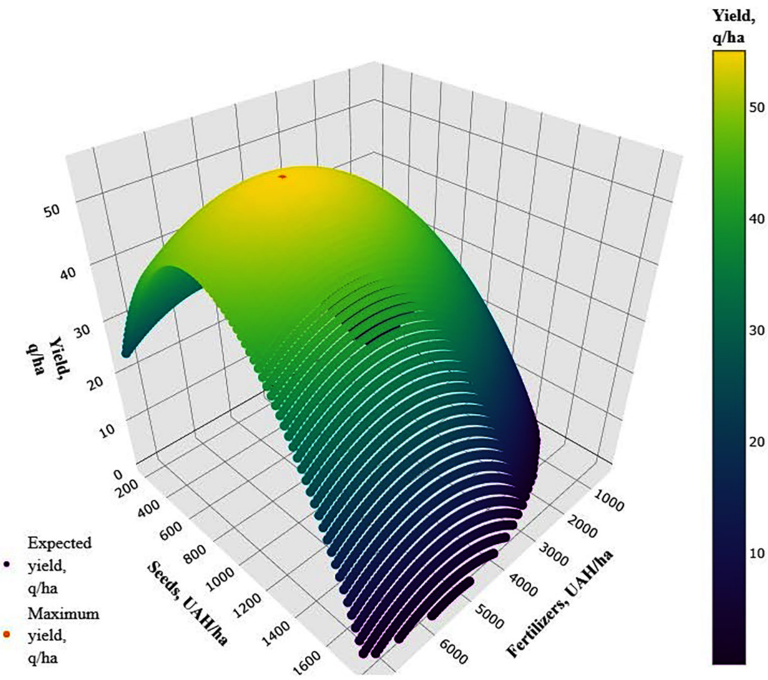

Figure 1. Dependence of wheat yield on expenditures for fertilisers and seeds
Notes: the yellow marker indicated the local maximum point of 55.1 c/ha
Source: State Statistics Service of Ukraine (2021)

Results represented the level of technological efficiency that an enterprise can achieve under a rational structure of variable costs. Thus, equation (10) reflected not only the production logic of the agricultural process but also created prerequisites for integrating financial indicators into the cost budgeting system, forming the basis for further scenario analysis and assessment of enterprise resilience. To evaluate the economic efficiency of production, a marginal profit function was constructed, which integrated variable costs and the selling price into the yield production function. The yield function was multiplied by the average selling price of third-class wheat grain in Ukrainian agricultural enterprises in 2020, which, according to the State Statistics Service of Ukraine (2021), amounted to 354 UAH/c. Revenue was then reduced by the amount of variable costs. After expanding the brackets and simplifying the coefficients, the formula for marginal profit as a function of variable costs at a fixed selling price took the form:

$$MP = -14.56 + 4.84 \cdot X_1 + 32.87 \cdot X_2 - 0.55 \cdot X_1^2 - 19.91 \cdot X_2^2 - 2.30 \cdot X_3 - 3.04 \cdot X_4 + 3.82 \cdot X_5 + 0.88 \cdot X_6. \quad (11)$$

Based on the constructed model, the local optimum of marginal profit was determined. The calculations showed that the maximum marginal profit was achieved under the following expenditure parameters: fertilisers – 4.40 thousand UAH/ha, seeds – 0.82 thousand UAH/ha, contractor services – 0.85 thousand UAH/ha, fuel and lubricants – 0.99 thousand UAH/ha, labour – 0.78 thousand UAH/ha, and other material costs – 1.88 thousand UAH/ha. At this optimum point, the predicted yield was 53.8 c/ha, variable costs amount to 9.73 thousand UAH/ha, and the maximum marginal profit was 9.32 thousand UAH/ha. The transition from physical results (equation 10) to monetary results (equation 11) through the inclusion of the price factor caused a shift in the expenditure optimum. As a result, the yield level at the point of maximum marginal profit was 53.8 c/ha, which was 1.3 c/ha lower than at the maximum of the production function yield (55.1 c/ha). The shift of the optimum towards lower yield was explained by the fact that the maximisation criterion accounted not only for the physical volume of production but also for the marginal effect of costs directly influencing revenue. The next step was to account for the enterprise's fixed costs, which allowed the transition from marginal profit to net profit. Considering the average level of fixed costs of 3,858 thousand UAH/ha, including depreciation, overhead, and administrative expenses per hectare, the net profit function took the form:

$$NP = -18.418 + 4.84 \cdot X_1 + 32.87 \cdot X_2 - 0.55 \cdot X_1^2 - 19.91 \cdot X_2^2 - 2.30 \cdot X_3 - 3.04 \cdot X_4 + 3.82 \cdot X_5 + 0.88 \cdot X_6. \quad (12)$$

The calculations showed that at the local optimum point, the predicted net profit was 5.46 thousand UAH/ha, which was almost 41% lower than the maximum marginal profit (9.32 thousand UAH/ha). This level of net profit can be used as a target value in the formation of production unit budgets (Fig. 2).

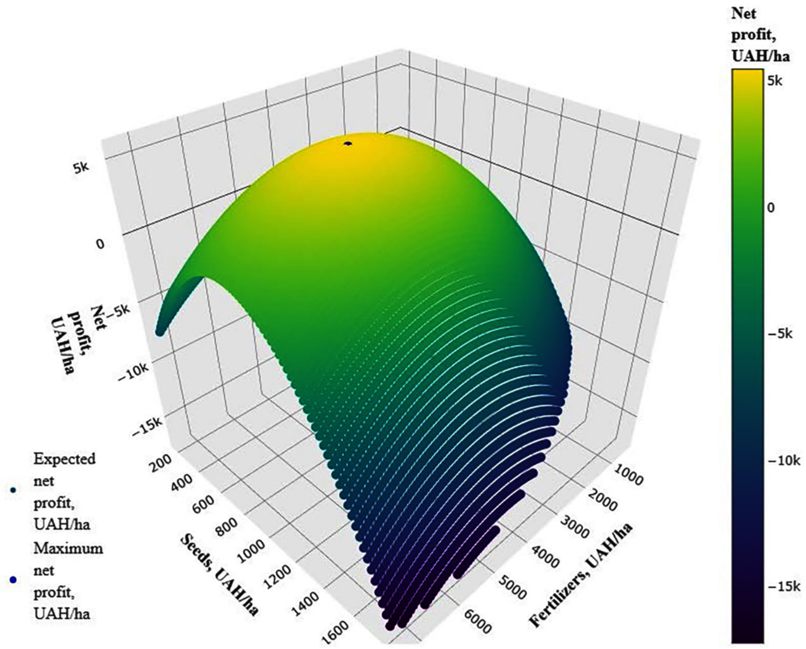

Figure 2. Dependence of net profit from wheat production and sales on expenditures for fertilisers and seeds
Notes: the blue marker indicated the local maximum point corresponding to a net profit level of 5.46 thousand UAH/ha at a yield of 53.8 c/ha
Source: State Statistics Service of Ukraine (2021)

Model (12) not only reflected the financial logic of the agricultural process but also created prerequisites for integrating the net profit indicator into managerial budgeting systems. This formed the basis for further scenario analysis and assessment of enterprise resilience under changing market conditions. Determining the local optimum of net profit allowed for evaluation of the final financial outcome of production. However, for comprehensive analysis it was important to consider not only absolute profit values but also the sensitivity of financial indicators to changes in cost structure. In this context, the key role was played by the operating leverage (DOL) indicator, defined as the ratio of marginal profit to net profit, which characterised the degree of risk associated with fluctuations in revenue or costs. The operation of the law of diminishing returned in grain production determined the choice of a parabolic production function, which implied that any deviation of the cost structure from the optimum unevenly affects performance. This nonlinearity transformed the behaviour of operating leverage: the DOL indicator became sensitive not only to fluctuations in revenue but also to the position of the enterprise along the production curve. Accordingly, budgeting of variable costs must account not only for their level but also for their position relative to the technological optimum point, forming a risk management logic through control of cost structure. To formalise this effect, a modified analytical form of the operating leverage indicator was used, which considered the marginal impact of expenditures on fertilisers and seeds both on net profit and on revenue. Taking into account the functional relationship of yield with expenditures (equation 10), as well as the dependence of net profit on yield (equation 12), the DOL indicator took the form:

$$DOL(X_1, X_2) = \frac{37.71 - 1.10 \cdot X_1 - 39.82 \cdot X_2}{3{,}540 \cdot (112.2 - 3.10 \cdot X_1 - 112.4 \cdot X_2)}. \quad (13)$$

Calculations based on the model showed that the maximum value of operating leverage reaches 9.99 at expenditures on fertilisers of 4.47 thousand UAH/ha and on seeds of 1.33 thousand UAH/ha (Fig. 3). At this point, the predicted yield was 41.2 c/ha, marginal profit – 4.29 thousand UAH/ha, and net profit – only 0.43 thousand UAH/ha. Such a DOL level was critically high: minimal deviations in revenue or costs can cause a sharp reversal of financial results, indicating increased operational instability.

High values of operating leverage in this case were a direct consequence of the enterprise entering a zone of low technological returns, where additional expenditures no longer provide proportional yield increases.

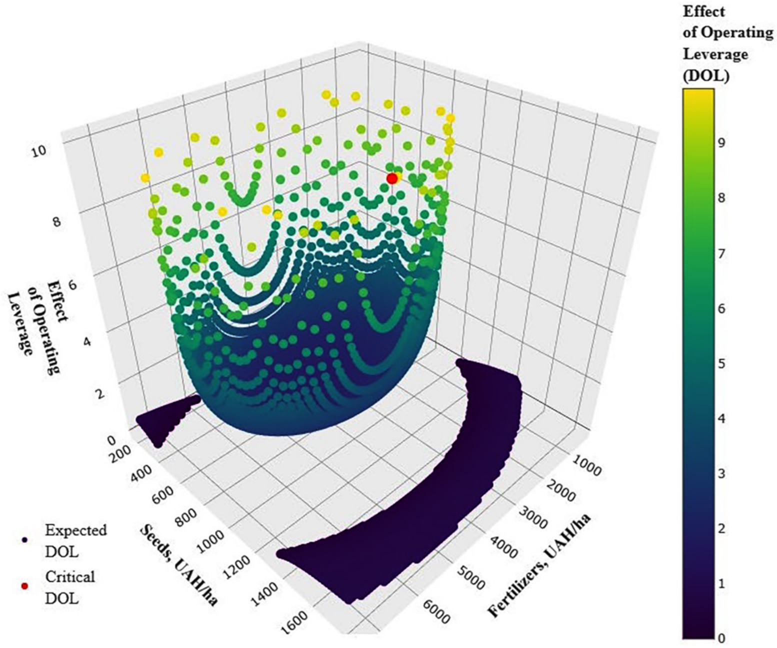

Figure 3. Dependence of operating leverage on expenditures for fertilisers and seeds
Notes: the red marker indicated the local maximum point of operating leverage (9.99) at a net profit of 0.43 thousand UAH/ha
Source: State Statistics Service of Ukraine (2021)

From a managerial perspective, it was advisable to focus on a moderate range of operating leverage – 1.1-1.6. This range was achieved at expenditures on fertilisers of 3.5-4.0 thousand UAH/ha and on seeds of 0.8-0.9 thousand UAH/ha. Within this interval, the predicted yield was 53-54 c/ha, and net profit was approximately 5.0-5.5 thousand UAH/ha, ensuring a balance between profitability and stability. Such a zone of operating leverage reflected a rational "result-risk" ratio and was appropriate for budgeting variable costs. It formed the basis for managerial control aimed at minimising operational risks, while maintaining the target level of profitability. Thus, budgeting variable costs in grain production must account not only for the absolute level of resources but also for their position relative to the technological optimum. The use of a parabolic specification of the production function made it possible to identify "safe zones" of investment in fertilisers and seeds, where financial risk was minimal and the effect of additional expenditures was predictable. This created the foundation for scenario-based budgets and the integration of sensitivity indicators (DOL) into the system of managerial control of agricultural enterprises' financial results.

Alongside the influence of variable cost structure on operating leverage, an important element of the financial strategy of agricultural producers was assessing how changes in external financial conditions transformed the final outcome. Since seasonal production largely relied on short-term credit, the interest rate became not merely a parameter of borrowing costs but a factor capable of shifting the optimal balance point between expenditures and expected yield. In this context, a logical continuation of the analysis was the determination of the elasticity of net profit with respect to changes in the interest rate. The cost of credit affects performance through two channels: directly – via increased debt servicing costs, and indirectly – through the transformation of optimal combinations of fertilisers and seeds in the production function. As a result, an increase in the interest rate narrowed the space of resource combinations, in which the enterprise can ensure positive net profit, justifying the need for credit elasticity analysis as the final stage of the study. For a multi-factor model, where revenue was formed as the product of yield and selling price, and yield itself was a function of expenditures on fertilisers (X_1) and seeds (X_2), the financial elasticity indicator was defined as:

$$E_{NP,r}(X_1,X_2)=\frac{\frac{\partial NP(X_1,X_2)}{\partial X_1}+\frac{\partial NP(X_1,X_2)}{\partial X_2}}{NP(X_1,X_2)}\cdot\frac{r(X_1,X_2)}{\frac{\partial r(X_1,X_2)}{\partial X_1}+\frac{\partial r(X_1,X_2)}{\partial X_2}}. \quad (14)$$

In a specified form, this formula became:

$$E_{NP,r}(X_1,X_2)=\frac{37.71-1.10X_1-39.82X_2}{NP(X_1,X_2)}\cdot\frac{Y(X_1,X_2)}{112.2-3.10X_1-112.4X_2}. \quad (15)$$

Thus, the financial elasticity indicator made it possible to assess how a percentage change in revenue translated into a percentage change in net profit depending on cost structure and credit conditions. It served as an indicator of enterprise financial resilience and complemented the analysis of operating leverage. The combined application of these two indicators within a methodological system allowed not only the determination of absolute profit levels but also the assessment of their sensitivity to changes in cost structure and credit resource costs, forming the basis for risk management and improving the efficiency of budgeting in grain production. To reveal the effect of financial elasticity, scenario analysis was conducted, in which the credit rate varied within ±20% of the baseline level. The results demonstrated pronounced spatial heterogeneity of net profit elasticity with respect to the interest rate (E_r) in the "fertilisers-seeds" plane. The maximum elasticity value (E_r = 0.10) was recorded at expenditures on fertilisers of about 1.9 thousand UAH/ha and expenditures on seeds of approximately 0.53 thousand UAH/ha (Fig. 4).

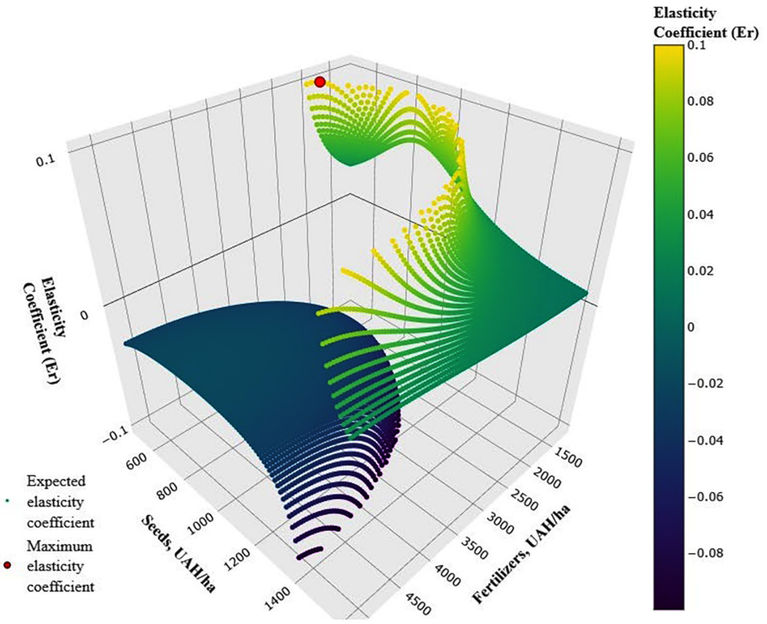

Figure 4. Dependence of the financial elasticity coefficient on expenditures for fertilisers and seeds
Notes: red marker indicated the local maximum point of the financial elasticity coefficient (0.10), at which the financial result amounted to -1.32 thousand UAH/ha
Source: State Statistics Service of Ukraine (2021)

It was indicated that yield was about 31.3 c/ha, and net profit was negative (-1.32 thousand UAH/ha). This meant that the zone of highest profit sensitivity to the credit rate coincided with the regime of technological underfunding, when resources were applied at a level insufficient to achieve economies of scale and avoid the law of diminishing returns. In such a regime, the enterprise operated "on the lower branch" of the production function, where each unit of resource still provides high marginal returns, but the baseline yield level was insufficient to cover fixed and financial costs. Overall, the analysis demonstrated that combining production and financial models allowed for a more comprehensive assessment of risk contours in agricultural production. The constructed quadratic production function revealed the technological optimum and identified the zone of rational budgeting of variable costs, while the evaluation of operating leverage showed how deviations from this optimum amplified financial instability of the enterprise. Additional consideration of net profit elasticity with respect to credit resource costs confirmed that sensitivity to the interest rate strongly depended on the enterprise's position on the production curve: in the zone of technological deficit, financial vulnerability increased sharply, whereas in the range of optimal expenditures a stable profitability profile was formed even under deteriorating credit conditions. Thus, the results of the study confirmed that effective budgeting of variable costs cannot be carried out in isolation from debt burden management. Decisions regarding cost structure and borrowing must be made in interconnection, since technological and financial risks reinforced each other. This created the foundation for developing an integrated financial strategy for agricultural enterprises, in which optimisation of the production cost structure, evaluation of operating leverage, and analysis of sensitivity to interest rate risk formed a unified system of managerial decision support.

▸ Discussion

The results obtained in this study provided a detailed quantitative assessment of the interrelationships between resource allocation, wheat yields, and financial indicators in grain production, situating the findings within the broader context of agricultural economics and farm management research. The constructed quadratic production function captured the nonlinear response of wheat yield to variable input expenditures, a characteristic feature emphasised in numerous empirical and theoretical studies. C.L. Escalante & P.J. Barry (2001) highlighted that effective farm management required the integration of production efficiency with financial constraints, particularly in environments characterised by input cost volatility. This interpretation is further supported by P.J. Barry & P.N. Ellinger (2012), who argued that agricultural financial management must simultaneously evaluate production decisions, liquidity, solvency, and risk-bearing capacity. The present results aligned with these conclusions by demonstrating that deviations from optimal resource allocation significantly amplified financial sensitivity, especially under conditions of technological underfunding.

B.-L. Miao *et al.* (2023), employing a portfolio optimisation approach to crop resource allocation, argued that the maximisation of physical output does not necessarily guarantee financial optimality, as cost interactions and price volatility often shift the economically efficient input combination away from the technological optimum. The findings of this study confirmed this divergence, revealing that the financially optimal combination of fertiliser, seed, and service expenditures differed from the point of maximum yield. In particular, under constrained resource conditions, technological optima failed to ensure adequate coverage of fixed and interest-related costs, reinforcing the necessity of integrated production-financial planning frameworks. F. Akhavizadegan *et al.* (2022) applied stochastic optimisation to farm management under uncertainty and demonstrated the critical role of scenario analysis in identifying risk-sensitive resource combinations. The methodology adopted in this research complemented this approach by operationalising scenario-based evaluation through indicators of operating leverage (DOL) and financial elasticity of net profit with respect to credit rates. The importance of evaluating credit conditions in agricultural production was also emphasised by V. Hmyrya (2017), who demonstrated that financial viability depends substantially on the structure and cost of borrowed capital. The results showed that enterprises operating below the technological optimum exhibited substantially higher vulnerability to interest rate increases, whereas those operating near the optimum maintained relatively stable profitability even under moderate financial shocks. This correspondence underscored the practical relevance of scenario-based modelling for agricultural financial planning.

M. Hernandez-Romero & G. Coenders (2025) analysed the resilience of agricultural enterprises to external shocks and concluded that balanced cost structures and moderate debt levels were crucial for sustaining financial stability. Consistent with this perspective, the present study demonstrated that the combination of optimal resource allocation and rational credit utilisation formed a protective buffer against financial stress. Estimates of financial elasticity confirmed that sensitivity to borrowing costs declined significantly near the technological optimum, providing empirical justification for integrating production modelling with capital structure decisions. Empirical evidence provided by Rissi & Herman (2021) similarly confirms that liquidity, profitability, and financial leverage are key predictors of financial distress, reinforcing the conclusion that excessive leverage amplifies vulnerability under volatile income conditions. The findings also extend the conceptual framework proposed by O. Kochetkov & J. Afanasova (2020), who developed a mechanism for managing the resource potential of agricultural enterprises. Their approach stressed that efficient allocation and utilisation of material, labour, and financial resources were prerequisites for sustainable enterprise development. The quantitative modelling implemented in this study operationalised this concept by explicitly linking resource inputs with yield response, marginal profitability, and financial sensitivity. This integration enabled a deeper understanding of how resource potential translated into financial performance under different economic scenarios, thus bridging a key gap between resource management theory and applied financial analysis.

Moreover, the results contributed to the debate on conservative financial strategies in volatile environments, as discussed by F. Morais *et al.* (2021) in their analysis of the zero-leverage phenomenon. Their study suggested that firms often deliberately avoided debt to mitigate financial risk, particularly under unstable market conditions. In the context of grain production, this research demonstrated that while excessive leverage amplifies financial sensitivity, complete avoidance of debt may also constrain technological optimisation and limit yield potential. Hence, the findings supported a balanced financial strategy, in which moderate leverage, aligned with optimal resource allocation, enhances both production efficiency and financial resilience.

From a strategic planning perspective, N.I. Okeke *et al.* (2024) emphasised the central role of integrated budgeting and revenue management systems in forecasting financial stability, particularly in small and medium-sized enterprises. The scenario-based budgeting framework developed in this study directly complemented their conclusions by offering a quantitative tool for forecasting profit volatility, liquidity risks, and credit sensitivity under alternative resource and price scenarios. This enabled managers to evaluate not only expected profitability but also downside risk, thereby improving the robustness of financial planning. In line with international policy perspectives, the OECD (n.d.) stresses that agricultural risk management should combine production risk mitigation, financial instruments, and strategic planning tools. The integrated modelling framework proposed in this study corresponds directly to this multidimensional view of agricultural risk governance.

V. Zdir *et al.* (2019) stressed that empirical yield and cost data were indispensable for constructing effective financial strategies in agriculture. By integrating actual expenditure data on fertilisers, seeds, labour, fuel, and contractor services, the models developed in this research generated concrete estimates of marginal productivity, operating leverage, and financial elasticity across different input combinations. This approach provided a granular assessment of both efficiency and risk, consistent with the empirical emphasis advocated by V. Zdir *et al.* (2019). Global statistical evidence provided by FAO (2021) further confirms that fluctuations in yields, input prices, and production costs remain among the most influential determinants of farm income variability worldwide. The present study bridged these macroeconomic insights with micro-level modelling, demonstrating that operational and financial risks were deeply interconnected, particularly under resource-constrained conditions.

Collectively, the comparative analysis of these sources yielded several key insights. Firstly, the nonlinear response of grain yield to variable inputs was consistently observed across different geographical and methodological contexts. Secondly, financial sensitivity was highly contingent on both resource allocation and debt structure, underscoring the necessity of joint consideration of production and financial parameters. Thirdly, scenario-based and stochastic modelling approaches proved effective in identifying risk-prone input combinations, thereby supporting more resilient budget planning. By explicitly quantifying the effects of individual inputs on yield, marginal profit, and net profit, this study extended prior research by offering a direct operational framework for scenario analysis in grain production. The incorporation of operating leverage and financial elasticity established a conceptual and analytical bridge between production efficiency and financial resilience. Findings demonstrated that enterprises operating below the technological optimum experience amplified negative effects from interest rate increases, while those operating near the optimum maintain greater financial stability. This reinforced the principle that maximising physical output alone is insufficient; financial planning must systematically account for cost structures, marginal efficiencies, and exposure to external shocks.

Overall, the proposed modelling framework provides a robust foundation for strategic resource planning, financial risk management, and adaptive budgeting in grain production under volatile market conditions. By integrating technological and financial dimensions, the study offers practical guidance for managers and policymakers seeking to enhance the sustainability and competitiveness of agricultural enterprises.

Conclusions

The study confirmed that the use of a parabolic production function was an adequate tool for modelling the technological behaviour of grain production and for further integration of its results into the financial planning system. The estimated yield function made it possible not only to establish the impact of individual cost items on productivity but also to determine the local optimum of their combination. With a rational structure of variable costs, the enterprise was capable of achieving a forecasted yield of 55.1 c/ha, which defined its technological efficiency. The transition to monetary indicators through the construction of marginal and net profit functions showed that the optimum of financial results does not coincide with the optimum of yield. At the point of maximum marginal profit, yield was lower (53.8 c/ha), reflecting the effect of marginal costs not accounted for in the physical model. The inclusion of fixed costs narrowed the area of economically feasible resource combinations, while the maximum net profit of 5.46 thousand UAH/ha outlined the real financial potential of production under rational budgeting. The analysis of the operating lever proved that its maximum values were formed in the zone of technological underfunding and were accompanied by a minimum or almost zero net profit, which indicated a high level of risk and instability of such regimes. In contrast, the safe and manageable operating leverage range of 1.1-1.6 corresponded to moderate expenditures on fertilisers and seeds and ensured stable profitability. The study of financial elasticity of net profit with respect to the interest rate revealed that the greatest credit risk was borne by enterprises operating in a resource underfunding regime. In this zone, even moderate increases in credit costs led to deepening losses due to the combination of low yields, uncovered fixed costs, and rising financial expenses. Thus, the credit rate in grain production acted not merely as a financial parameter but as a factor that changed the optimal proportions of resource use and transformed the "profitability landscape". Future studies can focus on refining scenario-based budgeting models, exploring the impact of credit and input price volatility on profitability, and developing adaptive strategies that enhanced the resilience of agricultural enterprises to both technological and financial risks.

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Conflict of Interest

None.

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Вплив операційного важеля та фінансової еластичності на бюджетування змінних витрат у виробництві зерна

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▸ **Анотація.** Стійкість фінансових стратегій в аграрних підприємствах залежить від точного прогнозування параметрів виробництва та супутніх кредитних ризиків в умовах нестабільного ринку. Метою цього дослідження було оцінити технологічну реакцію виробництва зерна на зміни у постачанні ресурсів і інтегрувати результати у прогнозування ліквідності та оцінку ризику негативних процентних ставок. Оцінена квадратична виробнича функція адекватно відображала нелінійну реакцію врожайності пшениці на змінні витрати, підтверджуючи закон спадної граничної віддачі. Модель продемонструвала задовільну статистичну ефективність ($R^2 = 0,606$, скориговане $R^2 = 0,409$) та була статистично значущою ($F = 3,073$, $p = 0,027$). Виявлений технологічний оптимум відповідав максимальному прогнозованому врожаю 55,1 ц/га, досягнутому при витратах на добрива і насіння приблизно 5,3 та 0,85 тис. грн/га відповідно. При застосуванні показників на основі вартості оптимум змістився в бік максимізації прибутку. Максимальний граничний прибуток досяг 9,32 тис. грн/га при трохи нижчих рівнях витрат, з відповідним врожаєм 53,8 ц/га, тоді як максимальний чистий прибуток склав 5,46 тис. грн/га після врахування постійних витрат. Аналіз операційного важеля виявив виражену нелінійність фінансової чутливості. Надзвичайно високі значення DOL (до 9,99) спостерігались в умовах недофінансованого виробництва, де чистий прибуток наближається до нуля, що вказує на критичну операційну нестабільність, в той час як стабільний діапазон DOL 1,1-1,6 відповідав помірним рівням витрат. Аналіз сценаріїв кредитних умов (±20 % зміна процентної ставки) показав асиметричний ризик процентної ставки. Найвища фінансова еластичність чистого прибутку ($E \approx 0,10$) спостерігалась у низьковитратних, збиткових режимах, тоді як поблизу технологічного оптимуму еластичність наближається до нуля, що свідчить про відносну фінансову стійкість. Результати підтвердили, що інтеграція виробничого моделювання з показниками фінансової чутливості покращує прогнозування ліквідності та кредитне планування в зерновому виробництві

▸ **Ключові слова:** параболічна виробнича функція; оптимізація ресурсів; граничний прибуток; ліквідність; ризик процентної ставки; фінансове планування

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Percolation models of competition and monopolisation in the agricultural market

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► **Abstract.** The study was relevant due to the growing risks of agricultural market monopolisation in Ukraine, which necessitated a quantitative analysis of concentration processes using modern modeling tools. The purpose of the study was to build a model of monopoly formation in the agricultural market by applying a percolation approach to forecasting phase transitions in a competitive environment. A two-dimensional percolation model of the agricultural market was developed to simulate the capture of market segments by large formations and assess concentration dynamics. Numerical experiments (200×200 domain) showed that as the control parameter approaches the critical value $P^*=0.5945$, the correlation coefficient of rating-frequency diagrams fell sharply from 0.94-0.97 at $P=0.50$-0.58 to 0.55 at $P=0.59$, indicating a phase transition interpreted as monopoly cluster formation. Using Ukrainian agricultural market data for 2017-2023, the model identified a critical percolation threshold at $P^*=0.59$, accompanied by a decline in correlation coefficients from 0.96 to 0.55. A logarithmic relationship $W=-0.3839-0.153\ ln|P-P^*|$, $R^2=0.9821$ described the growth of dominant clusters. The number of agricultural enterprises declined from 40.7 to 30 thousand (-26%) and average land per enterprise increased from 490 to 576 ha, confirming the intensification of concentration processes and illustrating how geometric cluster behaviour mirrors real structural shifts in the sector, thereby strengthening the applied significance of the developed modelling approach and providing a quantitative framework for detecting early signs of market dominance, assessing systemic vulnerabilities, and interpreting concentration dynamics through the lens of phase-transition phenomena. The practical value of the study lies in enabling early identification of market monopolisation and critical transition points, thereby supporting more accurate forecasting of structural shifts and the development of effective antitrust and regulatory measures

► **Keywords:** clustering; phase transition; market concentration; fractal dimension; market asymmetry; monopoly risk assessment

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Introduction

The growing concentration of agricultural capital, the decrease in the number of enterprises that own or use agricultural land, and the increasing influence of large agricultural formations on the Ukrainian market necessitated the application of the latest quantitative approaches to analyse and model monopolisation processes in agriculture. In the context of the modern globalised economy, the market operated as an open stochastic system prone to phase transitions and the formation of clusters with a high concentration of participants. In the agricultural sector, despite its traditional resistance to classical mechanisms of monopolisation, large corporate structures increasingly captured individual market segments, which was accompanied by a measurable decline in competition. M. Conyon *et al.* (2023) emphasised that consolidation processes in related industries often intensified due to nonlinear interactions and the accumulation of market power. These tendencies necessitated a quantitative assessment of monopolisation dynamics that accounted for the complexity, non-linearity, and multifactorial nature of interactions between market agents. Empirical studies in the agricultural economics literature also confirmed the growing structural asymmetries and the emergence of concentration clusters. P. Maranzano *et al.* (2025) demonstrated that farmland production in the European Union had experienced significant consolidation with a decline in the number of small farms and an increase in average operational trends that parallel the structural transformations observed in Ukraine. R. Cerqueti *et al.* (2025) employed a spatially-clustered spatial autoregressive model to identify regional "hotspots" of agricultural market concentration across Europe, revealing spatial patterns analogous to cluster formation in complex systems.

In addition to structural shifts driven by market forces, policy-induced dynamics also contributed to concentration. Researchers A. Mozdzen *et al.* (2024), using a Bayesian nonparametric partial clustering approach, showed that agricultural subsidies and institutional incentives often have heterogeneous effects and may reinforce consolidation tendencies in certain regions. E. Moretti *et al.* (2025) demonstrated through a spatial ecological-economic framework that farm size itself became a critical determinant of behavioural, ecological, and productivity characteristics, providing further theoretical justification for modelling agricultural markets as nonlinear systems with size-dependent dynamics. Economic studies, particularly within an interdisciplinary framework, increasingly integrates the tools of complex systems physics to explain economic phenomena. Percolation theory, phase-transition concepts, agent-based modelling, and mathematical ecology were widely applied to analyse transformations in competitive environments. R. Lucas (2022) demonstrated that network effects may induce nonequilibrium phase transitions in competitive markets, where monopolisation emerged as a consequence of symmetry breaking in conditions of unstable equilibrium. J.P. Nadal *et al.* (2003), using an agent-based computational economics (ACE) approach, revealed analogies between monopolistic pricing dynamics and first-order phase transitions in statistical physics. At the same time, the methodological versatility of percolation models was illustrated by their application in other scientific domains: W. Wang *et al.* (2023) modelled extraction and diffusion processes in pharmaceutical systems, demonstrating the potential of percolation-based approaches for studying the behaviour of complex multicomponent structures.

The study aimed to formalise and quantitatively model the processes of monopolisation in the agricultural market as cluster formation within a complex stochastic system, utilising methods from percolation theory and statistical physics tools. The study addressed the objectives: 1) to adapt percolation theory for modelling competitive market structures; 2) to identify critical thresholds of market concentration; 3) to assess socio-economic implications of monopolisation dynamics in agrarian sector. The scientific novelty consisted in applying percolation theory to quantify monopolisation processes in the agricultural market by identifying critical phase-transition thresholds and interpreting rating-frequency diagrams as indicators of emerging monopoly clusters within a stochastic competitive system.

Materials and Methods

Conceptual basis of modelling

The methodology was based on the concept of geometric phase transitions in complex stochastic systems, which was widely used in statistical physics, mathematical ecology, and complex network theory. At the first stage of the study, a hypothesis was formed about the similarity between market monopolisation processes and phase transitions in percolation systems. All types of competitive processes in science were characterised by an uneven distribution of results among participants, which can be generalised in the form of the parameter Q_i. In the context of this study, the parameter Q_i corresponded to the market share of an agricultural enterprise, which served as economic analogue of the cluster size in the percolation model. It has been established that in different types of systems, rating-frequency diagrams form patterns that were described by a semi-logarithmic function:

$$Q_i = a - b^* ln(i), \quad (1)$$

where Q_i – "achievements" of the i-th participant in the competitive process, i – participant number in the ranking, a, b – constants of the given competitive process, $ln(i)$ – natural logarithm of the ranking number i.

So, it was possible to construct quantitative models of such processes with high reliability. Particular attention has been given to geometric phase transitions, which were rigorously formalised within percolation theory as a mathematical framework that described how local interactions between elements of a system led to the formation of connected clusters and identified the critical threshold, at which a large-scale spanning structure emerges. This theoretical foundation made it possible to interpret the onset of monopolistic dominance in agrarian market environments as an analogue of a percolation-driven phase transition.

Building a two-component percolation model

In the second stage, a basic two-component percolation model was implemented, which described the interaction of two components – *A* (active market participants) and *B* (passive or displaced entities). In this model, a given area *G* with fractal dimension *D (*which may take integer or fractional values) was assumed to contain a mixture of components *A* and *B.* The area *G* is partitioned into *N* cells, each of which may be occupied by component *A* with probability *P* or by component *B* with probability (*1-P*) in accordance with the specified conditions:

$$\frac{N_A + N_B}{N} = 1. \quad (2)$$

The parameter *L* denoted the characteristic size of the region *G*, then:

$$L^D = N, \text{ thus } L = N^{1/D}, \quad (3)$$

where *D* – the fractal dimension of the space. When the control parameter was changed, the probability *P* of filling the area *G* with the component *A* was changed:

$$P \in [0; P_*]. \quad (4)$$

The probability of the appearance of a connecting cluster on the domain *G* can be found as:

$$W = \frac{1}{1 + exp[\lambda_L (P - P_*)]}, \quad (5)$$

where *W* – denoted the probability of the emergence of a system-spanning (connecting) cluster, λ_L – a scaling parameter controlling the steepness of the percolation transition, P_* – the percolation threshold. As the control parameter *P* approaches the percolation threshold P_* from below, the probability of the emergence of a system-spanning (connecting) cluster tends to unity:

$$lim_{P \to P_*} W \Longrightarrow 1. \quad (6)$$

Equation (6) described the critical behaviour of the system near the percolation threshold, where the probability of forming a system-spanning cluster rapidly increased. From the point of view of the theory of competitive processes, this meant the formation of a connecting cluster, or the monopolisation of a part or all of the region *G*. It has been demonstrated that the percolation threshold primarily depended on the fractal dimension of the region *G* (strong dependence) and weakly depended on the system size *L* and the way the region *G* was divided into elementary cells. In the case of a Cartesian partitioning of the domain *G*, the percolation threshold was described by the Cartesian approximation proposed in percolation and multifractal modelling studies (Grabar & Kubrak, 2025):

$$P_* = 1 - ln\frac{D+1}{2}, \quad (7)$$

where *D* – the spatial (topological) dimension of the domain *G*, which characterised the dimensionality of the Cartesian partitioning of the system into elementary cells.

In the statistical drawing of components *A* and *B* on the domain *G*, certain combinations of the same name components occurred along the vertices of elementary "cube-cells" and along the sides (planes). In the percolation problem, contact along the vertices (points) does not lead to the formation of a connecting cluster, but contact along the sides or planes does.

Implementation of the computational experiment

For numerical modelling, the proprietary software package included two modules: PERCOL and PERCOL-statistic, which ensured both the generation of percolation fields and the analytical processing of simulation outputs. PERCOL – set a statistical draw according to the specified control parameter *P(A)* on the domain *G* with dimensions $a_x a_y a_z$, where each a_j was [0…500], visualised the generated area and the clusters formed within it, automatically colours clusters, and determined the presence (YES) or absence (NO) of a spanning cluster connecting the boundaries of the domain. The module also generated a test report for each realisation. To extend these basic functions, PERCOL additionally provided standardised generation of multiple stochastic realisations, supported visualisation of cluster structures for different values of the control parameter *P*, and enabled automated detection of the transition from fragmented to connected configurations. This allowed interpreting the occurrence of a spanning cluster as an analogue of market monopoly formation within the simulated competitive environment. PERCOL-statistic performed the statistical processing of outputs, including ranking clusters by size, constructing rating-frequency diagrams, calculating correlation coefficients, and approximating the empirical distributions. Beyond these functions, the module aggregated the results from repeated realisations, computed averaged indicators to ensure the stability of quantitative patterns, and identified deviations in the correlation structure that signalled proximity to a geometric phase transition. These analytical capabilities enabled the diagnosis of threshold phenomena and the evaluation of monopolisation probability in a reproducible and formalised manner.

Model expansion:
Three- and polycomponent percolation

To study multifactorial processes of the agricultural market, the following has been implemented: three-component model, in which three types of participants were introduced (small, medium, and large enterprises) with probabilities P_a, P_b, P_c that satisfy the normalisation condition:

$$P_a, P_b, P_c + P_c = 1. \quad (8)$$

For convenience, as a special case, automodelling conditions were provided:

$$P_b = \lambda\, P_a\, P_c = \lambda\, P_b = \lambda^2\, P_a, \quad (9)$$

where λ – a scaling parameter describing the intensity of competitive advantage transfer between successive states, determining the relative weights of P_a, P_b, P_c.

Then the condition of normalisation:

$$P_a (1 + \lambda + \lambda^2) = 1. \quad (10)$$

Multicomponent model (for $n \geq 3$ components), which allowed taking into account more complex scenarios of market interaction. The procedures for generating, visualising, and statistical processing were in all cases similar to the two-component model, which ensured standardisation of the computational experiment.

Indicators for assessing market concentration and monopolisation

The approach was based on the following indicators:

1) concentration index (CR), defined as the sum of the shares of the three largest enterprises in the total market volume of homogeneous goods in percent:

$$\text{CR}_3 = \sum_{i=1}^{3} K_i, \quad (11)$$

where K – the share of the i-th enterprise's products in the industry, %. If the concentration index was close to 100%, the market was characterised by a high level of monopolisation;

2) Linda index was applied in EU competition analysis to identify dominance thresholds depending on the number of leading firms and was mainly used as a structural diagnostic indicator rather than a strict numerical threshold;

3) Herfindahl-Hirschman Index (IHH), used as a benchmark for determining the possibility of mergers and acquisitions. It was defined as the sum of the squares of the shares of production of the main enterprises producing products (services) in a certain industry (sphere of economic activity).

$$\text{IHH} = \sum_{i=1}^{n} k_i^2, \quad (12)$$

where k – the share of production of the i-th enterprise in the industry, %; n – the number of enterprises operating in the relevant market.

Verification of results

To verify the adequacy of the model, the modelling results were compared with empirical data for the Ukrainian market over the period 2017-2023. Attention was paid to comparing the change in the correlation coefficients of the rating-frequency diagrams with the transition of the system, in such a way that a decrease in correlation serves as an indicator of a phase transition, which was interpreted as an analogue of the monopolisation process. The percolation model was constructed on the basis of aggregated empirical data characterising the structural dynamics of the Ukrainian agricultural market for the period 2017-2023. In particular, the model parameters were calibrated using official statistical indicators, including: the number of agricultural enterprises operating in Ukraine; the number of enterprises owning or using agricultural land; the total area of agricultural land; and the average agricultural land area per enterprise. These indicators were obtained from the statistical yearbooks and sectoral datasets of the State Statistics Service of Ukraine (2024), which served as the empirical basis for validating the simulated clustering and monopolisation dynamics.

Results and Discussion

Results of computational percolation experiments for agrarian market clustering

Numerical simulations of a two-component, two-dimensional percolation model was applied to the agricultural market, illustrating the evolution of cluster structures and the corresponding rating-frequency diagrams for different values of the control parameter P, which reflected the transition from a fragmented competitive state to a connected (monopolised) configuration. The use of rating-frequency diagrams as a diagnostic tool aligns with graphical modelling approaches applied in other complex systems, where visual structures were employed to reveal latent dominance patterns and influence mechanisms (Savchuk, 2018). To achieve the stated research objective, computer modelling of the kinetics of cluster formation in the agricultural market was carried out using the percolation approach. The most significant results in the theory of critical phenomena and phase transitions were obtained in the two-component percolation, which was due to the simplicity of implementation, the availability of visualisation and analytical processing of the results, since there was single control parameter . In turn, of all the possible values of fractal dimension of the region G, metric spaces are most often used: $D = 1$; $D = 2$; $D = 3$. Then, the value of the percolation threshold according to the Cartesian approximation gave a result that corresponded with an error of less than 1% to theoretical and numerical results reported in percolation theory for two-dimensional Cartesian lattices (Feder *et al.*, 2022; Shevchuk *et al.*, 2022):

$$\begin{aligned} P_{*/D=1} &= 1 - ln\frac{1+1}{2} = 1; \\ P_{*/D=2} &= 1 - ln\frac{2+1}{2} = 0.5945; \\ P_{*/D=3} &= 1 - ln\frac{3+1}{2} = 0.3068. \end{aligned} \quad (13)$$

The most commonly used models were of domain G: "strips" $a \times B$ (a is 1…B), "squares" B x B (B is 2…500), "sandwiches" $B \times B \times a$ (a is 1…B). In the present study, the domain G was represented by three geometrical configurations. The "strips" correspond to quasi-one-dimensional lattices of size $a \times B$, modelling elongated systems. The "squares" represent classical two-dimensional lattices of size $B \times B$. The "sandwiches" denote quasi-two-dimensional layered systems of size $B \times B \times a$, where a is the thickness parameter. These configurations allow analysis of finite-size effects and the influence of dimensionality on stochastic percolation behavior. The results of computer modelling of a two-component ($A + B$) two-dimensional ($D = 2$) percolation process for the region $B \times B$ are presented. The study revealed that for values of $B > 100$, the character of the rating-frequency diagrams does not change significantly. The value of the control parameter P was varied over the range [0…1]. One of the most interesting was the range of these values:

$$P \text{ is } [0.85\ldots\ 1.1]\ P_*, \quad (14)$$

where with a high correlation coefficient $R^2_{1/1} > 0.95$, rating-frequency diagrams were described by semilogarithmic dependencies of type (1). Parameters:

$$P > 0.97\ P^*, \quad (15)$$

where corresponding to the region of geometric phase transition, or the capture (monopoly) of one or more giant clusters of the region G, the value of the correlation coefficient in the semilogarithmic model of rating-frequency diagrams dropped sharply.

The results of modelling the formation of clusters were obtained for a range of control parameter values $P \in [0.50\text{-}0.59]$. To illustrate the structural evolution of the percolation field without redundant graphical repetition, four representative regimes were selected for detailed presentation: $P = 0.50$, $P = 0.54$, $P = 0.58$, and $P = 0.59$. For a two-dimensional model ($D = 2$), according to (1), the percolation threshold was $P^* = 0.5945$. Computer modelling was performed using the author's software products PERCOL and PERCOL-statistic. Although the capabilities of percolation-based modelling frameworks may be extended to larger domains and more complex configurations (Grabar & Kubrak, 2025; Grabar & Kilnitska, 2025), a reduced lattice size $Q = 200\text{x}200$ was sufficient to capture critical phase-transition effects. From a modelling perspective, the separation of simulation and analytical modules implemented in the PERCOL and PERCOL-statistic software corresponded to structured system design approaches that combined conceptual and formal representations, as proposed by M. Fu *et al.* (2018) for complex operational modelling. The software product PERCOL-statistic enabled the determination of cluster sizes and the construction of their rating-frequency diagrams. The obtained rating-frequency diagrams were best approximated in semi-logarithmic coordinates, yielding the highest correlation coefficients. Analysis of the graphs showed that the onset of a phase transition dramatically changed the kinetics of the rating-frequency diagrams for $P = 0.59$, accompanied by a sharp dropped in the correlation coefficient from 0.9-0.97 to a critically low value of 0.55. This may serve as an additional quantitative criterion for identifying a phase transition, analogous to the emergence of a monopoly. The results of the statistical modelling were analysed for 40,000 market participants. Intermediate configurations within $P \in [0.51\text{-}0.57]$ demonstrated gradual quantitative cluster growth without qualitative topological transformation and therefore were not presented separately. Figure 1 illustrated the cluster configuration of the percolation field at $P = 0.50$, corresponding to a fragmented competitive market state.

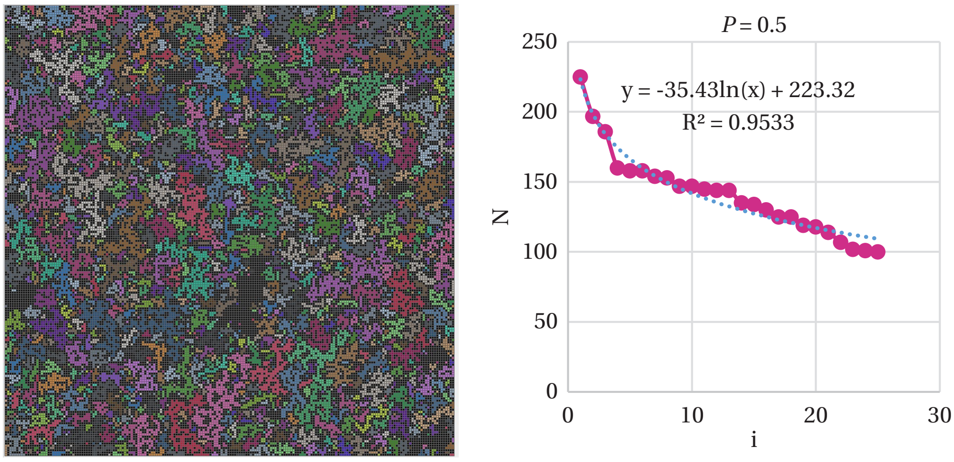


Figure 1. Model of cluster formation with the parameter $P = 0.5$
Notes: R^2 – the coefficient of determination, which characterised the goodness of fit of the logarithmic approximation to the simulation data and indicated the share of variance in the dependent variable explained by the model
Source: State Statistics Service of Ukraine (2024)

At $P = 0.50$, the percolation field was dominated by small, isolated clusters, and no system-spanning cluster was observed. This configuration corresponded to a decentralised market structure with a high level of competition and the absence of dominant market players. The spatial configuration at $P = 0.50$ demonstrated a highly fragmented topology characterised by numerous small clusters distributed relatively uniformly across the domain. The absence of large connected components indicated limited interaction between dominant agrarian market participants. The corresponding rating-frequency diagram preserved a stable semi-logarithmic pattern with a high coefficient of determination ($R^2 = 0.95$), confirming structural equilibrium. This regime reflects a competitive market state where resource distribution remains dispersed. A moderate increase in the control parameter within the range $P \in [0.51\text{-}0.53]$ led to gradual cluster enlargement and partial merging of neighbouring structures. However, the system remained below the percolation threshold, and no system-spanning cluster emerges. The rating-frequency diagrams within this interval maintain structural stability in semi-logarithmic approximation ($R^2 > 0.95$), indicating preservation of competitive balance. These intermediate configurations reflected quantitative growth without qualitative topological transformation. Figure 2 illustrated the cluster configuration at $P = 0.54$, where the enlargement of clusters became structurally pronounced and the first signs of large-scale aggregation emerge.

At $P = 0.54$, cluster enlargement became visually evident, and the spatial structure of the system begins to reorganise. Although a system-spanning cluster was still absent, several medium-sized clusters expand and absorb neighbouring elements, leading to increasing structural asymmetry. The corresponding rating-frequency diagram continues to follow a semi-logarithmic distribution, with a high coefficient of determination ($R^2 = 0.97$), indicating that the system remained within a competitive regime. However, the growth of dominant clusters signalled the gradual accumulation of structural instability. As the control parameter increased further within the interval $P \in [0.55\text{-}0.57]$, cluster coalescence intensifies, and the size distribution became increasingly uneven. The largest clusters began to dominate spatially, although full connectivity across the domain has not yet been achieved. In this range, the semi-logarithmic approximation remained generally valid, but fluctuations in the correlation coefficient indicated the system's approach to a critical state. Figure 3 illustrated the percolation field at $P = 0.58$, corresponding to a pre-critical configuration. At this stage, several large clusters occupied a substantial portion of the domain, and the system approaches the percolation threshold P^*. The spatial structure exhibited pronounced heterogeneity, and the emergence of near-spanning formations indicated imminent phase transition. At this stage, the correlation structure became less stable, reflecting the system's proximity to the critical percolation threshold.

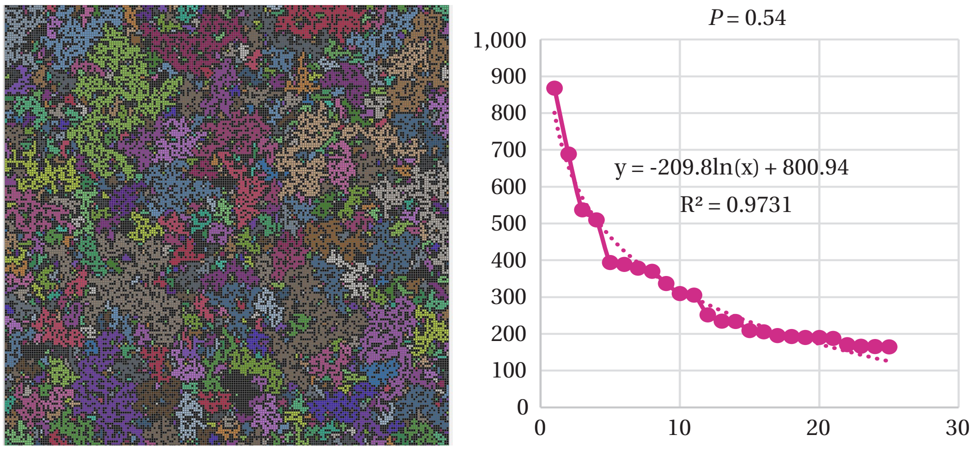


Figure 2. Model of cluster formation with parameter $P = 0.54$
Notes: R^2 – the coefficient of determination, which characterised the goodness of fit of the logarithmic approximation to the simulation data and indicated the share of variance in the dependent variable explained by the model
Source: State Statistics Service of Ukraine (2024)

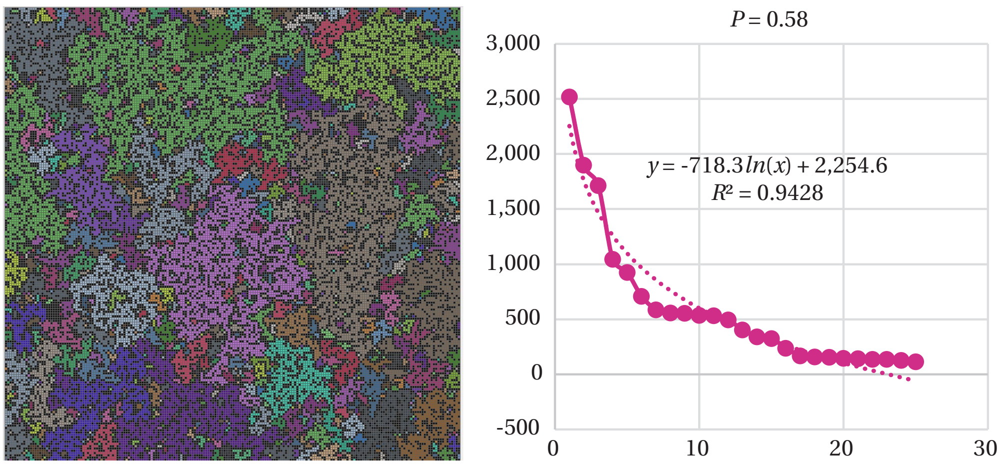
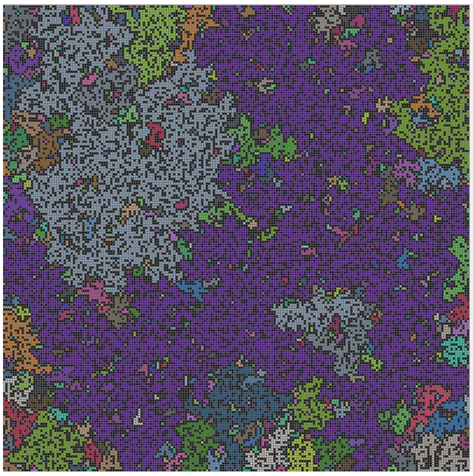


Figure 3. Model of cluster formation with parameter $P = 0.58$
Source: State Statistics Service of Ukraine (2024)

A further marginal increase of the control parameter to $P = 0.59$ results in a qualitative transformation of the system, marking the onset of a geometric phase transition at the percolation threshold. Figure 4 illustrated the formation of a system-spanning cluster, indicating that the percolation threshold has been effectively reached. In contrast to the pre-critical regime, connectivity now extended across the entire domain. Unlike the gradual structural evolution observed in previous regimes, this transition was abrupt and characterised by a fundamental reorganisation of spatial connectivity. At $P = 0.59$, the rating-frequency diagram deviates sharply from the previously stable semi-logarithmic behaviour. The coefficient of determination decreased dramatically from values in the range $R^2 = 0.94\text{-}0.97$ to approximately $R^2 = 0.55$, reflecting the breakdown of structural equilibrium. This abrupt declined serves as a quantitative signature of a geometric phase transition and can be interpreted as the emergence of monopolistic dominance within the modelled competitive system.



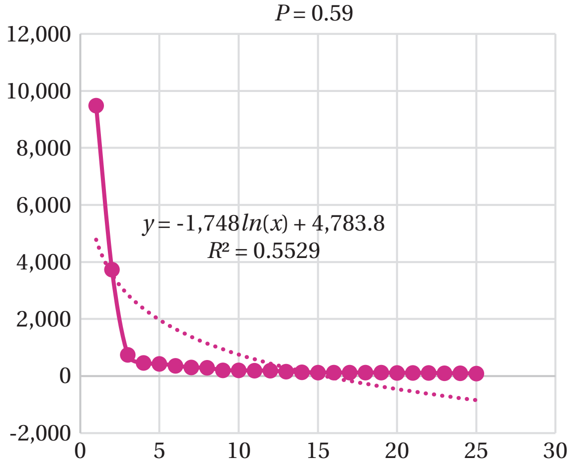


Figure 4. The model of cluster formation with the parameter $P = 0.59$
Source: State Statistics Service of Ukraine (2024)

The configuration shown in Figure 4 confirmed the formation of a system-spanning cluster, corresponding to a monopolised market structure, in which one dominant entity absorbed the majority of smaller participants. The rating-frequency diagram associated with this configuration (shown to the right of the spatial model) represents an ordered statistical distribution of cluster sizes for a system consisting of 40,000 elements. As the control parameter approaches the critical threshold P^*, the proportion of large clusters increased sharply, while smaller clusters were progressively absorbed, leading to rapid structural concentration. This reflected an accelerated process of structural stratification into "large" and "small" entities within the modelled competitive system. The dynamics of this transformation, observed as the parameter changes from $P = 0.50$ to $P = 0.59$, were quantitatively captured by the evolution of the correlation coefficient of the semi-logarithmic rating-frequency approximation. As illustrated in Figure 5, the correlation coefficient decreased from approximately 0.96 in the competitive regime to 0.55-0.60 near the phase transition point, providing a quantitative indicator of the breakdown of structural equilibrium.

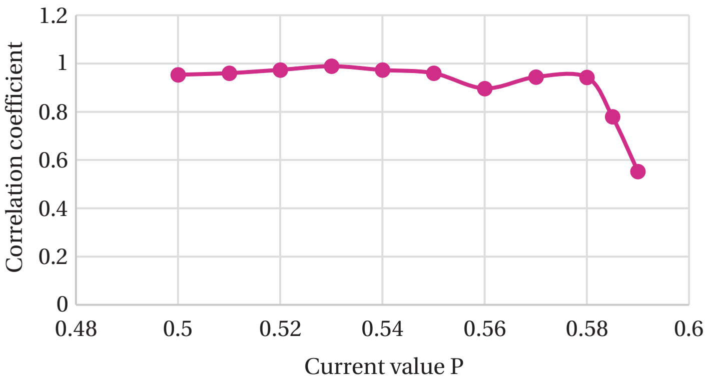


Figure 5. Dependence of the correlation coefficient of rating-frequency diagrams in semi-logarithmic coordinates, when approaching the percolation threshold P^*
Source: developed by the authors

Figure 6 presented the results of quantitative modelling of percolation-field coverage on a 200x200 (i.e., 40,000 participants) by the dominant clusters (row 1) and by the total of the three largest clusters (row 2), depending on the distance to the percolation threshold $|P - P^*|$. Each point of the graphs was obtained as the average value of ten independent simulation realisations performed in the "PERCOL statistician" environment. The obtained dependencies were accurately approximated by logarithmic models, as confirmed by high coefficients of determination. In particular, for the relative total share of the three leading clusters, the following relationship was obtained:

$$W = -0.3839 - 0.153\ ln|P - P^*|, \text{ with } R^2 = 0.9821. \qquad (16)$$

The concentration index CR_3 was additionally computed for each modelled configuration as the cumulative share of the three largest clusters in the total system size (40,000 elements). The results indicated that CR_3 remained at a moderate level within the interval $P \in [0.50\text{-}0.57]$, corresponding to a competitive regime. However, as the control parameter approaches the critical threshold P^*, CR_3 increased sharply, indicating accelerated structural concentration. At $P = 0.59$, the CR_3 value reached a level consistent with high market concentration, confirming the transition to a monopolised structural regime. The Linda index was applied as a complementary structural diagnostic measure to assess asymmetry among leading clusters. Its dynamics near the percolation threshold further support the interpretation of the identified phase transition as a shift toward monopolisation.

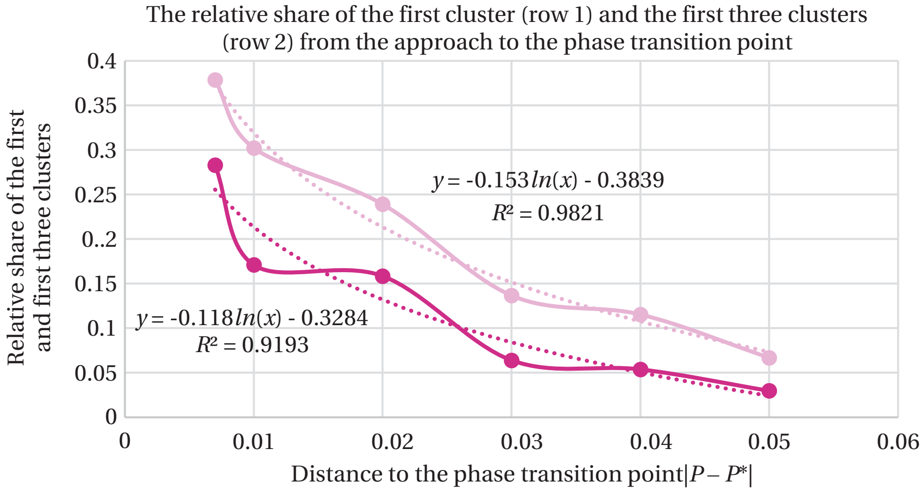


Figure 6. Results of quantitative modelling of the percolation field capture parameter 200x200 (40,000 participants), depending on the approach to the phase transition point
Source: developed by the authors

The dependencies shown in Figure 6 allowed the relationship between institutional antimonopoly constraints and the structural parameter $|P - P^*|$ to be conceptually assessed. The emergence of a system-spanning cluster may be interpreted not only as a structural transformation but also as an institutional threshold beyond, which regulatory mechanisms lose their effectiveness. As argued by D. Acemoglu & J.A. Robinson (2019), the balance between state capacity and societal constraints determined whether concentration processes remained controllable or evolve into extractive dominance. In this context, the identified percolation threshold may be interpreted as a structural boundary beyond, which institutional mechanisms became insufficient to restrain monopolisation dynamics.

Features of applying the percolation model of monopoly in the formation of agricultural holdings

The economy distinguished between different types of competition: perfect, imperfect, monopolistic (differentiated products), oligopoly (oligopsony), and monopoly. In practice, in real economic processes, the models function in conjunction, although one of them may be the basis. This was especially true of the level of manifestation – sectoral, territorial (local or regional), temporal, national. A monopoly in the market implied a dominant position of the producer, which was most often determined by the share (specific weight) of sales of the company's products in the total sales of homogeneous products of a particular industry. When studying the market structure (types of competition), quantitative methods were often used to assess the level of market concentration. The concentration of sellers reflected the relative size and number of enterprises, institutions, and organisations operating in a particular industry. The fewer business entities there were, the higher the level of concentration of sellers in the industry structure of the market. The greater the difference in size between businesses, the higher the level of concentration.

The legal criteria for enterprise size classification were defined in the Law of Ukraine No. 996-XIV (1999). According to this law, large enterprises were business entities with an average annual number of employees exceeding 250 and financial indicators (net revenue and/or balance sheet total) exceeding the thresholds established by national legislation and harmonised with EU accounting standards. Large enterprises tended to exert a dominant influence on market structure by contributing to increased concentration and centralisation of capital and production. On the one hand, this process was accompanied by economies of scale, while on the other hand, it may lead to intensified competition and the emergence of large corporate formations (cartels, syndicates, trusts, concerns, conglomerates) that occupied leading positions in specific industries or areas of economic activity. Key indicators of market monopolisation and enterprise size were: 1) share (specific weight) of sales of the enterprise's products in the total sales of homogeneous products of a certain industry; 2) share of employees in the enterprise in the total number of employees engaged in the production of these products; 3) share of the value of the enterprise's assets in the total value of assets of all business entities in the industry; 4) number of employees in the enterprise; 5) net income (revenue) from the sale of products (services); 6) cost of products (services) produced (Conyon *et al.*, 2023; Cerqueti *et al.*, 2025).

The relationship between monopolisation and the processes of concentration and centralisation was objective, i.e. functional. In O. Kilnitska's (2017) methodological approach, the assessment of an enterprise's monopoly power in the market was clarified. In particular, share of the company's products in the market of homogeneous goods (market niche in a particular industry or sphere of economic activity), which was determined as a percentage – *K*. Guided by the Law of Ukraine No. 2210-III (2001), a monopoly position was defined as a situation, in which an enterprise's shared in the market for a homogeneous product exceeds 35%. This criterion varied quantitatively across countries. For example, under Section 18 of the Act Against Restraints of Competition (1998), a single undertaking was generally presumed to be dominant if it held at least one third (33.3%) of the relevant market; dominance of two or three undertakings was presumed, when their combined market shared exceeds 50%, and of four or five undertakings, when it exceeded two thirds (66.7%). Based on the calculated indicator values, the level of agrarian market concentration was classified according to the criteria presented in Table 1.

Assessing the indicators of registered legal entities in the agricultural sector of Ukraine over the period 2017-2023, it can be concluded that overall market relations were becoming more competitive. Over this period, the number of registered agricultural enterprises has increased from 1,235,0 million in 2017 to 1,495,9 million in 2023. Thus, the number of business entities operating in the agricultural sector increased by an average of 37.2 thousand entities per year (Table 2).

Table 1. HHI thresholds applied for assessing concentration in the agricultural sector of Ukraine

Significance	Characteristics of market concentration	Implications for mergers and acquisitions
HHI < 1,000	Not concentrated	Mergers, acquisitions, and mergers are permitted
1,000 ≤ HHI ≤ 1,800	Moderately concentrated	If the HHI exceeds the 1,100 level, self-governing (management) bodies require verification of additional primary documents to permit business combinations
HHI > 1,800	Highly concentrated	Mergers, acquisitions, and mergers are prohibited

Source: developed by the authors

Table 2. Dynamics of registered legal entities in the agricultural sector of Ukraine by main indicators (2017-2023)

Indicator	2017	2018	2019	2020	2021	2022	2023	2023 to 2017	
								+/-	%
Total legal entities, thousand	1,235.0	1,298.4	1,350.6	1,395.4	1,437.0	1,464.9	1,495.9	260.9	121.1
of which: agriculture, forestry and fisheries	65,185	67,906	70,903	73,078	75,740	77,092	78,600	13,415	120.6
Share of agricultural, forestry and fisheries in the total number of legal entities, %	5.28	5.23	5.25	5.24	5.27	5.26	5.25	-0.03	99.4
Enterprises with agricultural land	40,735	40,333	38,523	36,277	39,301	29,631	29,991	-10,744	73.6
Share of enterprises with agricultural land in the total number of legal entities, agrarian land in the total number of agricultural, forestry and fishery enterprises, %	62.49	59.40	54.33	49.64	51.89	38.44	38.16	-24.33	61.1
Area of agricultural land, thousand ha	19,960.2	20,005.2	20,113.6	20,252.4	20,822.8	17,274.4	17,279.7	-2,680.5	86.6
Area of agricultural land on average per 1 agricultural enterprise, ha	490.0	496.0	522.1	558.3	529.8	583.0	576.2	86.2	117.6

Source: State Statistics Service of Ukraine (2024)

The data in Table 2 revealed several distinct trends in the agricultural sector during 2017-2023. First, the total number of enterprises engaged in agriculture, forestry, and fisheries increased from 65.2 thousand in 2017 to 78.6 thousand enterprises in 2023, reflecting a cumulative growth of 20.6% over the period under study. Their share in the total number of registered legal entities remained relatively stable at around 5.23-5.28%, indicating structural stability of the sector within the national economy. In contrast, the number of registered agricultural enterprises that owned or used agricultural land showed a downward trend during 2017-2023. In 2017, their number amounted to 40,735 thousand legal entities, whereas in 2023 it declined to 29,991 thousand enterprises, i.e., by 10,744 thousand entities over seven years, with the largest decrease recorded after February 2022. The share of enterprises with agricultural land in the total number of agricultural, forestry, and fisheries entities decreased from 62.49% in 2017 to 38.16% in 2023. These changes reflected not only human and business losses but also a contraction of production and land resources. Accordingly, the area of agricultural land owned by Ukrainian agricultural enterprises decreased from 19,960.2 thousand hectares in 2017 to 17,279.7 thousand hectares in 2023, i.e., by -2,680.5 thousand hectares. Monopolisation processes were closely linked to property relations. Therefore, when these processes were examined in agriculture, it became evident that, given the specific characteristics of this production sector, tendencies toward increasing concentration of agricultural land ownership have intensified. These trends indicated growing structural concentration in the Ukrainian agricultural sector. Against the background of a decrease in the number of agricultural enterprises engaged in land cultivation, the average agricultural land area per enterprise increased by 86.2 hectares over 2017-2023, from 490.0 hectares in 2017 to 576.2 hectares in 2023. During 2017-2023, according to the distribution of agricultural enterprises in Ukraine by the size of agricultural land, there was a reduction (through acquisition, merger, or liquidation) in the number of small and micro enterprises with land areas of up to 100 hectares, in favour of medium- and large-sized economic entities (Table 3).

Table 3. Dynamics of distribution of agricultural enterprises in Ukraine by the size of agricultural land, units

Size of agricultural land, ha	2017	2018	2019	2020	2021	2022	2023	2023 to 2017	
								+/-	%
Number of enterprises									
From 0.1 to 100.0	25,835	25,264	23,393	20,934	21,256	14,413	14,601	-11,234	56.5
From 100.1 to 1,000.0	10,023	10,277	10,389	10,605	12,599	10,670	10,857	834	108.3
More than 1,000.1	4,877	4,792	4,741	4,738	5,446	4,548	4,533	-344	92.9
Total	40,735	40,333	38,523	36,277	39,301	29,631	29,991	-10,744	73.6
Area of agricultural land, thousand hectares									
From 0.1 to 100.0	870.6	859.9	818.6	755.1	794.2	577.4	599.3	-271.3	68.8
From 100.1 to 1,000.0	3,688.5	3784	3,808.8	3,886	4,604.4	3,905.6	3,909.4	220.9	106.0
More than 1,000.1	15,401.1	15,361.3	15,486.2	15,611.3	15,424.2	12,791.4	12,771	-2,630.1	82.9
Total	19,960.2	20,005.2	20,113.6	20,252.4	20,822.8	17,274.4	17,279.7	-2,680.5	86.6

Source: State Statistics Service of Ukraine (2024)

The share of agricultural enterprises with land resources of up to 100 hectares decreased from 63.42% in 2017 to 48.68% in 2023. In contrast, the share of agricultural enterprises with an average land availability of 100.1 to 1,000 hectares increased from 24.61% in 2017 to 36.2% in 2023, and large enterprises (with an area of more than 1000.1 hectares) from 11.97% to 15.11%, respectively (Fig. 7).

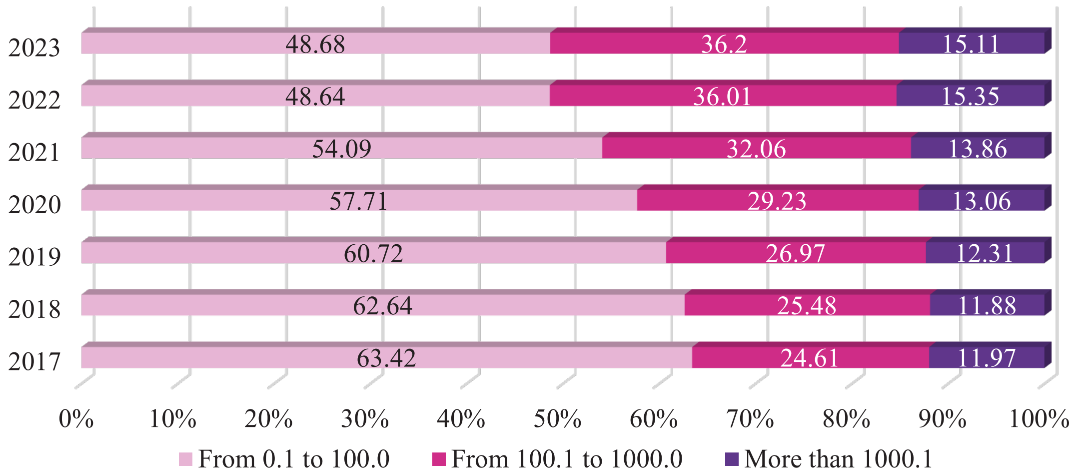


Figure 7. Structure of agricultural enterprises in Ukraine by size of agricultural land
Source: State Statistics Service of Ukraine (2024)

The redistribution of agricultural enterprises naturally affected the level of land use. While in 2017, 63.42% of enterprises had low land availability (up to 100 hectares per enterprise) and accounted for 4.36% of Ukraine's agricultural land, in 2023, 48.68% of these enterprises accounted for 3.47% of agricultural land. Large enterprises with the highest level of land availability (more than 1,000 hectares) increased their share in the structure of enterprises from 11.97% to 15.11% and, at the same time, controlled more than 73% of the country's agricultural land (Fig. 8).

The structural shifts illustrated in Figure 8 confirmed the tendency toward increasing concentration of land resources, which can be analytically interpreted within the framework of percolation-based modelling. The obtained results of quantitative modelling of clustering processes in the agricultural sector made it possible to interpret monopolisation not only as a legal or economic phenomenon, but also as a phase transition in a stochastic system, accompanied by the emergence of a connecting cluster, a dominant entity that covered a critical share of resources. Unlike traditional economic indices of concentration, such as the Herfindahl-Hirschman Index or concentration ratios, the percolation model allowed tracking the dynamics of monopoly structures during their formation, rather than merely recording existing market asymmetry. In particular, the Herfindahl-Hirschman Index and concentration ratios were ex post facto metrics, whereas the proposed model enabled identification of the critical zone, i.e., the moment, when the system loses competition as a mode of functioning.

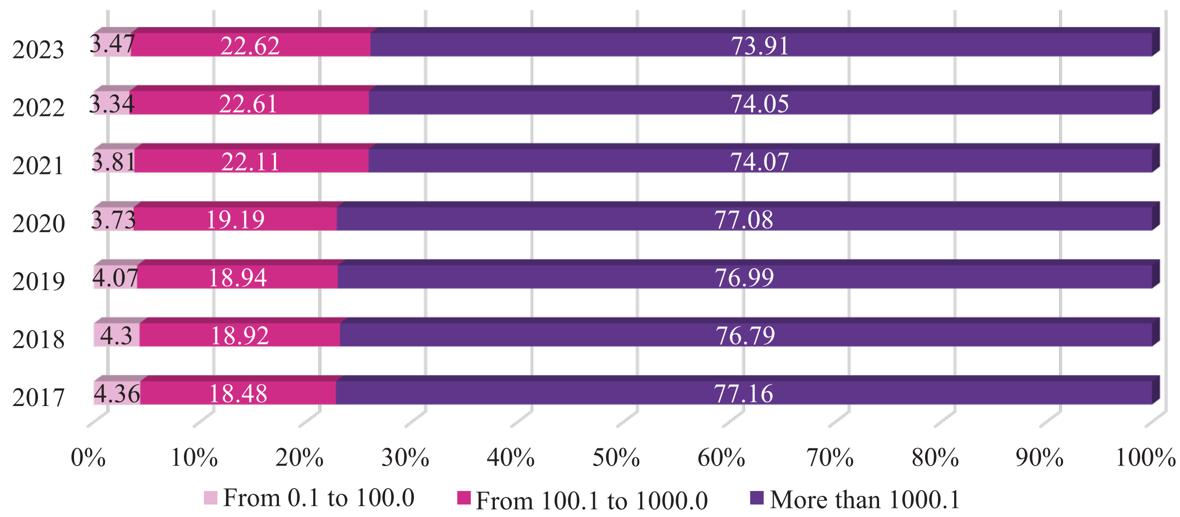


Figure 8. Structure of agricultural land owned by Ukrainian enterprises by size
Source: State Statistics Service of Ukraine (2024)

Contemporary economic research increasingly relied on interdisciplinary approaches that integrated methods of statistical physics, fractal analysis, and complex systems theory to study non-linear structural transformations. S. Donets *et al.* (2023) noted that fractal and percolation-based methods have proven effective for identifying clustering effects and critical thresholds in heterogeneous systems. E. Druzhinin *et al.* (2021) and D.L. Nguyen *et al.* (2023) emphasised that similar modelling approaches were actively applied in the analysis of distributed technical and network systems, including UAV swarms and decentralised control architectures, where cluster formation and phase-transition effects played a key role. These methodological advances provided a theoretical and computational foundation for applying percolation models to the analysis of market concentration and monopolisation processes in the agricultural sector. Recent advances in percolation theory and network-based modelling further demonstrated the applicability of phase-transition concepts to heterogeneous materials and distributed systems. T. Shevchuk *et al.* (2022) noted that percolation characteristics have been successfully employed to analyse structural connectivity and critical thresholds in complex media. These studies reinforced the relevance of percolation-based approaches for modelling the emergence of dominant structures in complex economic systems. I. Grabar & Y. Kubrak (2025) and I. Grabar & O. Kilnitska (2025) analysed percolation and fractal-based modelling tools for analysing clustering and phase-transition effects in complex systems. These methodological approaches provided a mathematical foundation for extending percolation-based models to the study of market concentration and monopolisation processes. Two-dimensional percolation model implemented in the software tools PERCOL and PERCOL-statistic enabled the analysis of conditions, under which connecting clusters-analogues of monopolistic formations-emerge. Furthermore, the study introduced rating-frequency diagrams as a quantitative diagnostic tool for identifying phase-transition signatures and determining critical thresholds of market concentration that signal an increased likelihood of monopolisation.

Conclusions

The agricultural market, despite its general structural resistance to monopolisation processes, demonstrated periodic manifestations of concentration that led to the absorption of small entities by large agricultural formations. Empirical analysis of the Ukrainian agricultural sector over the period 2017-2023 showed that the number of agricultural enterprises owning or using land decreased from 40,735 thousand to 29,991 thousand, while the average agricultural land area per enterprise increased from 490.0 to 576.2 hectares, indicating a significant intensification of land concentration. To quantitatively analyse and reproduce the kinetics of such processes, this study applied tools of percolation theory. The percolation model demonstrated its suitability as an approach to modelling the formation of monopoly structures in the market. The results indicated that the transition to a monopolised market structure occurs near $P = 0.59$, with a sharp decrease in structural stability indicators observed for the period 2017-2023. Numerical simulations revealed a critical percolation threshold at $P^* = 0.5945$, near which the correlation coefficient of rating-frequency diagrams sharply decreased from 0.94-0.97 to 0.55, indicating a geometric phase transition that corresponded to the emergence of monopoly dominance. It has been established that the capture of market segments by one or more large entities was physically analogous to phase transitions in statistical physics. The developed software tools PERCOL and PERCOL-statistic enabled visualisation and statistical diagnostics of clustering processes, providing a quantitative framework for early detection of monopolisation risks and supporting evidence-based antitrust regulation in the agricultural sector. Future research may focus on extending the percolation-based framework by incorporating dynamic institutional and policy factors, as well as applying the model to other sectors with heterogeneous spatial resource distribution.

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Conflict of Interest
None.

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Перколаційні моделі конкуренції та монополізації на аграрному ринку

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► **Анотація.** Дослідження є актуальним через зростаючі ризики монополізації аграрного ринку в Україні, що потребує кількісного аналізу процесів концентрації за допомогою сучасних інструментів моделювання. Метою дослідження було побудувати модель формування монополії на аграрному ринку, застосовуючи перколяційний підхід для прогнозування фазових переходів у конкурентному середовищі. Розроблено двовимірну перколаційну модель аграрного ринку для моделювання захоплення ринкових сегментів великими утвореннями та оцінки динаміки концентрації. Числові експерименти (область 200×200) показали, що з наближенням контрольного параметра до критичного значення $P^* = 0{,}5945$, коефіцієнт кореляції діаграм рейтингів і частот різко впав з 0,94-0,97 при $P = 0{,}50$-$0{,}58$ до 0,55 при $P = 0{,}59$, що вказує на фазовий перехід, що інтерпретується як формування монопольних кластерів. Використовуючи дані аграрного ринку України за 2017-2023 роки, модель виявила критичний поріг перколяції при $P^* = 0{,}59$, що супроводжувалося зниженням коефіцієнтів кореляції з 0,96 до 0,55. Логарифмічний зв'язок $W = -0{,}3839 - 0{,}153 \ln|P - P^*|$, $R^2 = 0{,}9821$ описує зростання домінуючих кластерів. Кількість аграрних підприємств знизилася з 40,7 до 30 тисяч (-26 %), а середня площа на одне підприємство збільшилася з 490 до 576 га, що підтверджує інтенсифікацію процесів концентрації та ілюструє, як геометрична поведінка кластерів відображає реальні структурні зрушення в секторі, тим самим зміцнюючи прикладне значення розробленого підходу до моделювання і надаючи кількісну основу для виявлення ранніх ознак монополізації ринку, оцінки системних вразливостей та інтерпретації динаміки концентрації через призму феноменів фазових переходів. Практична цінність дослідження полягає в можливості раннього виявлення монополізації ринку та критичних точок переходу, що сприяє більш точному прогнозуванню структурних змін і розробці ефективних антимонопольних та регуляторних заходів

► **Ключові слова:** кластеризація; фазовий перехід; концентрація ринку; фрактальна вимірність; асиметрія ринку; оцінка ризику монополії

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Agro-Industrial Complex and economic security of Ukraine: Strategic European integration vector

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▶ **Abstract.** The Agro-Industrial Complex of Ukraine was a critical determinant of National Economic Security, a relationship profoundly tested, particulary during the full-scale russian invasion initiated in 2022. The purpose of the study was to quantify the impact of the Agro-Industrial Complex and other key economic sectors on Ukraine's National Economic Security over the 2013-2022 period and drawn strategic lessons from the evolution of the European Union's Common Agricultural Policy. The results from Partial Least Squares Path Modeling showed the model explained 86.6% of the variance in economic security. The Agro-Industrial Complex emerged as the most significant positive driver, with a standardised path coefficient of 0.394. The industrial and financial sectors also contributed positively but to a lesser extent. The energy sector exerted a strong negative influence, acting as a primary channel for economic shocks, while investment demonstrated a negligible impact, indicating systemic barriers to capital deployment. Descriptive data revealed that despite a drop in average grain production from 75.5 million tonnes (2019-2021) to approximately 54 million tonnes in 2022, the Agro-Industrial Complex's shared of total exports surged from an average of 40.23% to 53.0% in 2022 and 60.8% in 2023, highlighting its role as a macroeconomic stabiliser. State intervention to modernise the energy grid and dismantle barriers to capital was the most supported path to converting the Agro-Industrial Complex's remarkable resilience into a lasting foundation for a secure and prosperous post-war economy. The

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findings provided an empirical foundation for Ukrainian policymakers to prioritise systemic reforms in the energy and investment sectors alongside agricultural development to build resilient National Economic Security

▸ **Keywords:** agricultural policy; economic resilience; Common Agricultural Policy; decoupling; sustainability

▸ Introduction

The relevance of this study was driven by the strategic necessity of developing a new model for Ukraine's economic security, grounded in strengthening the resilience of key sectors, particularly the Agro-Industrial Complex (AIC), amid persistent geopolitical challenges and the process of European integration. T. Glauben *et al.* (2022) noted that Ukraine occupied a dual role of immense strategic importance: it was simultaneously a cornerstone of the national economy and a critical node in the architecture of global food security, the disruption of which has had worldwide repercussions. I. Domanetskyi *et al.* (2025) highlighted that the AIC was crucial for National Economic Security. T.B. Hassen & H. El Bilali (2022) were linking stable growth, food self-sufficiency, and employment with AIC. M. Dorosh-Kizym *et al.* (2024) had articulated the stability and resilience of the AIC were inextricably linked to the broader concept of National Economic Security, encompassing not only food self-sufficiency but also macroeconomic stability, employment, and foreign currency generation. K. Mazur & O. Alieksieieva (2024) underscored Ukraine's pre-2022 status as a top-tier global exporter of grains and sunflower oil, highlighting the sheer scale of its contribution to the world's food supply as well as a potential thoroughly documented in analyses of the sector's development. L. Beyko *et al.* (2024) focused on the benefits of alignment, such as smoother trade facilitation. The authors complemented optimistic outlook by providing a historical analysis of the EU's Common Agricultural Policy (CAP), offering a cautionary perspective on the challenges of policy alignment and the need for Ukraine to avoid the pitfalls of subsidy dependency and policy inertia that characterised earlier CAP iterations.

Researcher M. Martynyuk (2024) advocated for strategic state regulation and investment in innovation to foster sustainable development and competitiveness. A. Peshko (2022) focused on the importance of state intervention (through direct and indirect regulation) to ensure the sustainable and competitive development of Ukraine's AIC. findings, which revealed a strong negative impact from the energy sector and a weak impact from investment, demonstrated precisely, where state-led reform was most critically needed to unlock the AIC's full potential. The long-term transformation of the Ukrainian AIC towards higher value-added production and sustainability was identified as a crucial strategic goal, a direction supported by the research of I. Kryvetskyi (2022). This strategic imperative in the challenging context of economic instability was emphasised by O. Radchenko *et al.* (2020). The path forward required not only modernisation and sustainable practices but also a strategy robust enough to navigate ongoing economic uncertainty, as highlighted by the work of O. Kinzerska *et al.* (2021). Considering 2022-2025 geopolitical dynamics, Ukraine harbors the strategic ambition to evolve beyond its traditional role as a large-scale commodity producer. This implied a qualitative transformation encompassing not only increased production volume but also significant advancements in value-added processing, enhanced market influence, the adoption of sustainable and innovative practices, and deeper integration into European and global value chains.

Such kind of transformation requires a nuanced approach to address complex Ukrainian challenges, while strategically integrating Ukraine into the wider European agricultural framework. L. Golovko *et al.* (2024) noted that it was essential to understand the evolution, mechanisms, and foundational principles of the European Union's CAP, especially considering Ukraine's candidacy for EU membership. A comprehensive grasp of the CAP required examining both its historical development and its modern strategic direction. The policy's evolution was a critical starting point, as it revealed a long-term trajectory of reactive reforms – from managing food security to tackling the structural surpluses and trade disputes that arose from production-linked subsidies. Historical path, as outlined by L. Golovko *et al.* (2024), provided vital context for the contemporary mechanisms and foundational principles of the CAP, which were increasingly intertwined with ambitious environmental objectives. The latest CAP reforms were deeply connected to the European Green Deal, presenting both opportunities and significant challenges in aligning agricultural practices with sustainability goals and climate action, a key focus of analysis by researchers such as I. Cuadros-Casanova *et al.* (2023). For Ukraine green-focused principles was paramount for successful policy alignment and integration. A comparative analysis of agricultural support mechanism (focusing on the disparities in subsidy rates and structures between the EU and Ukraine) could provide critical insights that can guide Ukraine's policy development and strategic alignment within the European context. The aim of research was to determine a strategic trajectory for transforming Ukraine's AIC and positioning it as a leading agricultural force in Europe, using data from 2013-2022.

▸ Materials and Methods

The core methodological approach involved a synthesis of existing information, comparative analysis, and conceptual model development. It was analysed quantitative time-series data for the 2013-2022 model, including indicators on production, sown area, and investment, were sourced from the official databases of the State Statistics Service of Ukraine (n.d.). To analyse the impact of the russian full-scale invasion on the Ukrainian AIC, the study utilised the data of Food and Agriculture Organization of the United Nations (2022) to assess threats to livelihoods and production, alongside quantitative data from the European Parliament (2024) report. The crucial historical context for European integration was based on the analysis of the Common Agricultural Policy's development provided by the S. Zorya & O. Nivyevskyi (2005), which informed the study's overview of the policy's phases, academic researches and specialised industry analyses. The analytical process covered the historical analysis of policy developments, focusing primarily on the evolution of the EU's Common Agricultural Policy (Stehel *et al.*, 2019). The assessment of the contemporary situation of Ukraine's AIC, covering both pre-war performance and the impacts of the russian full-scale invasion, drew upon analytical reports from institutions Insecurity Insight (2022), Vox Ukraine (Ahapova, 2025). Qualitative analysis was underpinned by quantitative data from the statistical databases of the National Bank of Ukraine (n.d.), the World Bank Group (n.d.), and the United States Department of Agriculture (n.d.). The core contribution of this study was synthesising the findings from these historical and contemporary sources to propose an evidence-based pathway and future-oriented strategic planning and modeling. To empirically investigate the complex interrelationships of factors underlying Ukraine's National Economic Security, especially in the context of the ongoing war and recovery, the PLS-PM method was chosen. The analysis aimed to evaluate both the measurement model (reliability and validity of constructs) and the structural model (hypothesised relationships between constructs). The reliability and validity of the measurement model were rigorously assessed according to established guidelines (Hair *et al.*, 2019). Internal consistency reliability was determined through Cronbach's Alpha and Composite Reliability (ρa, ρc). Convergent validity was evaluated using the Average Variance Extracted (AVE), ensuring that the indicators of each construct were sufficiently correlated. Furthermore, Cohen's f2 was employed to assess the effect size of each predictor, thereby quantifying its contribution to the explanation of the dependent construct.

▸ Results and Discussion

Ukraine's vast agricultural capacity had traditionally allowed the country to meet internal demand for essential food products, such as grains, sunflower oil, sugar, poultry, and eggs, achieving high levels of self-sufficiency. Additionally, the efficiency of the AIC directly impacted food affordability, which was a crucial aspect of household economic security. However, the full-scale russian invasion in 2022 had introduced significant challenges. Direct hostilities, the occupation of territories, destruction of storage facilities and processing plants, disruption of logistics, and land contamination (for instance, by mines) have severely hindered production and internal distribution networks. This had led to a difficult economic situation, where a Ukraine known as a global food exporter faces acute food insecurity challenges because of logistical breakdowns. Maintaining functional internal supply chains and ensuring access for vulnerable populations, even amid reduced overall production, had become critical for managing National Economic Security during wartime.

The agricultural sector faced significant vulnerabilities that impacted its contribution to economic security. Producers were highly dependent on global commodity markets, which exposed them to price fluctuations that were beyond their control. Logistical bottlenecks, particularly the reliance on Black Sea ports for bulk exports, have proven to be a critical weakness – this had been dramatically highlighted by wartime blockades and the complexities surrounding alternative export routes, such as the "Solidarity Lanes". Dependence on imported inputs, including fuel, fertilizers, pesticides, and advanced machinery, increased exposure to supply chain disruptions and price shocks. Climate change posed an additional threat, resulting in more frequent droughts, heatwaves, and extreme weather events that affected crop yields and necessitate significant adaptation efforts. The war had amplified these pre-existing weaknesses. It demonstrated that the economic security derived from the AIC was not solely rely on production potential – it was also dependent on functional infrastructure, secure market access, geopolitical stability, war risks. Table 1 underscored the substantial economic weight of the AIC and provided quantitative context for understanding, how the warhas directly impacted key metrics relevant to economic security.

Table 1. Key indicators of Ukraine's AIC contribution to the economy (pre- and post-full-scale invasion comparison in 2022)

Indicator	Avg 2019-2021 (calculated)	Verified data 2022	Verified data 2023	Significance for economic security
AIC share of GDP (%)	9.73	8.2	7.4 >10	Demonstrated sector's core economic contribution and impact of disruption
AIC share of total exports (%)	40.23	53.0	60.8/59	Showed critical role in generating foreign currency, vulnerability to export route disruptions
Agri-food trade balance (USD billion)	+17.38	+17.36	+15.07	Indicated ability to earn foreign exchange, impacted by lower export volumes/higher costs
Grain production (million tonnes)	75.5	~54	59.7 (grains only)	Reflected impact on core output, affecting both Ukrainian supply and export potential
Grain exports (million tonnes, marketing year (MY))	50.0	49.2 (MY 2022/23)	50.8 (MY 2023/24)	Quantified the direct impact of war and logistical constraints on key revenue stream

Source: World Bank (2008), International Trade Administration (2023), European Parliament (2024), V. Ahapova (2025), United States Department of Agriculture (n.d.), National Bank of Ukraine (n.d.)

The performance of the AIC haв direct and substantial implications for Ukraine's overall economic and social stability. The availability of food, supported by production, were fundamental determinanted of social welfare and stability. Conversely, significant shocks to the AIC – whether from market volatility, climate events – can rapidly transmit negative economic impacts, affecting foreign exchange reserves, inflation, and employment, and potentially leading to social unrest. Strengthening the resilience and productivity of the AIC was not just a sectoral goal but a strategic imperative for enhancing Ukraine's overall National Economic Security. Understanding the trajectory of the European Union's CAP provided important insights for the national economy as it shaped its agricultural future and seeks deeper European integration. The CAP was established in 1962 in response to post-World War II food shortages and significant rural-to-urban migration. While it was effective in its early years, the initial emphasis on production fostered strong vested interests among farmers reliant on the subsidy system (Zorya & Nivyevskyi, 2005). This dependency created political challenges, when attempting to shift away from production-linked support, even as the negative consequences (like budgetary crises, inefficient resource allocation leading to surpluses, and international trade friction) became more evident (Ilchuk *et al.*, 2025). Substantial reform only took place, when mounting pressures from unsustainable budgets and binding international commitments necessitated change. In such a way, this experience highlighted the importance of Ukraine designing policies that anticipated long-term consequences and incorporated mechanisms for adaptation, thus avoiding the creation of dependencies that could hinder future adjustments.

In response to increasing internal criticism regarding costs and inefficiencies, as well as international obligations under the WTO (World Trade Organization) agreement, the European Commission implemented a reform of the CAP in 2003 system (Communication from the Commission…, 2003). The cornerstone of this reform was the principle of "decoupling", which aimed to sever the direct link between subsidy payments and the amount of goods produced. The rationale behind decoupling was multifaceted: 1) it aimed to reduce the incentive for overproduction, thereby helping to eliminate structural surpluses; 2) it made EU agricultural support more compatible with WTO rules by prioritising less trade-distorting "Green box" measures; 3) it allowed for better control over the rapidly increasing CAP budget. This evolution illustrated a clear process of policy learning, though often reactive. Furthermore, each major phase of the CAP addressed the unintended negative consequences of the previous phase: production subsidies led to surpluses, intervention buying exacerbated them, export subsidies caused trade disputes, and while decoupling resolved the surplus issue, it raised new questions about supporting potentially idle land management. Table 2 provided a condensed overview of the CAP's dynamic history, illustrating the shift in priorities and instruments over time.

Table 2. Evolution of EU CAP support mechanisms and objectives

Period	Primary goals	Key mechanisms	Key outcomes/Issues
1962-1990s	Food security, farmer income parity	Market price support, production-linked subsidies (per tonne)	Rapid production increase, self-sufficiency achieved, structural surpluses emerge
~1990s-2003	Surplus management, budget control (emerging)	Intervention buying, export subsidies, early supply controls	Massive surpluses ("mountains/lakes"), extreme budget strain (75% peak), WTO pressure
2003-~2013	Budget control, WTO compliance, decoupling	Decoupled Basic Payment Scheme (BPS) linked to land area	Significant reduction in surpluses, improved budget control, shift away from production focus
~2013-2025	Sustainability, climate action, environmental protection	BPS + mandatory "greening" payments, Agri-Environment Schemes (AECMs), enhanced conditionality	Increased focus on environmental outcomes, integration with "Green Deal", farmer friction over regulations

Source: based on S. Zorya & O. Nivyevskyi (2005)

So, it was indicated that agricultural policy required continuous monitoring and adaptability to unforeseen outcomes, a vital consideration for Ukraine as it developed its long-term strategy. A critical analysis of the lessons derived from the EU's extensive experience, Ukraine can avoid policy failures and develop more sustainable and resilient agricultural strategies tailored to its unique national context and strategic objectives. To empirically investigate the complex interplay of factors underpinning Ukraine's National Economic Security, particularly in the context of ongoing war started in 2014 and recovery, PLS-PM offerred a suitable framework. This revised model conceptualised National Economic Security as the central endogenous (outcome) construct. It posited that this overall security was built upon and influenced by several critical exogenous (driver) constructs, representing key pillars of the national system. The performance and resilience of the AIC was modeled as one of these crucial contributing pillars. The model structure hypothesised that positive performance and resilience in each of these driver constructs (AIC Performance, Energy Security, Finance) contributed positively and significantly to the overall level of National Economic Security (Fig. 1).

This framework underscored that despite the essential role of the AIC, National Economic Security was a multidimensional outcome dependent on the synergistic functioning of various parts of the national system. Weakness in any single part, such as severely damaged infrastructure or macroeconomic instability, can undermine overall economic security, even with a potentially strong agricultural sector. The AVE for each construct was presented in Table 3.

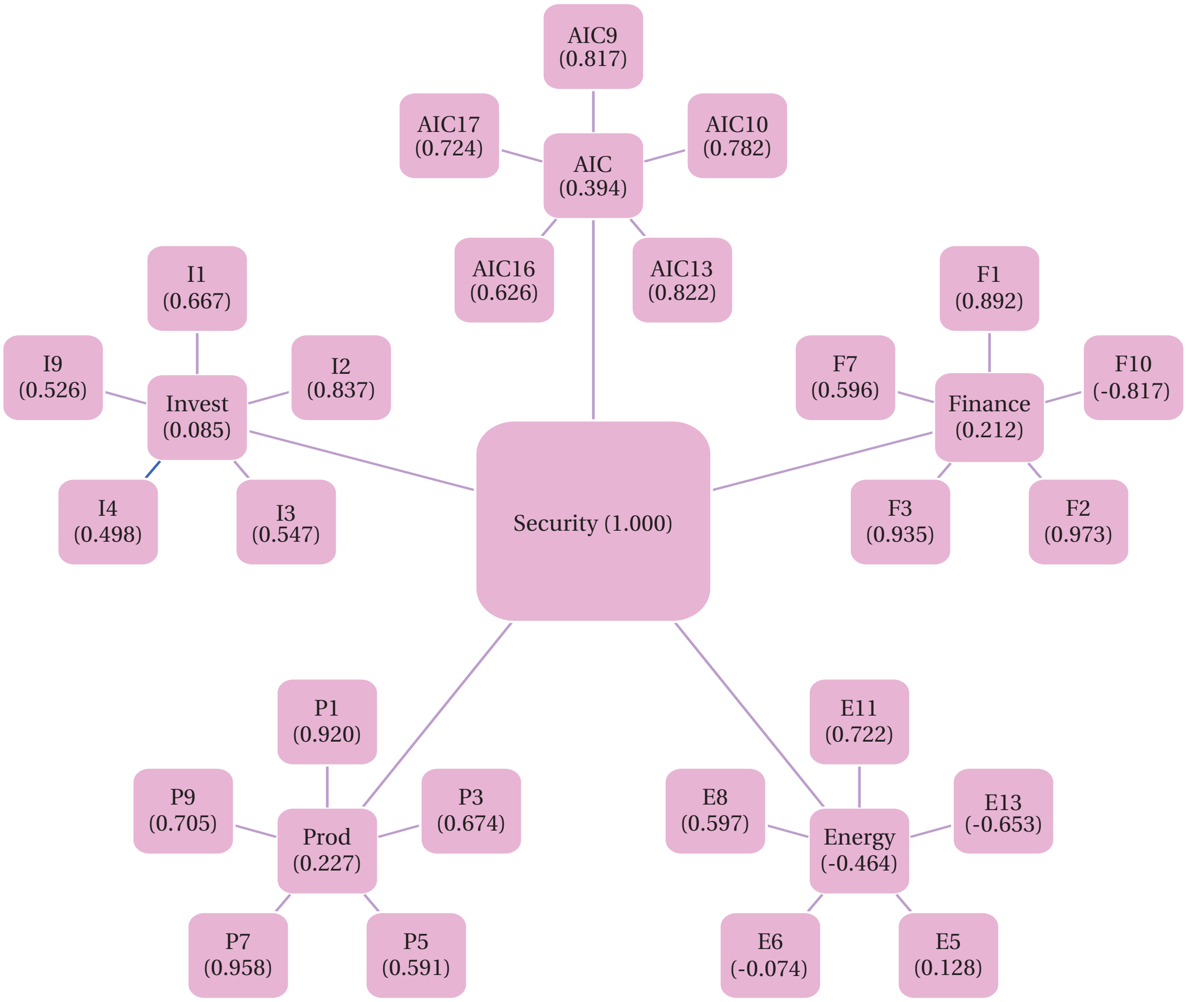

Figure 1. PLS-PM model of National Economic Security

Notes: F – Finance, I – Invest, P – Production, E – Energy. This model covered the period from 2013 to 2022

Source: Insecurity Insight (2022)

Table 3. Measurement model evaluation

Construct	Indicator (full name)	Outer loading	Indicator reliability
AIC			
Cronbach's Alpha (for construct) – 0.811 Composite Reliability (ρa) – 0.824 Composite Reliability (ρc) – 0.870 AVE – 0.574	AIC9: Sown area of agricultural crops	0.817	0.667
	AIC10: Gross harvest of grain crops	0.782	0.612
	AIC13: Investments in agriculture	0.822	0.676
	AIC16: Share of employed in agriculture	0.626	0.392
	AIC17: Share of state funding for agriculture in the consolidated budget	0.724	0.524
Energy			
Cronbach's Alpha (for construct) – 0.888 Composite Reliability (ρa) – 0.290 Composite Reliability (ρc) – 0.123 AVE – 0.265	E5: Natural gas prices	0.128	0.016
	E6: Electricity prices	-0.074	0.005
	E8: Cost of gasoline (A-95)	0.597	0.356
	E11: Cost of automotive gas (LPG)	0.722	0.521

Table 3, Continued

Construct	Indicator (full name)	Outer loading	Indicator reliability
	E13: Renewable energy consumption (% of total final energy consumption)	-0.653	0.426
Finance			
Cronbach's Alpha (for construct) – 0.359 Composite Reliability (ρa) – 1.065 Composite Reliability (ρc) – 0.830 AVE – 0.728	F1: Revenues of the state budget of Ukraine	0.892	0.796
	F2: Expenditures of the state budget of Ukraine	0.973	0.947
	F3: State budget deficit, % of GDP	0.935	0.874
	F7: Gold and foreign exchange reserves of Ukraine	0.596	0.355
	F10: Loan-to-Deposit Ratio (LDR), %	-0.817	0.667
Production			
Cronbach's Alpha (for construct) – 0.833 Composite Reliability (ρa) – 0.896 Composite Reliability (ρc) – 0.884 AVE – 0.613	P1: Industrial production index	0.920	0.846
	P3: Share of manufacturing in GDP	0.674	0.454
	P5: Manufactures imports (% of merchandise imports)	0.591	0.349
	P7: Construction output indices, %	0.958	0.918
	P9: Index of industrial output sales, %	0.705	0.497
Invest			
Cronbach's Alpha (for construct) – 0.671 Composite Reliability (ρa) – 0.646 Composite Reliability (ρc) – 0.757 AVE – 0.394	I1: Foreign direct investment	0.667	0.445
	I2: Capital investment to GDP, %	0.837	0.701
	I3: Share of R&D expenditure in GDP, %	0.547	0.299
	I4: Share of enterprises that introduced innovations	0.498	0.248
	I9: Charges for the use of intellectual property, receipts	0.526	0.277

Source: State Statistics Service of Ukraine (n.d.)

Standardised path coefficients (β), indicating the strength and direction of the relationship between each exogenous construct (AIC, Energy, Finance, Invest, Production) and the endogenous construct (Economic Security – SEC1) in Table 4 showed that AIC had the strongest positive direct impact on economic security (β = 0.394); Production (β = 0.227) and Finance (β = 0.212) also demonstrated positive direct impacts, although smaller in strength than AIC. The R2 value for the Economic Security construct (SEC1) was 0.866. This meant that 86.6% of the variance in the economic security index was explained by the combined impact of the five exogenous constructs. The adjusted R2 (SEC1 Radj2) was 0.699. The decrease from R2 to Radj2 indicated that the model might be somewhat complex for the given sample size, or some predictors had low explanatory power. Nevertheless, even the adjusted R2 suggested high explanatory power of the model. Cohen's f2 values for each exogenous construct, assessing its substantive impact on economic security, were provided in Table 4. Interpretation of effect sizes (e.g., 0.02 – small, 0.15 – medium, 0.35 – large effect) showed that AIC had a medium effect, while Energy, Finance, and Production had a weak effect, and Invest had a negligible or absent effect.

Table 4. Structural model evaluation – impact on economic security

Path	Standardised path coefficient (β)	F-square (f2)	Interpretation of effect size
AIC → SEC1	0.394	0.140	Medium effect
Energy → SEC1	-0.464	0.100	Weak effect
Finance → SEC1	0.212	0.070	Weak effect
Invest → SEC1	0.085	0.008	Absent/negligible effect
Production → SEC1	0.227	0.046	Weak effect

Source: developed by the authors

Data noted in Table 4 aligned with the consensus of scholars M. Dorosh-Kizym *et al.* (2024), who had long identified the AIC as a pillar of national security, and researchers K. Mazur & O. Alieksieieva (2024), who analysed its contributions to food self-sufficiency and employment. It also found strong support in reports from international bodies. World Bank (2008) identified the sector as key to economic growth and reconstruction, while the Food and Agriculture Organization of the United Nations (2022) highlighted its critical role in national and global food security, noting that 30% of Ukraine's population depended on it for their livelihoods. The model's other results – the strong negative impact of the energy sector and the insignificant role of investment – served as proxies for deep systemic challenges. The negative path coefficient for "Energy" (β = -0.464) was not imply that energy production was harmful; it reflected that the energy sector was the primary channel for transmitting economic damage from the war. Since 2014, Ukraine lost critical energy assets in Crimea and Donbas, leading to a sharp decline in internal production and a costly increase in imports, which directly harmed the trade balance and economic stability (Trostianska, 2024). The energy sector acted as a powerful and persistent brake on the economy. The negligible impact of "Investment" (β = 0.085) suggested its potential was systematically neutralised by a hostile investment climate. Foreign investors and international bodies consistently cited corruption, particularly in the judiciary, as a key deterrent (International Trade Administration, 2023). This aligned with academic research by Q. Le & M. Rishi (2006) showing a significant link between corruption and capital flight. The weak investment effect was a quantitative scar left by years of institutional weakness, preventing the capital needed for the AIC's modernisation-for instance, developing higher value-added processing – from being effectively deployed. The results indicated of a powerful engine (AIC) starved of fuel (energy security) and unable to upgrade its components (investment).

The authors L. Sarkisian & A. Savchuk (2025) analysed the strategic imperatives for Ukraine's agricultural sector, emphasising that its export potential was a cornerstone of economic security but required significant institutional modernisation to realise fully. Their findings supported this research model's results by highlighting the sector's macroeconomic importance, while implicitly pointing to the systemic barriers, like weak investment, that constrained it. In a similar vein, M. Nehrey & R. Finger (2024) focused on the direct impact of the russian invasion on agricultural production and food security, providing a detailed account of the physical destruction of infrastructure and logistical disruptions. This perspective directly aligned with model's finding of a strong negative impact from the energy sector, as energy infrastructure was a critical component of the logistics and production chains. Furthermore, the work of V. Rudevska *et al.* (2024) explored the low level of investment attractiveness in the agricultural sector even before the full-scale war, linking it to imperfect legislation and significant business risks. Their research provided a strong explanatory basis for model's discovery in this study of the negligible impact of investment, linking it to pre-existing systemic problems. So, modern dynamics of the agricultural sector were shaped by a complex configuration of factors, where the destruction of energy logistics was an immediate threat, and the imperfection of the investment climate was a chronic obstacle. This confirmed the thesis that a simple increase in capital investments without addressing structural and infrastructural issues will not have the expected positive effect on the industry's economic security.

Conclusions

Result of the study was the confirmation of the dominant role of the Agro-Industrial Complex as the most important positive driver of Ukraine's economic security within the studied 2013-2022 period. Its path coefficient (β = 0.394) and effect size (f2 = 0.140 – medium) were the highest among positively impacting factors. It was followed by the industrial (Production) and financial (Finance) sectors, which also positively, though to a lesser extent, affected economic security. These results were consistent with the general conclusion that the Agro-Industrial Complex had the greatest impact on economic security, along with industry and finance. The PLS-PM model's results demonstrated the complex nature of relationships between economic security factors. These findings confirmed that structural vulnerabilities related to energy and investment were key obstacles to achieving sustainable economic security in Ukraine. The AIC emerged as the strongest positive contributor to economic security (β = 0.394). While the Production (β = 0.227) and Finance (β = 0.212) sectors also exerted positive influences, their effects were comparatively weaker. This quantitative result validated descriptive data showing the Agro-Industrial Complex's substantial and growing share of GDP and exports. However, the study emphasised that National Economic Security was a broader, multidimensional construct. It depended not only on a functional agricultural sector but also critically on macroeconomic stability, resilient infrastructure across transport and energy sectors, the performance of other industries, energy security. The study was limited by timeframe, which predated the russian full-scale invasion's most devastating impacts, and its use of aggregated data, which masked disparities between farm types and regions. Future research should re-evaluate these relationships using post-2022 data and employ disaggregated analysis to compare the socio-economic impacts of agro-holdings versus smaller farms. This will be critical for designing a sustainable agricultural future for Ukraine.

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Conflict of Interest

None.

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Агропромисловий комплекс та економічна безпека України: стратегічний вектор європейської інтеграції

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▸ **Анотація.** Агропромисловий комплекс України є ключовим чинником забезпечення національної економічної безпеки, що особливо інтенсивно підтвердилося в умовах повномасштабної російської агресії, розпочатої у 2022 році. Метою дослідження було кількісно оцінити вплив агропромислового комплексу та інших провідних секторів економіки на національну економічну безпеку України у 2013-2022 роках, а також виокремити стратегічні уроки з еволюції Спільної аграрної політики Європейського Союзу. Результати моделювання методом часткових найменших квадратів продемонстрували, що побудована модель пояснює 86,6 % варіації економічної безпеки. Агропромисловий комплекс виявився найпотужнішим позитивним драйвером зі стандартизованим коефіцієнтом шляху 0,394. Промисловий та фінансовий сектори також забезпечили позитивний внесок, хоча й менш значний. Проте, енергетичний сектор здійснював сильний негативний вплив, виступаючи основним каналом поширення економічних шоків, тоді як інвестиції продемонстрували незначний ефект, що вказав на системні бар'єри для розміщення капіталу. Описові дані засвідчили, що попри зниження середнього виробництва зернових з 75,5 млн тонн (2019-2021 роки) до приблизно 54 млн тонн у 2022 році, частка агропромислового комплексу в загальному експорті зросла з середніх 40,23 % до 53,0 % у 2022 році та 60,8 % у 2023 році, підкреслюючи його роль макроекономічного стабілізатора. Найбільш обґрунтованим напрямом державного втручання визначено модернізацію енергетичної інфраструктури та усунення бар'єрів для капіталовкладень як умову перетворення виняткової стійкості агропромислового комплексу на основу безпечного та процвітаючого повоєнного економічного розвитку. Отримані результати сформували емпіричну основу для українських політиків щодо пріоритизації системних реформ у енергетичному та інвестиційному секторах у поєднанні з подальшим розвитком сільського господарства для забезпечення стійкої національної економічної безпеки

▸ **Ключові слова:** аграрна політика; економічна стійкість; Спільна аграрна політика; декаплінг; сталість

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Improving the methodology for calculating the average statistical market priceof agricultural land

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▸ **Abstract.** Accurate determination of agricultural land market price was essential for informed economic decisions, yet traditional statistical methods demonstrated unacceptably high discrepancies due to statistical outliers and market structural features. The aim of the study was to develop and validate an improved methodology for calculating the market price of agricultural land that ensured stability and reliability of results through the comprehensive application of multi-level data filtering and an adaptive weighting system. The proposed methodology achieved a threefold reduction in price estimate variability (coefficient of variation 17.2% vs. 54% for traditional methods), while maintaining high representativeness of the sample, this ensured more reliable market price calculations. The analysis revealed that traditional methods produced results ranging from 40.4 to 62.2 thousand UAH per hectare with an amplitude of fluctuations of 54%, whereas the developed methodology provided an estimate of 50.3 thousand UAH per hectare with a coefficient of variation of 17.2%, indicating a threefold improvement in estimation stability. Monthly analysis confirmed the methodology's resilience to seasonal fluctuations and varying intensities of market activity, revealing a price growth trend of 9.3% over 2024-2025 period. Comparison with official calculations of the State Service of Ukraine for Geodesy, Cartography and Cadastre showed a systematic deviation within 17.8%, reflecting objective methodological differences in approaches to processing market information. The practical value of the developed methodology lies in its applicability for analysing the goals of land market monitoring, valuation activities, and state regulation of land relations

▸ **Keywords:** pricing methodology; transaction data analysis; multilevel filtering; adaptive weighting; price accuracy; land valuation; data outliers

▸ Introduction

The determination of the average statistical market price of agricultural land based on purchase and sale transaction data was a complex methodological problem that required consideration of both the structural features of the land market and the specifics of statistical data processing. Traditional statistical methods often demonstrated significant discrepancies in results due to the influence of outliers and the heterogeneity of market transactions, which actualised the need to improve existing approaches. C. Leys *et al.* (2013) highlighted that detecting outliers by determining an interval spanning over the mean plus/minus three standard deviations remained a common practice among researchers, however, since both the mean and the standard deviation were particularly sensitive to outliers, this method was problematic. The authors presented the median absolute deviation as an alternative and more robust measure of dispersion that was easy to implement. P.-L. Loh (2025) provided a theoretical review of modern robust statistics, emphasising that the field had drawn a new surge of attention from 2015 to 2025 due to a desire to recast robust statistical principles in the context of high-dimensional statistics, demonstrating the need for further research in robust estimation that embraced new estimation settings and computational tractability.

The problem of land valuation methodology was directly related to the accuracy of market price calculations.

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H. Cherevko & M. Hryso (2023) identified that the modern methodology for land valuation in Ukraine wasn't ensure an adequate level of assessment for the needs of the real land market, which wasn't allow for a realistic assessment of the land resource potential. Researchers emphasised the need to improve the methodology based on the application of market approaches and the experience of European countries, where mass appraisal methods were widely used. B. Khakhula & N. Svynous (2024) examined the problem of applying new methodological approaches to the valuation of agricultural land in the conditions of land market formation. Scientists noted that the market value of land depended on supply and demand in the market and the nature of competition between sellers and buyers. The authors emphasised that market value was determined as the most probable price, at which land can be alienated on the open market under competitive conditions, when the parties to the transaction act reasonably with equal access to the necessary information.

The specifics of the agricultural land market in post-socialist countries created additional challenges for price calculation. M. Gorgan & M. Hartvigsen (2022) assessed the modern development stage of land markets in countries in Eastern Europe and Central Asia and discussed the main constraints including informalities, technical errors, and complicated land transaction procedures. The authors noted that agricultural land markets remained weak and still face many constraints, with most countries having farm structures characterised by excessive land fragmentation and small average farm sizes. S. Ibatullin *et al.* (2024) examined the functioning of the agricultural land market in Ukraine and found that prices for land plots remained at the level of their normative monetary value and were still relatively low, indicating significant undercapitalisation of agricultural land as a production factor. The stability of agricultural land prices under the influence of various factors indicated their relative virtuality, which complicated the application of standard statistical methods for calculating average market prices.

M. Kalinchyk & O. Mogylnyi (2024) generalised the experience of EU member states regarding the formation of agricultural land prices and established that the factors increasing land capitalisation included the dominance of high-margin crops in the structure of sown areas, as well as the productivity of crop and livestock production. The author's research demonstrated that price formation in the agricultural land market was influenced by multiple factors that must be taken into account, when developing calculation methodologies. S. Zrobek *et al.* (2020) proposed the application of fuzzy logic theory to perform tasks of determining the market value of agricultural lands, noting that such tasks were of a multi-criteria character as multiple factors were taken into consideration during the land value valuation process. Researchers emphasised that proposed method was particularly useful for countries, where the agricultural real estate market was still in its early stages of development.

Despite the significant volume of research on land valuation and statistical methods, the problem of developing a comprehensive methodology for calculating the average statistical market price of agricultural land based on purchase and sale transaction data, taking into account statistical outliers and structural heterogeneity of the market, remained insufficiently resolved. Existing approaches either ignored the economic weight of transactions, or were overly sensitive to extreme values, or do not account for the specifics of different market segments. The purpose of this research was to address the critical challenge of obtaining consistent agricultural land price estimates by proposing a novel analytical framework that integrates hierarchical data filtering with dynamic weighting mechanisms. The objectives included: 1) comparative evaluation of traditional statistical methods for land price calculation; 2) development and validation of a multi-method analytical framework with hierarchical filtering and adaptive weighting; 3) empirical testing using official transaction data and comparison with state cadastral estimates. The novelty of the study lies in the proposed integrated approach that combined five complementary calculation methods with an adaptive weighting system, which ensured a threefold reduction in the coefficient of variation compared to traditional statistical approaches.

▸ Materials and Methods

The empirical basis of this study comprised official data from the State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.) on purchase and sale transactions of agricultural land plots conducted during January-August of 2025. After data cleaning and verification, 81,026 transactions representing 93% of initially recorded operations were included in the analysis. The geographical coverage encompassed all regions of Ukraine, ensuring sample representativeness and national-level applicability. The temporal scope of eight calendar months enabled consideration of seasonal price fluctuations and evaluation of methodological stability under varying market conditions. The research employed a combination of general scientific and specialised statistical methods. Comparative analysis was applied to evaluate traditional statistical approaches for land price calculation, including arithmetic mean, median, and area-weighted mean methods. Statistical analysis encompassed descriptive statistics, distribution analysis, and variability assessment through standard deviation, coefficient of variation, and range metrics. Systematic approach was utilised in developing the multi-level filtering framework and integrating multiple calculation methods. Empirical validation involved benchmarking the developed methodology against official state cadastral estimates and traditional statistical methods.

The core methodological innovation consisted of five complementary calculation methods, each designed to address specific data characteristics and minimise particular types of statistical anomalies. The hybrid weighted method applied broad filtering boundaries (1-500 thousand UAH per hectare) to eliminate extreme outliers, while preserving sample representativeness, excluding symbolic transactions and speculative deals. The conservative weighted method employed narrower constraints (15-150 thousand UAH per hectare) to focus on typical market transactions under standard conditions. The balanced method with area consideration combined price filtering (8-250 thousand UAH per hectare) with plot size restrictions (0.1-50 hectares), targeting the most representative market segment that accounted for 89.2% of transactions and 76.4% of total traded area. The ultraconservative method applied the strictest criteria (20-100 thousand UAH per hectare), concentrating on the central price core that comprised 42.8% of operations but demonstrated the lowest variability and highest stability. The adaptive weighting method dynamically adjusted coefficients based on data structure, where methods with larger numbers of valid observations received higher weights, ensuring optimal information utilisation.

The integration framework operated through a dual-level weighting system. The first level combined four basic methods using fixed theoretical weights reflecting each approach's reliability. The second level employed the adaptive method with dynamic coefficients determined by observation counts. Final estimates emerged from equally weighted averaging of both integration levels, balancing theoretical validity with empirical adaptability. Monthly dynamics analysis was conducted to assess the methodology's resilience to temporal fluctuations in market activity. The selection of filtering thresholds was grounded in statistical distribution analysis and expert evaluation of typical agricultural land market conditions, with lower bounds corresponding to minimum economically justified prices and upper bounds covering premium lands, while excluding speculative transactions.

Results and Discussion

Determining the market price of agricultural land remained a pressing issue for economic analysis of Ukraine's agricultural sector (Cherevko & Hryso, 2023). Traditional statistical methods for processing purchase and sale transaction data often demonstrated significant discrepancies in results due to the influence of outliers and structural features of the land market. The application of an improved methodology to an array of real data allowed for the assessment of the effectiveness of different approaches to calculating the average statistical market price and substantiated the advantages of comprehensive statistical analysis. The structural analysis of the sample demonstrated significant variability in land plot sizes – from minimal shares of 0.0006 hectares to large arrays exceeding 300 hectares. The price range of transactions was characterised by an even greater amplitude of fluctuations: from symbolic amounts to anomalously high values exceeding UAH 2.8 billion per hectare. Such significant variability of price indicators confirmed the relevance of the problem of statistical processing of land market data and the necessity of applying robust analysis methods to minimise the impact of outliers on the final result (Gorgan & Hartvigsen, 2022; Loh, 2025). The arithmetic mean represented the most common and simplest approach to determining central tendency in the statistical analysis of land plot market prices. This method was based on the classical principle of equal weighting of all observations in the sample, regardless of their economic significance or potential representativeness for the general population of transactions. The mathematical formula for the arithmetic mean for calculating the price per hectare was as follows:

$$\bar{x} = (\sum (P_i / S_i)) / n, \quad (1)$$

where $\bar{x}$ – arithmetic mean of the price per hectare; P_i – total transaction price; S_i – area of the land plot; n – total number of transactions in the sample.

The application of the arithmetic mean to the dataset of 81,026 purchase and sale transactions yielded a result of 62.2 thousand UAH per hectare. However, a detailed analysis of the distribution of price indicators revealed critical shortcomings of this approach in the context of land market data processing (Hunko *et al.*, 2023). The main problem lain in the excessive sensitivity of the arithmetic mean to extreme values, which in the studied sample were represented by transactions with prices exceeding 500 thousand UAH per hectare, including anomalous cases with values exceeding 2 billion UAH per hectare. Structural analysis showed that only 11.8% of transactions can be classified as statistical outliers according to the interquartile range rule; however, their influence on the arithmetic mean was disproportionately large. This situation led to systematic overestimation of the calculated price compared to actual market conditions, as extremely high prices of individual transactions may reflect specific circumstances (proximity to cities, infrastructural advantages, speculative operations) that were not typical for the majority of agricultural land plots (Leys *et al.*, 2013; Kionka *et al.*, 2021). The median as a statistical indicator represented an alternative approach to determining central tendency, which was theoretically less sensitive to the influence of extreme values compared to the arithmetic mean (Loh, 2025). This method was based on the principle of ranking all observations in ascending order and identifying the middle value that divided the ordered sample in half. The mathematical formula for the median of the price per hectare was as follows:

$$M_e = \{(P_i / S_i)((n+1)/2)\}, \text{ if } n - \text{odd}; \\ \{[(P_i / S_i)(n/2) + (P_i / S_i)((n/2)+1)]/2\}, \text{ is } n - \text{even}, \quad (2)$$

where M_e – median value of the price per hectare; (P_i/S_i) – price per hectare values arranged in ascending order; n – total number of transactions in the sample.

The application of the median method to the studied dataset yielded a result of 43.7 thousand UAH per hectare, which differed significantly from the arithmetic mean result and demonstrated an opposite tendency. While the arithmetic mean overestimated the value due to the influence of extremely high prices, the median tended to underestimate the result due to the structural features of Ukraine's land market. The critical shortcoming of the median approach in the context of land market price analysis lain in ignoring the economic weight of individual transactions. The median assigns equal significance to the sale of a small plot of 0.1 hectares and a large land array of 100 hectares, which contradicted the economic logic of market price formation. Moreover, the analysis of the distribution of transactions by size showed that a significant proportion of operations involved small land plots, the prices of which were often formed under the influence of specific factors not characteristic of the main segment of agricultural land. Thus, the median estimate may reflect the price level predominantly of small land plots rather than a representative market price for agricultural land in general (Udovenko *et al.*, 2024). The attempt to eliminate the shortcomings of both the arithmetic mean and the median led to the consideration of a third traditional approach – the area-weighted arithmetic mean. This method represented a compromise solution that took into account both individual transaction prices and their economic weight through the size of land plots. The fundamental concept of the weighted mean was that larger plots had a greater influence on the formation of the overall market price, which corresponded to the economic logic of land market functioning (Yurchenko, 2024). The mathematical formula for the area-weighted arithmetic mean was as follows:

$$\bar{x}w = (\sum P_i) / (\sum S_i), \quad (3)$$

where $\bar{x}w$ – area-weighted arithmetic mean of the price per hectare; P_i – total price of the i-th transaction; S_i – area of the i-th land plot; $\sum$ – summation sign across all transactions in the sample.

The application of the area-weighted arithmetic mean method to the studied dataset yielded a result of 40.4 thousand UAH per hectare, which proved to be the lowest value among the three traditional approaches considered. The obtained result confirmed the hypothesis that large land arrays were typically sold at lower unit prices compared to small plots, reflecting the economy of scale effect and the specifics of price formation in different segments of the land market (Kalinchyk & Mogylnyi, 2024). The weighted approach demonstrated an opposite tendency compared to the simple arithmetic mean – it tended to underestimate the market price due to the dominance in the total area structure of large land plots with relatively lower unit prices. At the same time, this method retained sensitivity to outliers in cases, where anomalously high or low prices were characteristic of large land plots. Despite accounting for the economic weight of transactions, the weighted mean does not resolve the fundamental problem of statistical processing of data with a wide range of values and the presence of structural features across different segments of the land market. This necessitated the application of a more sophisticated methodological approach capable of ensuring the robustness of results to various types of anomalies in the source data.

A comparative analysis of the three traditional statistical methods revealed significant discrepancies in the results of calculating the market price of agricultural land: the arithmetic mean showed 62.2 thousand UAH per hectare, the median – 43.7 thousand UAH per hectare, and the weighted mean – 40.4 thousand UAH per hectare. Such an amplitude of fluctuations within 54% from the lowest to the highest value indicated systemic shortcomings of each of the considered approaches and their inability to adequately reflected actual market conditions. Each method demonstrated specific distortions: the arithmetic mean tended to overestimate due to the influence of extreme values, the median ignored the economic weight of transactions, and the weighted mean may underestimate the result due to the dominance of large land arrays with lower unit prices (Khakhula & Svynous, 2024). The shortcomings of traditional statistical methods necessitated the development of a comprehensive methodological approach that would combine the advantages of different statistical techniques, while mitigating their individual weaknesses (Yalpir *et al.*, 2021). The conceptual foundation of the improved methodology was the creation of a multi-stage data filtering system with subsequent application of differentiated statistical analysis methods and their integration through a weighting system. The main principle of the developed approach lain in recognising the heterogeneity of the land market and the necessity of applying different analytical tools for different segments of market operations. The methodology provided for the simultaneous use of five complementary calculation methods, each optimised for specific characteristics of the source data and aimed at minimising the impact of specific types of statistical anomalies. The final result was formed through weighted combination of individual estimates, ensuring stability and reliability of the ultimate indicator of land market price (Zrobek *et al.*, 2020).

The hybrid weighted method represented the basic approach in the developed methodology, aimed at eliminating the most obvious statistical anomalies, while preserving the maximum volume of analysed data. The fundamental concept of this method lain in establishing broad limits of acceptable price values that allowed filtering out only extreme outliers, while maintaining sample representativeness. The lower filtering limit was set at 1 thousand UAH per hectare, which excluded from analysis transactions with symbolic prices reflecting intra-family transfers, donations, or technical operations. The upper limit was defined at 500 thousand UAH per hectare, which allowed for the elimination of speculative operations and transactions involving lands with special status or location. The mathematical formula for the hybrid weighted method was as follows:

$$PHH = (\sum P_i) / (\sum S_i), \text{ where } P_i \in [1{,}000; 500{,}000]^* S_i, \quad (4)$$

where PHH – price per hectare according to the hybrid weighted method; P_i – total price of the i-th transaction that satisfies the price criteria; S_i – area of the i-th land plot; $\sum$ – summation across all transactions that passed the filtering.

The justification for the selection of threshold values was based on statistical analysis of price distribution in the sample and expert assessment of typical market conditions for agricultural land (Veklych & Boiko, 2021). The lower limit of 1 thousand UAH corresponds to the minimum economically justified price for the least fertile lands in remote regions, while the upper limit of 500 thousand UAH covered even the most expensive agricultural lands near large cities, excluding only obviously speculative operations. The conservative weighted method represented a more restrictive approach to filtering source data, aimed at analysing the most typical market operations with agricultural land. This method was based on the hypothesis that the most accurate estimate of the average market price can be obtained by concentrating the analysis on transactions with moderate price characteristics that most likely reflected standard market conditions. The lower filtering limit was set at 15 thousand UAH per hectare, which excluded transactions with potentially underestimated prices caused by specific circumstances of sale. The upper limit was defined at 150 thousand UAH per hectare, which allowed retaining in the analysis the vast majority of typical market operations, while excluding transactions with premium prices. The mathematical formula for the conservative weighted method was as follows:

$$PHC = (\sum P_i) / (\sum S_i), \text{ where } P_i \in [15{,}000;\ 150{,}000]^* S_i, \quad (5)$$

where *PHC* – price per hectare according to the conservative weighted method; P_i – total price of the *i*-th transaction that satisfies the narrowed price criteria; S_i – area of the *i*-th land plot; $\sum$ – summation across all transactions that passed the conservative filtering.

The justification for threshold values was based on the analysis of interquartile price distribution and the determination of a range that covered the central 70% of transactions by price characteristics. The lower limit of 15 thousand UAH corresponded to the price level below, which transactions may reflect forced sales, intra-corporate operations, or other non-standard market situations. The upper limit of 150 thousand UAH covered even transactions with high-quality lands in economically developed regions, excluding only operations with clearly premium characteristics. The balanced method with area consideration represented an approach that combined price filtering with additional selection criteria based on land plot size. The concept of this method was based on the hypothesis that the most representative market prices were formed in the segment of land plots of typical size, which belong neither to small shares nor to large arrays. Price limits were set in the range from 8 to 250 thousand UAH per hectare, which ensured broad coverage of market operations, while excluding extreme anomalies. Additionally, a filter by land plot area within the range from 0.1 to 50 hectares had been introduced, which allowed focusing the analysis on land use sizes typical for the Ukrainian agricultural sector. The mathematical formula for the balanced method with area consideration was as follows:

$$PHB = (\sum P_i) / (\sum S_i), \text{ where } P_i \in [8{,}000;\ 250{,}000]^* S_i \text{ and } P_i \in [0.1;50], \quad (6)$$

where *PHB* – price per hectare according to the balanced method with area consideration; P_i – total price of the *i*-th transaction that satisfies both price and area criteria; S_i – area of the *i*-th land plot within the permissible range; $\sum$ – summation across all transactions that passed the dual filtering.

The justification for filtering parameters was based on structural analysis of the Ukrainian land market and the features of the national model of agricultural land use. Statistical analysis of the distribution of transactions by area showed that land plots ranging from 0.1 to 50 hectares constituted 89.2% of the total number of operations and covered 76.4% of the total area of sold land (State Service of Ukraine for Geodesy, Cartography and Cadastre, n.d.). The lower area limit of 0.1 hectares excluded micro plots (4.7% of transactions), the pricing of which may be influenced by specific factors not characteristic of the main segment of agricultural land. The upper limit of 50 hectares removed from the analysis large agro-industrial arrays (6.1% of transactions), where prices were formed under the influence of corporate strategies and may not reflect general market trends. The expanded price range compared to the conservative method allowed for accounting for a larger number of legitimate market operations, while maintaining control over statistical outliers. Thus, the balanced method concentrated the analysis on the most representative segment of the land market, which was characterised by both typical plot sizes and standard market pricing mechanisms. The ultraconservative method represented the most restrictive approach to the selection of market data, aimed at analysing exclusively those transactions that most likely reflected standard market conditions without any specific circumstances. The concept of this method was based on the principle of maximum selectivity, where only transactions with price characteristics falling within a narrow range of the most typical market operations were included in the analysis. Price limits were set from 20 to 100 thousand UAH per hectare, which covered the central core of market prices and excluded both potentially underestimated and overestimated land plot valuations. The mathematical formula for the ultraconservative method was as follows:

$$PHU = (\sum P_i) / (\sum S_i), \text{ where } P_i \in [20{,}000;\ 100{,}000]^* S_i, \quad (7)$$

where *PHU* – price per hectare according to the ultraconservative method; P_i – total price of the *i*-th transaction that satisfies the strict price criteria; S_i – area of the *i*-th land plot; $\sum$ – summation across all transactions that passed the most stringent filtering.

The justification for narrow threshold values was based on the analysis of median characteristics of market prices and the identification of a range that covered the central 40% of transactions by price parameters. Statistical analysis showed that transactions in the range of 20-100 thousand UAH per hectare constitute 42.8% of the total number of operations but were characterised by the lowest variability of price indicators and the highest stability of market conditions (State Service of Ukraine for Geodesy, Cartography and Cadastre, n.d.). The lower limit of 20 thousand UAH excluded transactions that may reflect forced sales, technical operations, or lands with limited production characteristics. The upper limit of 100 thousand UAH excluded operations with premium prices caused by special location, infrastructural advantages, or speculative motives of buyers. The adaptive weighting method represented the most sophisticated component of the developed methodology, which dynamically adjusted the weight coefficients of individual methods depending on the structural characteristics of the source data (Sasu *et al.*, 2024). Unlike the previous four approaches that use fixed filtering criteria, the adaptive method was based on the principle of self-regulation, where the importance of each statistical approach was determined by its representativeness in the specific sample. The fundamental concept was that methods with a larger number of valid observations received higher weight coefficients, which ensured optimal use of available information and minimisation of the influence of methods with a limited statistical base. The mathematical formula for the adaptive weighting method was as follows:

$$PHA = (\sum (R_i^* B_i^* C_i)) / (\sum (B_i^* C_i)), \quad (8)$$

where *PHA* – price per hectare according to the adaptive weighting method; R_i – result of the *i*-th calculation method; B_i – base weight coefficient of the *i*-th method; C_i – adjustment coefficient equal to the ratio of the number of transactions in the *i*-th method to the total number of transactions; $\sum$ – summation across all methods included in the adaptive system.

The system of base weight coefficients was developed taking into account the theoretical advantages and limitations of each method: the hybrid weighted method received a coefficient of 0.8 as a basic approach with broad coverage; the conservative weighted method – 1.4 as the most stable indicator; the balanced method with area consideration – 0.8 given the additional restrictions; the ultraconservative method – 1.2 due to high selectivity. Adjustment coefficients change dynamically depending on the actual number of transactions that satisfied the criteria of each method, ensuring automatic adaptation of the weighting system to the specifics of a particular dataset. The proposed system of five complementary methods created a multidimensional approach to analysing market prices of agricultural land, where each component performed a specific function in the overall architecture of the methodology. The hybrid weighted method ensured broad coverage of market data, the conservative weighted method guarantees stability of results, the balanced method with area consideration accounts for structural features of the national land market, the ultraconservative method minimised the influence of atypical operations, and the adaptive weighting method provided dynamic optimisation of the system. Such a comprehensive approach allowed for the simultaneous utilisation of the advantages of different statistical techniques, while compensating for their individual limitations, creating a synergistic effect, where the integrity of the methodology exceeded the sum of its individual components.

The effectiveness of the developed methodology depended not only on the quality of individual calculation methods but also on the manner of their integration into a unified analytical system. The key task became creating an optimal algorithm for combining the results of five methods that would account for their relative reliability, representativeness, and complementarity. The integration system should ensure not mechanical averaging of obtained values but intelligent weighting that considered both the theoretical advantages of each approach and the practical characteristics of a specific dataset. The developed integration system was based on the principle of double weighting, which combined the advantages of fixed and adaptive weight coefficients (Wu *et al.*, 2024). The first level of integration involved combining four basic methods (hybrid, conservative, balanced, and ultraconservative) through a system of fixed weights reflecting the theoretical reliability of each approach. The second level was represented by the adaptive weighting method, which used the same basic methods but applied dynamic coefficients depending on the number of valid observations in each of them. The final result was formed through equally weighted averaging of the results from both levels of integration, ensuring a balance between theoretical validity and empirical adaptability of the methodology. The mathematical formula for the final integration was as follows:

$$P_{fin} = (P_{fix} + P_{adapt})/2, \quad (9)$$

where P_{fin} – final market price per hectare; P_{fix} – result of combining methods with fixed weights; P_{adapt} – result of the adaptive weighting method.

The result with fixed weights was calculated as:

$$P_{fix} = (PHH^{*}0.8 + PHC^{*}1.5 + PHB^{*}0.9 + PHU^{*}1.2)/4.4, \quad (10)$$

where the coefficients 0.8, 1.5, 0.9, and 1.2 reflected the relative importance of each method in the overall evaluation system.

The application of the developed methodology to the dataset of 81,026 purchase and sale transactions of agricultural land yielded a final result of 50.3 thousand UAH per hectare. This indicator occupied an intermediate position between the results of traditional methods, which confirmed its balance and ability to mitigate extreme tendencies toward overestimation or underestimation. Compared to the arithmetic mean (62.2 thousand UAH per hectare), the developed methodology provided a reduction of 19.1%, reflecting the effectiveness of the extreme value filtering system. At the same time, the result exceeded the weighted mean indicator (40.4 thousand UAH per hectare) by 24.5% and the median (43.7 thousand UAH per hectare) by 15.1%, indicating that the economic weight of transactions was taken into account, while simultaneously eliminating the underestimation effect caused by the dominance of large land arrays. The stability of the developed methodology was confirmed by the insignificant variation in the results of individual system components. The analysis showed that the results of the four basic methods vary within a narrow range, representing a spread of less than 7% from the mean value. This contrasted with the amplitude of fluctuations of traditional methods at 54%, demonstrating a significant improvement in the accuracy and predictability of the estimate. The final result of 50.3 thousand UAH per hectare can be interpreted as the most reliable estimate of the average market price of agricultural land in Ukraine for the study period, which accounted for the structural heterogeneity of the land market and minimised the impact of statistical anomalies. The dynamics of land market prices according to different calculation methods demonstrated significant discrepancies, which confirmed the relevance of the problem of methodological improvement of statistical analysis (Table 1).

The results of the developed methodology demonstrated stable dynamics throughout the study period with gradual growth from 49.8 thousand UAH per hectare in January to 52.5 thousand UAH per hectare in August, reflecting general market trends of rising agricultural land prices. At the same time, traditional methods showed significantly greater variability of results: the arithmetic mean fluctuated from 54 to 72.2 thousand UAH per hectare, the median – from 42 to 45.7 thousand UAH per hectare, and the weighted mean – from 38.5 to 42.2 thousand UAH per hectare. The developed methodology occupied a balanced position between these extreme estimates and demonstrated the smallest amplitude of fluctuations. Particularly, illustrative was April, when the arithmetic mean reached its maximum value of 72.2 thousand UAH per hectare due to the influence of outliers, while the developed methodology remained at 50.1 thousand UAH per hectare, indicating its resilience to statistical anomalies. A comparison of the developed methodology with official data from the State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.) showed a high degree of correlation of results with systematically lower values of the improved approach. The deviation from official calculations ranged from -7.8% to -29.4%, which may indicate the presence of certain methodological differences in calculation approaches (Table 2).

Table 1. Dynamics of the market price of agricultural land according to different calculation methods (January-August 2025)

Month	Number of transactions	Arithmetic mean	Median	Weighted mean	Cadastre data	New method
	thousand	thousand UAH/ha	thousand UAH/ha	thousand UAH/ha	thousand UAH/ha	thousand UAH/ha
January	4.4	54.7	42.8	38.7	54	49.8
February	12.6	57.7	42	38.5	56.9	48.1
March	11.3	54	42	38.8	54.3	48.5
April	11.4	72.2	43.5	40.6	71	50.1
May	11.7	61.4	45.6	41.8	61	51
June	9.8	60.7	44.2	40.6	60	51
July	10.1	69.7	45.7	41.6	68.5	52.6
August	9.7	63.6	45.4	42.2	63.5	52.5
Total	81	62.2	43.7	40.4	61.2	50.3

Source: State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.)

Table 2. Comparative analysis of deviations of the developed methodology from traditional methods and official data

Month	Deviation from arithmetic mean, %	Deviation from median, %	Deviation from weighted mean, %	Deviation from cadastre data, %
January	-8.9	+16.4	+28.7	-7.8
February	-16.6	+14.5	+25	-15.5
March	-10.2	+16	+25	-10.7
April	-30.6	+15.2	+23.4	-29.4
May	-16.9	+11.8	+22	-16.4
June	-16	+15.4	+25.6	-15.0
July	-24.5	+15.1	+26.4	-23.2
August	-17.5	+15.6	+24.4	-17.3
Total	-19.1	+15.1	+24.5	-17.8

Source: State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.)

The analysis of deviations revealed a systematic interrelationship between methods. The developed methodology consistently provided a reduction in estimates compared to the arithmetic mean (from -8.9% to -30.6%) and an increase compared to the median (from +11.8% to +16.4%) and weighted mean (from +22% to +28.7%). Such consistency of deviations confirmed that the developed methodology does not simply mechanically average traditional approaches but applied a consistent logic for correcting their systematic errors. The largest deviations from the arithmetic mean were observed in April (-30.6%) and July (-24.5%), which was explained by the particularly high influence of outliers in these months. Statistical variability indicators confirmed a significant improvement in estimation stability, when using the developed methodology compared to traditional approaches (Table 3).

Table 3. Comparative analysis of deviations of the developed methodology from traditional methods and official data

Month	Standard deviation (thousand UAH/ha)	Coefficient of variation, %	Range of variation (max-min) (thousand UAH/ha)
January	6.5	13.9	16
February	8	16.9	19
March	6.5	14	15
April	13.2	24.6	31.6
May	8.3	15.6	19.6
June	8.4	16.1	20.1
July	11.7	20.7	28.1
August	9	16.5	21.4
Total	9.2	17.2	21.8

Source: State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.)

The coefficient of variation, which characterised the relative variability of price estimates, ranges from 13.9% in January to 24.6% in April, with a mean value of 17.2% for the entire period. The mean coefficient of variation of 17.2% represented a threefold improvement compared to the 54% variation observed for traditional methods (arithmetic mean, median, weighted mean) applied to the same dataset, demonstrating substantially enhanced homogeneity of estimates. The standard deviation varied from 6.5 to 13.2 thousand UAH per hectare, reflecting the absolute magnitude of discrepancies between methods and demonstrating the highest values in April and July – months with the greatest market activity and price volatility. The range of variation, defined as the difference between maximum and minimum values among all methods, ranges from 15.2 to 31.6 thousand UAH per hectare depending on the month. The mean range value of 21.8 thousand UAH per hectare meant that in a typical month, the difference between the highest and lowest estimate constituted 43% of the mean value, which underscored the critical importance of methodology selection for obtaining reliable results. At the same time, the developed methodology demonstrated systematic positioning in the central part of the estimation range, avoiding both extremely high and extremely low values.

The analysis of monthly dynamics revealed a trend of gradual market price growth throughout January-August of 2025. The developed methodology showed an increase from 48.1 thousand UAH per hectare in February to 52.6 thousand UAH per hectare in July, representing a growth of 9.3% over six months or approximately 1.5% per month. This growth reflected general economic trends and seasonal factors of price formation in the land market, when the spring-summer period was characterised by increased buyer activity and higher prices compared to winter months. All calculation methods demonstrated similar dynamics; however, the developed methodology provided a smoother growth trajectory without the sharp fluctuations characteristic of traditional approaches. The developed methodology demonstrated fundamental advantages over traditional statistical approaches through the implementation of principles of multi-level filtering and differentiated weighting. Unlike one-dimensional methods that applied a single criterion for data selection or processing, the proposed approach integrated five independent analytical procedures, each optimised for a specific segment of market operations. Such architecture of the methodology ensured a synergistic effect, where the weaknesses of individual components were compensated by the strengths of others, creating a system of mutual balancing and correction of systematic errors. Empirical confirmation of this advantage was the reduction of the coefficient of variation from 54% for traditional methods to 17.2% for the developed methodology, indicating a threefold improvement in estimation stability.

A critically important advantage of the developed approach was its adaptability to the structural features of a specific dataset without the need for manual researcher intervention. The dynamic weighting system automatically adjusted the influence of each method depending on the number of valid observations that satisfied its criteria, ensuring optimal utilisation of the informational potential of the sample. This fundamentally distinguished the proposed methodology from static approaches, where filtering and weighting parameters were established a priori and remained unchanged regardless of data characteristics. The results of the comparative analysis showed that the developed methodology provided a systematic deviation from the official data of the State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.) within 7.8-29.4%, which may reflect objective differences in approaches to processing extreme values and indicates the potential for further methodological dialogue regarding the standardisation of procedures for calculating land market prices. The results obtained in this study demonstrated a significant improvement in the methodology for calculating the average statistical market price of agricultural land compared to both traditional approaches and previous research. The developed five-component methodology with an adaptive weighting system provided a final estimate of 50.3 thousand UAH per hectare with a coefficient of variation of 17.2%, which represented a threefold reduction in variability compared to traditional statistical methods showing an amplitude of fluctuations of 54%.

I. Yurchenko (2024) analysed 137,357 purchase and sale transactions for the period 2021-2023 using three traditional methods: arithmetic mean, weighted mean, and median. The results showed that the arithmetic mean produced significantly inflated values of 134 thousand UAH per hectare, which were 2-3 times higher than official data and did not reflect the real market situation. The weighted mean yielded 27.8 thousand UAH per hectare, while the median showed 32.5 thousand UAH per hectare. It was concluded that the arithmetic mean method was unsuitable for calculating land prices due to its sensitivity to extreme values, which constituted more than 20% of transactions. This research substantially advanced the methodology by introducing a multi-level filtering system and an adaptive weighting mechanism that dynamically adjusted the contribution of each calculation method based on the structural characteristics of the data. The comparative analysis revealed that, while I. Yurchenko (2024) identified the problem of significant discrepancies between traditional methods, methodology of this research provided a balanced estimate that systematically positioned itself between the extreme values, avoiding both overestimation inherent to the arithmetic mean and underestimation characteristic of the weighted mean. The developed methodology's emphasis on multi-level filtering and adaptive weighting found strong support in systematic analyses of agricultural land markets. M. Agosta *et al.* (2025) conducted a comprehensive literature review identifying both intrinsic factors (soil fertility, water access, plot size, location) and extrinsic factors (urban pressure, fiscal policies, demographic changes, climate variations) as critical determinants of land prices. The author's framework underscored that accurate price calculation required methodologies capable of simultaneously addressing multiple interacting variables – precisely the approach implemented in five-component system developed in this study. The systematic deviation of 17.8% from official calculations observed in this research reflected the inherent complexity of land market dynamics, where different methodological approaches captured distinct aspects of market reality.

The challenge of price variability in transitional agricultural markets extended beyond Ukraine's borders. A. Wasilewski *et al.* (2024) analysed agricultural land price dynamics across EU member states from 2006 to 2022, revealing similar patterns of convergence and divergence. Eastern European countries, including Poland and Romania, demonstrated price convergence driven by EU policies and foreign investment, while maintaining substantial internal price variation – a coefficient of variation oscillating between 0.97 and 1.03 across the analysed period. Scientist's findings that relative price diversity remained stable despite absolute price increased parallel observation of this study that traditional statistical methods yielded unacceptably high discrepancies (54% amplitude of fluctuations). This cross-national evidence validated the necessity of robust filtering mechanisms to isolate meaningful price signals from market noise, particularly in markets characterised by fragmented land ownership and varying transaction intensities. The methodological advancement achieved through adaptive weighting system aligned with emerging trends in land price prediction technologies. S. Doğan *et al.* (2025) compared traditional multiple linear regression with the Extreme Gradient Boosting (XGBoost) algorithm for agricultural land price prediction in Turkey, demonstrating that advanced analytical approaches substantially outperformed conventional methods ($R^2 = 0.66$ versus $R^2 = 0.01$). While researcher's study focused on machine learning algorithms rather than statistical filtering, the underlying principle remained consistent: accurate land price determination required methodologies that can capture complex, non-linear relationships among multiple variables. Five-method integration with dynamic weighting, developed in this research, represented a parallel evolution in statistical methodology, achieving threefold improvement in estimation stability through intelligent combination of complementary analytical approaches rather than reliance on single-method calculations.

The regional dimension of agricultural land productivity assessment also warranted consideration in the context of price methodology. I. Smaga *et al.* (2023) assessed the productive potential and efficiency of agroland use in the Chernivtsi region, demonstrating that regional variations in land quality and utilisation efficiency directly influenced market price formation – a finding that underscored the necessity of robust filtering mechanisms capable of handling heterogeneous transaction data. The temporal dynamics of land price behaviour further complicated methodological choices. J. Valtiala (2020) identified regime-switching behaviour in Finnish agricultural land prices, demonstrating that land markets periodically shifted between distinct price regimes characterised by different mean levels and volatility patterns. This non-linear price dynamics validated the adaptive weighting approach developed in this study, where dynamic weight coefficients automatically responded to structural shifts in transaction data distribution rather than assuming a stationary price-generating process.

The broader context of land valuation methodology improvement was evident across diverse agricultural markets. A.H. Valiyev & N.S. Mirzayev (2023) examined land assessment methods in Azerbaijan, identifying that existing approaches to determining normative land prices do not fully correspond to market reality – a conclusion remarkably similar to findings regarding Ukrainian official methodology. Emphasis on optimising quality assessment and economic valuation methods to establish efficient farming systems and reliable price determination resonated with this research objectives. The convergence of methodological concerns across geographically and economically diverse contexts – from EU member states to post-Soviet agricultural markets – suggested that the challenge of accurate land price calculation represented a fundamental issue requiring systematic methodological innovation rather than market-specific solutions. The systematic deviation of 17.8% from the official data of the State Service of Ukraine for Geodesy, Cartography and Cadastre (n.d.) observed in this study was consistent with the findings of research, where it was noted an average difference of 8 thousand UAH per hectare between calculated values and official statistics. The monthly analysis confirming the stability of the developed methodology under conditions of seasonal fluctuations represented an important advancement compared to this research, which did not assess temporal stability. The identified price growth trend of 9.3% over six months reflected general economic tendencies in the land market and demonstrated the methodology's capacity to capture real market dynamics, while filtering out statistical noise.

▸ Conclusions

The study confirmed the critical necessity of improving methodological approaches to calculating the market price of agricultural land based on purchase and sale transaction data. The analysis of a dataset of 81,026 transactions for the period January-August of 2025 revealed an unacceptably high discrepancy in the results of traditional statistical methods: the arithmetic mean (62.2 thousand UAH per hectare), median (43.7 thousand UAH per hectare), and weighted mean (40.4 thousand UAH per hectare) demonstrated an amplitude of fluctuations of 54%, which made their use for reliable market price estimation impossible without additional methodological corrections. The developed comprehensive methodology, based on the integration of five complementary methods with different filtering levels and an adaptive weighting system, provided a market price calculation of 50.3 thousand UAH per hectare with a coefficient of variation of 17.2%. The threefold reduction in variability compared to traditional approaches confirmed the effectiveness of the proposed system of multi-stage outlier filtering and intelligent result combination. The systematic deviation from official within 17.8% indicated objective methodological differences in approaches to processing market information and actualised the need for further standardisation of calculation procedures. Monthly analysis confirmed the stability of the methodology under conditions of seasonal fluctuations in market prices and varying transaction intensity. The identified trend of market price growth of 9.3% during January-July of 2025 reflected general economic processes in Ukraine's land market under conditions of ongoing military operations. Further research directions will include annual cycle analysis, regional methodology adaptation, and comparative assessment of international land market monitoring practices.

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▸ Conflict of Interest

None.

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Удосконалення методології розрахунку середньостатистичної ринкової ціни земель сільськогосподарського призначення

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▸ **Анотація.** Точне визначення ринкової вартості сільськогосподарських земель стало важливим для прийняття обґрунтованих економічних рішень, однак традиційні статистичні методи продемонстрували неприйнятно великі розбіжності через статистичні викиди та структурні особливості ринку. Метою дослідження було розробити та перевірити покращену методологію розрахунку ринкової вартості сільськогосподарських земель, яка забезпечила стабільність та надійність результатів через комплексне застосування багаторівневого фільтрування даних та адаптивної системи ваг. Запропонована методологія дозволила знизити варіативність оцінки ціни в три рази (коефіцієнт варіації 17,2 % проти 54 % для традиційних методів), зберігаючи високу репрезентативність вибірки, що забезпечило більш надійні розрахунки ринкової ціни. Аналіз показав, що традиційні методи дали результати в межах від 40,4 до 62,2 тис. грн за гектар з амплітудою коливань 54 %, тоді як розроблена методологія надала оцінку 50,3 тис. грн за гектар з коефіцієнтом варіації 17,2 %, що свідчило про триразове поліпшення стабільності оцінки. Щомісячний аналіз підтвердив стійкість методології до сезонних коливань та різної інтенсивності ринкової активності, виявивши тенденцію до зростання ціни на 9,3 % протягом 2024-2025 років. Порівняння з офіційними розрахунками Державної служби України з геодезії, картографії та кадастру показало систематичне відхилення в межах 17,8 %, що відображало об'єктивні методологічні різниці в підходах до обробки ринкової інформації. Практична цінність розробленої методології полягає в її застосовності для аналізу цілей моніторингу ринку земель, оцінної діяльності та державного регулювання земельних відносин

▸ **Ключові слова:** методологія ціноутворення; аналіз транзакційних даних; багаторівневе фільтрування; адаптивне зважування; точність ціни; оцінка земель; викиди даних

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Structural analysis of the development of competitive agricultural activity in Ukraine under wartime conditions

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▶ **Abstract.** The relevance of the study was determined by the need to identify structural changes in the agricultural sector that occurred under wartime conditions, as well as by the search for effective managerial decisions capable of ensuring the competitiveness of agrarian entrepreneurship within the new economic realities of a shifting institutional environment. The aim of the study was to conduct a structural analysis of the efficiency of agricultural enterprises across regions in order to identify spatial development patterns and to assess the degree of influence of the wartime factor on the economic performance of agricultural production. The study employed the method of cluster analysis, which made it possible to group the regions of Ukraine according to the level of economic efficiency of agricultural enterprises on the basis of multidimensional statistical indicators, including gross output, revenue, profitability, return on investment and investment activity per hectare of agricultural land. The analysis yielded four clusters of regions, which demonstrated significant differences in the level of enterprise performance, resource provision and adaptation to wartime conditions. It was established that the greatest damage was sustained by regions with a high level of concentration in crop production, whilst territories with a more diversified structure demonstrated relatively higher resilience. As a result of the study, the resource base and productive performance of agricultural enterprises were analysed across the identified clusters. The research hypothesis regarding the significant influence of production specialisation on enterprise resilience under adverse institutional conditions was confirmed. The specific features of

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the current territorial zoning of agricultural production were analysed and enterprise development strategies were identified across the respective clusters. The economic effects of agricultural enterprise operation were determined across the respective clusters, and the relationship between the level of specialisation and enterprise losses arising from the deterioration of farming conditions in 2022 was established. The practical value of the study lies in the possibility of using the results obtained to develop targeted support programmes for agrarian entrepreneurship, to plan measures for the spatial development of the sector and to formulate policy for the recovery of agriculture in the post-war period

Keywords: formation of competitiveness; economic efficiency; wartime impact; agrarian entrepreneurship; structural changes; spatial development

Introduction

Contemporary trends and prospects for the development of agricultural activity in Ukraine were shaped by the influence of wartime conditions (2022-2025). The wartime factor acted as a trigger for the transformation of economic management systems, causing structural changes in their competitiveness and socioeconomic performance. In the structural dimension of the analysis, the agricultural sector was examined from the perspective of assessing opportunities, the potential to adapt to wartime risks and the prospects for post-war recovery. Wartime risks exerted a destructive influence on agricultural production with regard to the physical accessibility of production and economic potential, restructured product marketing channels and altered the competitiveness of businesses. The sector's ecosystem found itself in a situation that required a search for opportunities to respond effectively to changes in market conditions. The deepening of destructive factors, the decline in enterprise competitiveness, the deactivation of numerous support mechanisms for agrarian business and the shifting cost-benefit ratio provided grounds for timely monitoring of the structural changes that had occurred within the sector.

As noted by Yu. Lupenko *et al.* (2023a), active hostilities caused a range of far-reaching impacts on the agricultural sector of Ukraine. Numerous agricultural and processing enterprises were destroyed or substantially damaged; cultivated areas and production volumes declined; logistical links were severed and sales markets were blocked, which substantially distorted the structure of the sector. The post-war reconstruction of agriculture was intended to address the damage inflicted on the agricultural sector by Russian aggression and to determine the direction of structural transformations. Agricultural activity was carried out within diverse organisational structures that organised the production of competitive goods. Such activity took place within an ecosystem oriented towards ensuring efficiency and competitiveness. A.-I. García-Agüero *et al.* (2023) indicated that accessible infrastructure, the natural resources of a territory, applied technologies, education, agricultural worker training and policy constraints were of decisive importance. Cluster analysis proved to be an effective instrument of structural analysis of the development of competitive agricultural activity. It made it possible to identify the strengths and weaknesses of a set of producers, as well as to delineate the cost-benefit balance of constructing agrarian business along territorial lines. A.H. Sadeli *et al.* (2023) noted that within the agri-food chain, the competitiveness of an agricultural commodity was established through the formation of its consumer quality. Achieving competitive and successful development of agricultural activity was made possible under conditions of effective coordination of the interests of the chain's participants. It was important to address this issue in a balanced manner so as to ensure that agriculture worldwide remained sustainable and beneficial to all stakeholders. I. Ali & I. Gölgeci (2020) identified the established level of trust among participants in agricultural activity structures as a significant component of social capital, a factor of particular relevance for small enterprises. L. Bartóková & J. Ďurčová (2022) noted that small forms faced competition from large resource suppliers and consumer demands, which affected their market position.

The realisation of business capabilities in achieving the development of competitive agricultural activity was multifaceted. Agricultural activity in Ukraine traditionally had its own national characteristics. The possibilities became real within the sector to ensure: national and global food security; territorial development; and the resilience of the economy to numerous destructive external influences, including wartime risks. A. Dibrova *et al.* (2023) argued that food security in Ukraine had become an obligation of both agribusiness and the state, which was required to be taken into account in assessments of the development of competitive agricultural activity. Ukraine's agricultural sector found itself in a difficult situation owing to hostilities and export restrictions since 2022; accordingly, it was important to achieve a balance to ensure sustainable growth. O. Skydan *et al.* (2023) noted that achieving this balance was to be of decisive importance for ensuring the long-term success of the sector, particularly in respect of developing competitive agricultural activity. Its development in Ukraine was institutionally dependent on the entrepreneurship system. Yu. Lupenko *et al.* (2023b) indicated that the essence of agrarian entrepreneurship as a form of economic management was revealed through its principal functions: resource mobilisation, organisational-productive and creative-innovative, which methodologically denoted the factors of competitiveness. M. Malik *et al.* (2023) argued that, given the destructive influence of the wartime factor, the processes of integrating cooperative formations were of particular importance for the organisational-economic provision of food security stability and the rational use of agricultural resources. Through capable entrepreneurship and cooperation, the relatively stable development of competitive agricultural activity in Ukraine was structurally built up.

The food security aspect in the context of qualitatively meeting the needs of the population was also of importance, since addressing the challenges of providing

Ukraine's citizens with essential foodstuffs under martial law required a comprehensive approach and immediate measures. These measures included the development of effective strategies for the supply and distribution of food resources, ensuring the accessibility and quality of foodstuffs, the introduction of social support programmes for vulnerable population groups, support for agriculture and the development of local food markets, as well as the attraction of international aid and support. Corresponding analytical confirmation of the above and other practical aspects of agricultural activity was positioned through empirical assessments of development trends. The aim of the study was to conduct a structural analysis of the development of agricultural activity under the influence of wartime conditions. This was necessary in order to substantiate the hypothetical conclusion that economic entities exhibited, on the one hand, an inability to rapidly restructure their businesses, whilst on the other hand remaining relatively resilient depending on their specialisation, which affirmed their competitiveness in conditions of progressively increasing market turbulence.

▸ Materials and Methods

The study was carried out within the framework of a project aimed at assessing the consequences of Russia's military aggression for Ukraine's agricultural sector and determining the directions of compensatory policy for the development of agrarian entrepreneurship. The methodological foundation was provided by the principles of structural analysis of the economic efficiency of agricultural enterprises, employing the tools of cluster analysis. Cluster analysis was applied as the primary method of synthesising multidimensional data and identifying internally homogeneous groups (clusters) of regions according to the level of economic efficiency of agricultural production. This approach made it possible, with a high degree of analytical precision, to systematise the set of research objects according to a range of indicators, to determine the spatial characteristics of agricultural enterprise performance and to characterise the structural heterogeneity of the agricultural sector under wartime conditions. The classification of Ukraine's regions was conducted using the within-group means method (k-means algorithm), which was based on minimising distances between objects within clusters and maximising distances between cluster centroids. This method made it possible to identify latent patterns within large datasets and to produce an interpretable classification of regions according to the selected characteristics. The number of clusters (K = 4) was determined empirically on the basis of the balance between cluster homogeneity and the representativeness of the grouping. Calculations were conducted within 100 iterations in order to achieve a stable distribution of objects across groups.

The analytical base of the study encompassed statistical information published on the website of the State Statistics Service of Ukraine (n.d.) for 2022, pertaining to the activity of agricultural enterprises across all oblasts of Ukraine. The following indicators were used for classification, characterising the economic efficiency of enterprises per 1 hectare of agricultural land: X_1 – gross crop output, UAH thousand; X_2 – gross livestock output, UAH thousand; X_3 – revenue, UAH thousand; X_4 – profit (loss), UAH thousand; X_5 – capital investment, UAH thousand; X_6 – investment attraction ratio, kopiyky per UAH of revenue; X_7 – return on total activity, %; X_8 – return on capital, %; X_9 – return on equity, %. All indicators were of a relative character, which ensured correct comparison of regions with differing areas of agricultural land. The selection of these parameters in particular was determined by their significance for assessing enterprise performance and their representativeness under the conditions of transformational pressure on the sector in the context of full-scale war (2022-2025). The application of the cluster approach made it possible not only to identify the typology of the territorial development of agricultural production but also to characterise the nature of the wartime factor's influence on enterprise economic efficiency across regions, which was of importance for substantiating adaptation strategies and formulating support policies.

▸ Results and Discussion

Russia's military aggression against Ukraine, which commenced in 2022, transformed the institutional structure, dynamics, priorities and resultant indicators of agrarian entrepreneurship development, as well as its role in guaranteeing national food security. Entrepreneurship, as an important market institution, embodied the concepts of innovativeness, realising the functional role of innovation creation and diffusion, and constituted the organisational-economic foundation for ensuring the sustainable development of rural territories. The capacity to achieve sustainability depended directly on the performance and qualities of entrepreneurship, which were shaped under the influence of institutional policy and stimulation mechanisms, the subjects of which were the state and the market. The war, having created risks for agricultural business, formed an environment of general compulsion for producers to restructure economic management systems, to reorganise and to relocate – an accelerated transformation involving the adaptation of entrepreneurial activity institutions in connection with the movement of the economy and the state towards the coalitions of the European Union, whose market in 2022 became established as the primary and largest market for the sale of Ukraine's agri-food sector products.

As a result of analysing the principal problematic factors relating to the agricultural sector, a structural – specifically institutional – model was identified that projected the potential level of entrepreneurial efficiency. Attention was focused on this aspect in the course of analysing the composition of economic entities and assessing the institutional efficiency of organisational forms according to criteria of their adaptation to wartime conditions. In this regard, the institutional capacity of various forms to perform economic and social functions was manifested, demonstrating the competitive viability of entrepreneurial projects. The efficiency of agricultural enterprises was examined through an understanding of the functional role of their organisational-legal forms. Under force majeure circumstances and market turbulence caused by Russian military aggression, organisational form was of significance for: achieving entrepreneurial resilience and a balanced cost–benefit ratio; preserving production capacity; and readiness to rationally relocate business. In this context, aspects of institutional efficiency were delineated, since the organisational-legal form conditioned the statuses, norms and traditions within which, and under the influence of which, an enterprise functioned and achieved certain results. The formation of the Ukrainian entrepreneurship model proceeded in an evolutionary manner (Table 1).

Table 1. Characteristics of the entrepreneurial management model in the agricultural sector of Ukraine's economy

Period	Enterprise subject structure
Before 1991 (Soviet era)	Agricultural enterprises, by organisational-legal form – collective farms and state farms
1991-1999 (early period of Ukrainian independence)	Agricultural enterprises, by organisational-legal form – collective agricultural enterprises, state enterprises. Farming enterprises
1999-2005 (period of formation, consolidation and development of the institutional model of entrepreneurial management)	Agricultural enterprises, by organisational-legal form – business partnerships, agricultural cooperatives, private and state enterprises. Farming enterprises
2006-2025 (period of development of integrated corporate-type structures through attracted, including foreign, capital)	Large-scale integrated corporate-type structures. Agricultural enterprises, by organisational-legal form – business partnerships, agricultural cooperatives, private and state enterprises. Farming enterprises. Small family farming enterprises and household farms

Source: compiled by the authors

Market transformations made it possible to form a powerful entrepreneurial sector in Ukrainian agriculture, capable of realising the favourable potential of Ukraine's natural and climatic conditions in producing quality goods with high competitiveness on global food markets. The development of the export potential of Ukrainian agricultural producers was facilitated by foreign policy directed towards integration into the European Union. The importance of the European Union's single agricultural product market for Ukrainian exporters can hardly be overestimated, both in view of its convenient geographical location and developed logistics, and in view of the substantial volume of solvent demand. Prior to the commencement of the active phase of armed aggression in 2022, the combined market of European Union countries had, in 2021, become the world's third largest importer of agri-food products, second only to China and the United States. Total external purchases of agricultural products amounted to USD 199 billion (9.1% of global agricultural imports), in which Ukraine's share reached 3.9%, a high figure considering that the European Union had become the world's largest exporter of agricultural products. Over the period from 2017, when the Association Agreement between Ukraine and the EU came fully into force, to 2021, exports of Ukrainian agricultural products grew at an average annual rate of 12.6% and reached USD 27.7 billion (State Statistics Service of Ukraine, n.d.). Alongside this, agricultural exports were concentrated on a narrow range of goods: grain crops (wheat and maize), vegetable oil and meal, and oilseed crops (soya and rapeseed), whose combined share as of 2021 reached 85%. It should be noted that this tendency was maintained during the acute phase of military aggression (after 2022) (Fig. 1).

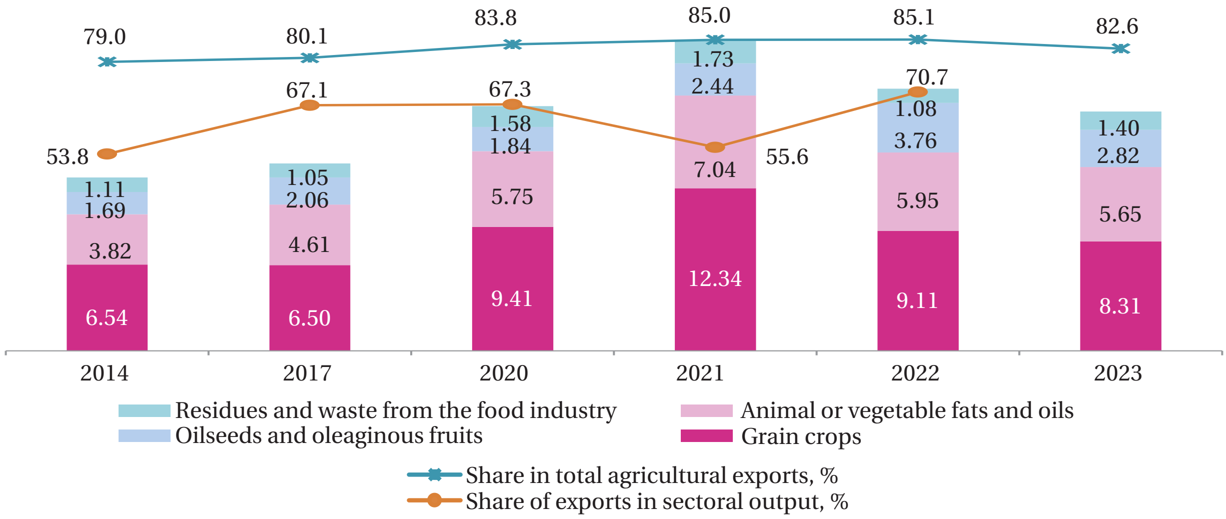

Figure 1. Dynamics of Ukraine's agricultural exports by major commodity groups, USD billion
Source: State Statistics Service of Ukraine (n.d.)

The orientation of Ukraine's agricultural sector towards a narrow commodity export segment conferred advantages from production specialisation, but entailed significant risks associated both with the intensification of competition in target sales markets and with the disruption of traditional supply chains for these products as a result of crises linked to the worsening of the geopolitical situation. Given that exports accounted for up to 70% of total sectoral output, changes in export volumes directly affected the functioning of Ukraine's agricultural sector as a whole (Fig. 2).

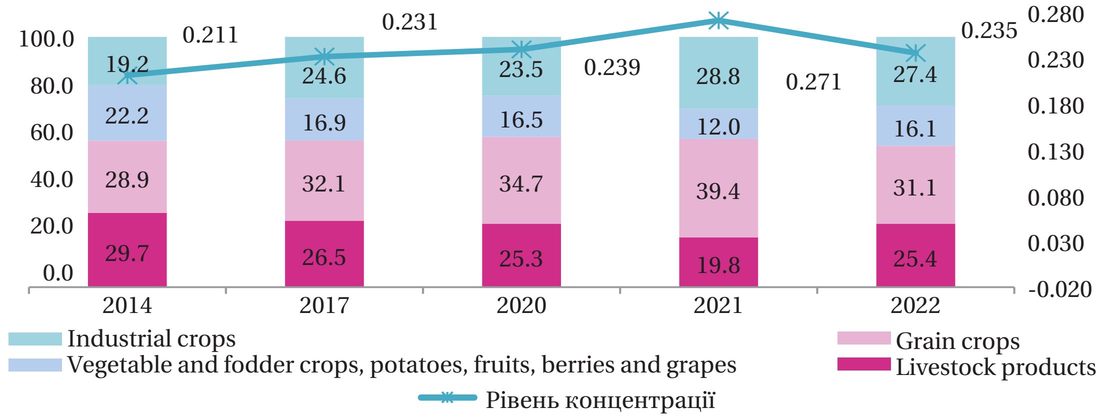

Figure 2. Structure and concentration level of agricultural output (across all categories of farm households), %
Source: State Statistics Service of Ukraine (n.d.)

From 2014, the structure of agricultural output underwent substantial changes. The share of grain crops rose from 28.9% to 39.4%, and the share of industrial crops increased from 19.2% to 28.8% in 2014 and 2021 respectively. In 2022, when exports were impeded by the disruption of traditional logistical routes, the share of grain and industrial crops in this period stood at 31.1% and 27.4% respectively. The calculated specialisation coefficients indicated their growth in 2014-2021 within a range corresponding to the average level of 0.211, whilst in 2012-2013 the value stood at 0.196-0.201, indicating a low level of specialisation (State Statistics Service of Ukraine, n.d.). The growth in the level of specialisation was driven by agricultural producers' aspiration to concentrate efforts on the production of high-margin goods in demand on external markets, in the absence of alternative state policy incentives. Given that raw materials with low added value were being exported, this tendency was to be considered negative at the sectoral level, as it carried risks of a reduction in the level of national food security and a decline in the incomes of sector participants as a result of deteriorating export conditions.

At the level of Ukraine's agricultural enterprises, this tendency was manifested even more acutely. Unlike household farms, which operated to meet the population's food needs, entrepreneurial structures were directed exclusively towards the maximisation of profit through the production of export-oriented crop products: the combined share of grain, grain-legume and industrial crops over the period from 2019 to 2023 fluctuated at the level of 78.6-82.6%, and specialisation coefficients stood at 0.33-0.36, gravitating towards a high level of specialisation (State Statistics Service of Ukraine, n.d.). The production structure of agricultural enterprises was formed accordingly – concentration on three crops occurred: sunflower, wheat and maize, whose combined share in sown area grew from 65.3% in 2014 to 75.9% in 2021, and concentration coefficients from 0.184 to 0.215 respectively (Fig. 3). With the beginning of the active phase of Russia's military aggression against Ukraine, the share of wheat and maize decreased, which was associated with a decline in the economic efficiency of their cultivation due to the complication of export conditions caused by the destruction of traditional logistics routes.

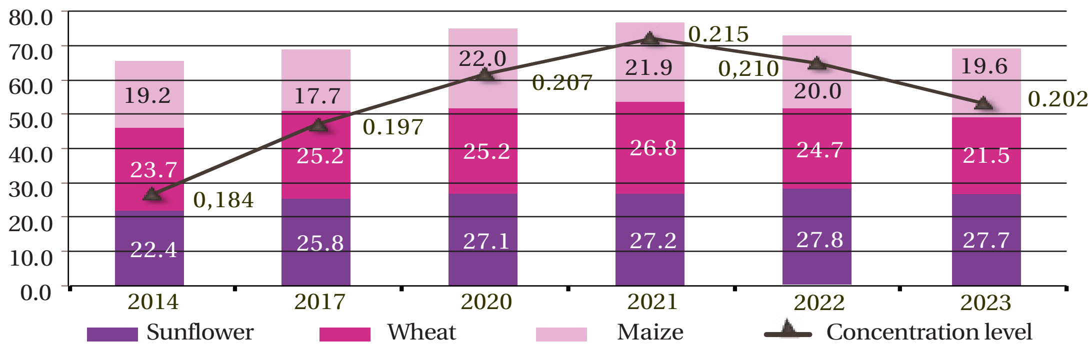

Figure 3. Share of sown areas under wheat, maize and sunflower and the concentration level in total sown area of agricultural enterprises, %
Source: State Statistics Service of Ukraine (n.d.)

In the relatively favourable period before 2022 – the beginning of the acute phase of military aggression – such a level of concentration was justified by increased revenues of enterprises resulting from favourable conditions in global agricultural commodity markets. Since 2014, the volumes of produced and sold output, as well as the value added of enterprises in the sector, had been growing at a high rate, and during 2019-2021 value added began to grow at a rate exceeding that of sales volumes. This stimulated sector enterprises to expand sown areas – by 1.4 million hectares from 2014 (State Statistics Service of Ukraine, n.d.). The number of enterprises in the sector grew until 2020, when a general decline in business activity began, caused by the onset of the COVID-19 pandemic. Alongside this, specialisation in less labour-intensive types of crop products led to a 15% reduction in the number of persons employed in the sector. With the onset of the acute phase of Russia's military aggression against Ukraine (from February 2022), owing to occupation, bombardment, contamination with explosive ordnance and a significant deterioration in the economic conditions of farming, the resource base of agricultural enterprises was substantially reduced. Compared with average values for 2019-2023, by 2023 a loss of 16.3% of sown area and 22,700 employed workers was recorded, the number of active enterprises declined by 16.8%, whilst volumes of produced and sold output remained unchanged against a background of rising food prices and exchange rate. Value added declined sharply in 2022-2023, which narrowed the financial base for the development of agricultural enterprises. Table 2 summarises the key data on the development of enterprises not only in agriculture as a whole but also in hunting and related services.

Table 2. Key development indicators of agricultural, hunting and related service enterprises

Indicators	2014	2015	2015 relative to 2014	Rate of change, 2016-2018	2019	2021	Rate of change, 2019-2021	Average for 2019-2021	2022/2023	2022/2023 relative to average for 2019-2021
Volume of produced output, UAH billion	273.5	394.6	144.3	113.3	592.0	974.9	119.3	733.8	706.8/734.4	96.3/100.1
Volume of sold output, UAH billion	213.9	362.3	169.4	113.2	556.3	918.7	120.5	693.5	680.5/780.1	98.1/112.5
Value added, UAH billion	125.5	183.9	146.6	103.2	205.4	521.3	137.2	330.1	278.3/246.0	84.3/74.5
Number of enterprises, thousand units	46.0	46.7	101.6	102.6	50.2	47.8	98.2	49.1	32.8/40.9	66.8/83.2
Number of employed workers, thousand persons	628.9	597.6	95.0	99.1	566.7	535.7	97.3	545.7	454.5/422.0	83.3/77.3
Sown areas, million ha	18.9	18.8	99.2	101.2	19.7	20.3	101.4	19.9	16.5/16.7	82.8/83.7

Source: State Statistics Service of Ukraine (n.d.)

The performance of Ukraine's agricultural enterprises was shaped at the regional level where, despite equal institutional and economic conditions, characteristic features of a natural-climatic and sociocultural nature determined the specific character of entrepreneurship development within these territorial complexes. From 2014, wartime risks were added to these factors, which constrained entrepreneurial activity in regions affected by the war in eastern Ukraine. Therefore, in order to obtain substantiated conclusions regarding the interdependence of the established structure of Ukraine's agriculture and its performance characteristics, the structural analysis was deepened by an examination of the spatial features of agricultural sector enterprise functioning. To address the problem of synthesising multidimensional characteristics of regional conditions for agricultural enterprise development, the apparatus of cluster analysis was employed.

The cluster classification of Ukraine's regions according to indicators of agricultural enterprise activity in 2022 yielded 4 clusters. Cluster 1 comprised Vinnytsia, Zhytomyr, Kirovohrad, Sumy and Chernihiv regions; Cluster 2 comprised Volyn, Zakarpattia, Ivano-Frankivsk, Lviv, Rivne, Ternopil, Khmelnytskyi, Cherkasy and Chernivtsi regions; Cluster 3 comprised Dnipropetrovsk, Mykolaiv, Odesa and Kharkiv regions. The average performance indicators of enterprises in Cluster 4 (Donetsk, Zaporizhzhia, Luhansk and Kherson regions) proved to be the worst. Enterprises in these regions suffered most severely from hostilities and incurred the greatest losses. It should be noted that from 2014 the average indicators of all four clusters remained at a fairly high level: the wartime factor's influence on the agricultural sector was of a localised character – at that time only individual districts of Luhansk and Donetsk regions were occupied, the economic activity of which was predominantly of an industrial specialisation. Nevertheless, from 2014 onwards differences in the development of the resource base of agricultural enterprises across the different clusters could already be observed (Table 3).

Table 3. Resources by cluster

Clusters	2014	2015	Rate of change, 2014-2015	Rate of change, 2016-2018	2019	2021	Rate of change, 2019-2021	Average for 2019-2021	2022/2023	2022/2023 relative to average for 2019-2021
Number of enterprises, thousand units										
Cluster 1	11.4	11.6	101.9	103.0	13.0	12.9	100.4	12.9	11.0/12.5	85.3/96.6
Cluster 2	13.3	13.4	100.9	102.8	14.5	14.1	99.0	14.3	10.7/12.9	74.9/89.7
Cluster 3	13.9	14.4	103.1	102.2	14.9	13.5	95.7	14.3	9.6/11.8	66.6/82.1
Cluster 4	7.4	7.4	99.5	102.4	7.8	7.3	97.5	7.6	1.5/3.8	20.3/50.0
Number of employed workers, thousand persons										
Cluster 1	206.8	197.5	95.5	98.4	185.5	176.5	97.9	179.6	167.6/147.9	93.4/82.3
Cluster 2	204.4	196.7	96.2	100.7	197.7	182.6	96.9	188.1	181.8/181.7	96.6/96.6
Cluster 3	129.9	122.3	94.1	97.8	108.7	103.3	96.6	104.1	84.9/79.2	81.5/76.1
Cluster 4	87.8	81.2	92.4	98.6	74.7	73.3	98.0	73.9	20.2/13.2	27.3/17.9
Sown areas, million ha										
Cluster 1	6.22	6.31	101.4	100.8	6.53	6.72	101.3	6.63	6.54/6.46	98.6/97.4
Cluster 2	4.39	4.38	99.8	101.9	4.68	4.85	101.6	4.77	4.85/4.81	101.7/100.9
Cluster 3	4.90	4.88	99.5	100.7	5.03	5.10	100.8	5.01	4.37/4.90	87.3/97.8
Cluster 4	3.40	3.21	94.3	101.8	3.43	3.58	102.0	3.50	0.72/0.50	20.7/14.2

Source: State Statistics Service of Ukraine (n.d.)

Favorable conditions on global agricultural markets led to the expansion of sown areas and the growth in the number of enterprises across Ukraine. The full-scale invasion of 2022 caused catastrophic changes in the operating conditions of agricultural enterprises, primarily in regions where occupation and active hostilities took place, as well as those bordering them. In 2022, Clusters 3 and 4 respectively recorded 33.4% and 79.7% fewer active enterprises compared with the 2014-2021 period. Sown areas there contracted by 12.7% and 79.3% respectively. In contrast, in regions belonging to Clusters 1 and 2 it proved possible to preserve the productive foundation of agricultural entrepreneurship. In 2023, sown areas were restored in regions belonging to Cluster 3; however, in Cluster 4 the contraction of sown areas continued. A negative tendency was the contraction of areas in regions belonging to Cluster 2, which had not been directly affected by hostilities. Changes in the resource base of agricultural enterprises were correspondingly reflected in the performance of economic activity (Table 4).

Table 4. Performance by cluster

Clusters	2014	2015	2015 relative to 2014	Rate of change, 201612018	2019	2021	Rate of change, 2019–2021	Average for 2019-2021	2022/2023	2022/2023 relative to average for 2019-2021
Volume of produced output, UAH billion										
Cluster 1	93.3	147.3	157.9	110.7	205.9	412.9	127.4	284.1	268.1/ 283.6	94.3/ 99.8
Cluster 2	98.2	128.2	130.6	117.5	220.7	297.9	112.7	246.6	295.1/ 306.1	119.7/ 124.2
Cluster 3	51.9	76.6	147.4	111.5	104.0	163.7	115.5	125.0	119.5/ 134.0	95.6/ 107.2
Cluster 4	30.0	42.5	141.6	112.1	61.4	100.4	118.8	78.1	24.0/ 10.6	30.8/ 13.6
Volume of sold output, UAH billion										
Cluster 1	68.6	132.9	193.8	108.6	191.1	381.8	131.0	260.6	246.6/ 281.4	94.6/ 108.0
Cluster 2	80.2	123.6	154.1	118.7	213.6	296.5	112.8	245.5	305.1/ 355.7	124.3/ 144.9
Cluster 3	40.8	68.3	167.2	111.7	96.6	149.0	116.1	115.7	105.4/ 132.2	91.1/ 114.3
Cluster 4	24.4	37.6	154.2	112.2	55.1	91.3	119.8	71.8	23.4/ 10.7	32.6/ 15.0
Value added, UAH billion										
Cluster 1	40.5	70.2	173.2	92.7	53.7	249.7	164.7	133.9	103.4/ 84.5	77.3/ 63.1
Cluster 2	48.1	61.5	127.9	112.1	98.0	145.2	118.8	112.8	111.0/ 111.5	98.4/ 98.9

Table 4, Continued

Clusters	2014	2015	2015 relative to 2014	Rate of change, 201612018	2019	2021	Rate of change, 2019–2021	Average for 2019-2021	2022/2023	2022/2023 relative to average for 2019-2021
Value added, UAH billion										
Cluster 3	24.7	34.7	140.3	106.1	35.7	77.0	123.0	51.8	50.4/ 46.2	97.4/ 89.2
Cluster 4	12.1	17.5	144.5	101.2	18.0	49.4	139.7	31.7	13.5/ 3.9	42.5/ 12.3

Source: State Statistics Service of Ukraine (n.d.)

The period from 2014 to 2021 was characterised by high rates of growth in the value-based results of agricultural enterprise economic activity; however, in the spatial dimension these indicators changed unevenly. Cluster 1 demonstrated the greatest amplitude of changes, where accelerated growth in volumes of sold output alternated with periods of the greatest decline. With the onset of the acute phase of military aggression, the indicators of Cluster 4, comprising the most severely affected regions, declined catastrophically and continued to fall in 2023. In regions belonging to Cluster 2, agricultural enterprises managed to restore growth rates in production and sales volumes to a level corresponding to prevailing inflation rates, thereby maintaining value added at the average level for 2014-2021. Enterprises of Cluster 3, despite the decline in production volumes in 2022, ensured positive development dynamics in 2023, arresting the fall in value added at 11% below the average level for 2019-2021. In contrast, in regions belonging to Cluster 1 a decline in production volumes continued, alongside a corresponding fall in value added of 36.9% compared with the average level for 2014-2021 (State Statistics Service of Ukraine, n.d.). Considering that these included regions distant from the zone of hostilities and taking into account the preceding trends in performance changes, the hypothesis regarding the influence of the level of production specialisation on the resilience of agricultural enterprises under adverse conditions became relevant. Given the concentration of Ukrainian agricultural enterprises primarily on the production of crop products and the absence of current statistical information, the assessment of the level of specialisation at the regional and cluster level was carried out using the indicator of the concentration level of sown areas under individual agricultural crops: sunflower, wheat and maize (Table 5).

Table 5. Concentration level of sown areas under sunflower, wheat and maize in agricultural enterprises by cluster

Clusters	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Cluster 1	0.198	0.200	0.208	0.208	0.208	0.225	0.245	0.246	0.228	0.215
Cluster 2	0.172	0.177	0.177	0.177	0.177	0.182	0.195	0.201	0.194	0.181
Cluster 3	0.228	0.253	0.254	0.254	0.254	0.248	0.253	0.269	0.263	0.236
Cluster 4	0.216	0.274	0.268	0.268	0.268	0.249	0.270	0.275	0.323	0.346

Source: State Statistics Service of Ukraine (n.d.)

Following the characterised general tendencies towards the growth in the shares of sunflower, wheat and maize sown areas, agricultural producers chose between strategies of deepening specialisation to maximise profits or diversification to reduce risks, depending on the natural-climatic potential of the territory and the economic-organisational capabilities of the region's enterprises. The spatial differentiation of economic conditions for entrepreneurship development was determined by the characteristics of social and human capital in individual territories, the presence of large-scale integrated structures and the distance from the zone of hostilities. The calculated cluster indicators of sown area concentration clearly demonstrated the specific features of the current territorial zoning of agricultural production. Clusters 3 and 4 were characterised by high concentration coefficients compared with the remaining clusters and encompassed the arid southern and eastern regions of Ukraine. Concentration on less water-demanding crops – wheat and sunflower, and in Odesa, Mykolaiv and Kherson regions on barley – pursued the objective of optimising costs per unit of produced output. Regions belonging to Cluster 1 were well supplied with moisture, which made it possible to maximise revenue per unit of sown area by combining high-margin crops – maize, sunflower and wheat. Clusters 1, 3 and 4 were represented by regions in whose economic system agro-holdings occupied a prominent position – structures that had powerful financial resources for compensating revenue losses during adverse periods. In contrast, the mental and cultural-historical characteristics of the rural population of western regions belonging to Cluster 2 promoted the development of individual forms of entrepreneurship which, in the absence of a powerful financial base, diversified production to guard against the risks of adverse market conditions. The difference in the performance of the aforementioned strategies was demonstrated by graphs of the dynamics of sold output volumes and value added per unit of sown area (Fig. 4).

The strategies of Clusters 3 and 4 yielded small but stable levels of revenue and value added per unit of cultivated area. Concentration on high-margin crops in Cluster 2 under favourable conditions made it possible to achieve significant growth in value added per 1 ha of sown area; however, in dynamic terms this indicator demonstrated considerable volatility, and in adverse periods declined to the level of the preceding clusters. The most successful proved to be the diversification strategy, which ensured stable performance indicators, demonstrated relative resilience to crisis economic conditions and, over the long term, made it possible to accumulate a greater mass of value added from agricultural activity. Alongside this, the aforementioned strategies led to fundamentally different outcomes under conditions of wartime uncertainty. The performance of agricultural enterprise economic activity across clusters exhibited differences, which were characterised by calculated losses. The corresponding assessment of these losses is presented in Table 6 – using the example of the principal agricultural crops (wheat, maize and sunflower).

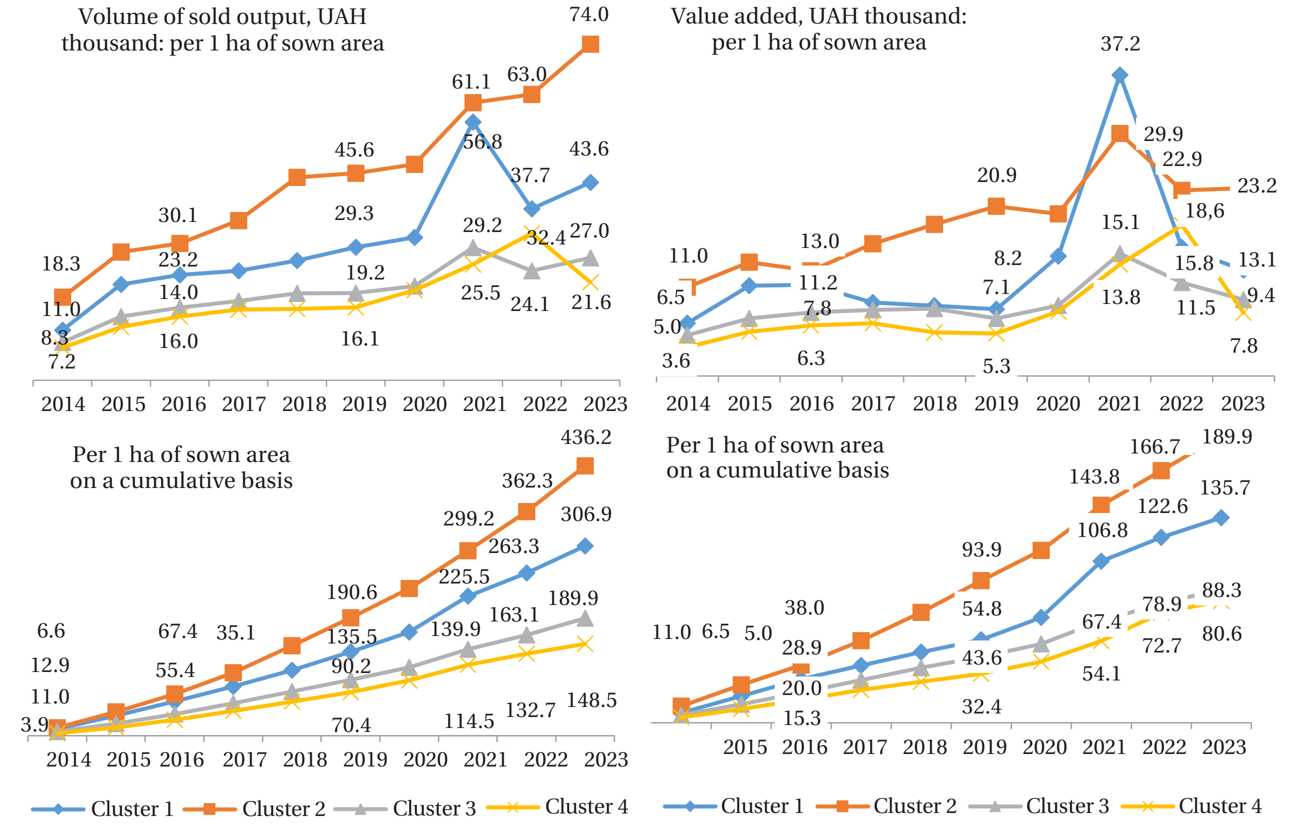

Figure 4. Performance of agricultural enterprise economic activity by cluster, UAH thousand
Source: State Statistics Service of Ukraine (n.d.)

Table 6. Estimated losses of agricultural enterprises by cluster due to changes in wheat, maize and sunflower production volumes (2022)

Clusters	Harvested area, thousand ha: average for 2019-2021	Harvested area, thousand ha: 2022	Yield, t/ha: average for 2019-2021	Yield, t/ha: 2022	Production volume, thousand tonnes in 2022: (actual)	Production volume, thousand tonnes in 2022: (estimated)	Total losses, million tonnes	Due to losses, million tonnes: area	Due to losses, million tonnes: yield losses	Value of losses, UAH billion
Wheat										
Cluster 1	1,158.2	1,217.9	49.1	44.7	5.45	5.69	-0.24	0.29	-0.53	-1.07
Cluster 2	970.2	978.8	53.3	51.8	5.07	5.17	-0.10	0.05	-0.15	-0.46
Cluster 3	1,704.2	1,520.6	39.2	32.6	4.96	6.69	-1.73	-0.72	-1.01	-7.66
Cluster 4	1,360.5	257.6	37.5	30.4	0.78	5.10	-4.32	-4.14	-0.18	-19.16
Total	5,193.1	3,974.9	43.6	40.9	16.26	22.65	-6.39	-4.52	-1.87	-28.35
Maize										
Cluster 1	2,374.3	1,753.9	73.5	68.3	11.98	17.46	-5.47	-4.56	-0.91	-23.40
Cluster 2	1,315.8	1,167.2	82.3	75.3	8.79	10.83	-2.04	-1.22	-0.81	-8.71
Cluster 3	417.8	296.1	54.0	49.9	1.48	2.26	-0.78	-0.66	-0.12	-3.34
Cluster 4	110.8	8.8	63.4	41.4	0.04	0.70	-0.67	-0.65	-0.02	-2.85
Total	4,218.6	3,226.0	74.1	69.1	22.29	31.25	-8.95	-7.09	-1.87	-38.29
Sunflower										
Cluster 1	1624.1	1927.6	27.9	24.3	4.69	4.53	0.16	0.85	-0.69	1.80

Table 6, Continued

Clusters	Harvested area, thousand ha		Yield, t/ha		Production volume, thousand tonnes in 2022		Total losses, million tonnes	Due to losses, million tonnes		Value of losses, UAH billion
	average for 2019-2021	2022	average for 2019-2021	2022	(actual)	(estimated)		area	yield losses	
Sunflower										
Cluster 2	780.3	939.9	30.1	26.2	2.46	2.35	0.11	0.48	-0.37	1.27
Cluster 3	1659.0	1401.4	22.1	17.7	2.48	3.67	-1.19	-0.57	-0.62	-13.43
Cluster 4	1202.7	197.9	19.8	17.9	0.35	2.38	-2.03	-1.99	-0.04	-22.85
Total	5266.1	4466.8	24.6	22.4	9.99	12.93	-2.94	-1.23	-1.71	-33.20

Source: State Statistics Service of Ukraine (n.d.)

Thus, complex transformations had occurred in agriculture and it continued to develop under difficult conditions; however, Ukraine had international support, which assisted in resisting external challenges. O. Goncharenko *et al.* (2023) outlined the introduction of new organisational management models in crop and livestock production based on integration principles and support of small farm operation, which contributed to sectoral resilience and competitiveness; even under the influence of the wartime factor, the sector followed the efficiency patterns of the sectoral production structure. D. Khalizov (2023) noted that, given that Ukraine had become one of the world leaders in the export of grain and oilseed crops, Russia's invasion had a significant impact on agriculture and food security throughout the world. In 2020-2021, Ukraine exported nearly 6 million tonnes of vegetable oil, accounting for over 47% of global sales of the product. The beginning of 2022 caused a shock on the global oilseed market: prices rose substantially and supply volumes declined. In February 2022, the global food price index reached a historic high following steady growth during 2019-2021. It was determined that the number of people suffering from inadequate food security worldwide could reach a 15-year high as a result of the consequences of the war and COVID-19. S. Moshenskyi *et al.* (2024) noted that these problems were substantially exacerbated under the conditions of full-scale war, which complicated the implementation of effective state agricultural policy. The temporary occupation of Ukrainian territories, contamination and mining of agricultural lands and the unstable front line led to a reduction in the production volumes of principal crops. Russia's military invasion caused a shortage of financial and material-technical resources – seeds, fertilisers and fuel – which made it impossible to maintain technological standards and reduced the areas of cultivated land.

K. Happe *et al.* (2008) emphasised that the effectiveness of state policy as a regulator depended on the structure of agricultural entities – their form, size and specialisation. Small agricultural business was considered the most adaptive to a turbulent market, demonstrating flexibility, resource mobility and innovative activity. M. Humeniuk *et al.* (2022) and O. Shpykuliak *et al.* (2024) reached the conclusion that small enterprises were capable of promptly changing their asset structure and introducing modern production organisation practices. In general, effective agricultural activity was required to be based not only on consideration of socioeconomic conditions but also on ecological responsibility. In the context of growing challenges associated with climate change, soil degradation and the depletion of natural resources, the concept of sustainable land use acquired particular relevance. U. Karbivska *et al.* (2024) noted that this implied not only conservation but also the active replenishment of energy and natural resources, as well as the restoration of agroecosystems, which became the foundation for long-term productivity and ecological balance. This required a balanced approach that ensured agriculture throughout the world was sustainable and beneficial to all stakeholders. From a social and economic perspective, the level of labour productivity became one of the key factors in developing competitive agricultural activity. Yu. Bilenko (2022) observed that the substitution of labour with other production factors was not always sufficient for its effective maximisation, particularly under conditions of workforce shortages caused by war and migration processes.

In the context of the infrastructural provision of competitive activity in the agricultural sector, agrologistics became important, acquiring critical significance under wartime conditions. H. Kryshtal (2023) noted that the organisation of effective logistical routes, the reconstruction of railway, road and waterway infrastructure, and ensuring quality product transportation became necessary conditions for the stable functioning of agricultural production. The war became a destabilising factor for all segments of the organisational-economic development of Ukraine's agricultural sector. O. Nechyporenko *et al.* (2022) warned that the physical destruction of enterprises, farming businesses and production capacities would lead to a decline in gross output volumes and a disruption of food security. One of the key directions for enhancing competitiveness was the introduction of a model of precision management of production and trade processes based on digitalisation. W. Liu *et al.* (2022) noted that the use of digital tools facilitated the coordination of supply chains, the innovative development of marketing, improved access to resources, the strengthening of production and distribution infrastructure and the enhancement of institutional support for the resilience of agricultural activity. Thus, Russia's military invasion had a significant impact on Ukraine's agriculture, resulting in a decline in production volumes, a disruption of food security and a deterioration of the economic situation. At the same time, innovative approaches became important for adapting to wartime conditions and maintaining the competitiveness of the agricultural sector, including sustainable development, digitalisation and the improvement of logistical processes.

▸ Conclusions

The structural analysis based on the cluster methodology made it possible to characterise the economics of the regional development of Ukraine's agricultural sector. It was established that the agrarian management system underwent deformation in accordance with the configuration of the resource base and the natural and economic conditions of the regions. In particular, as a result of the relocation of production facilities and enterprise management systems to safer areas, certain production capacities were lost or underwent unproductive relocation. It should be noted that the economic unviability, natural-climatic unsuitability and entrepreneurial inexpediency of cultivating certain types of products in a different region were evident. In particular, the physiological characteristics of certain agricultural crops cultivated by enterprises relocated from the occupied south of Ukraine were such as to render this process naturally and economically impractical.

Russia's war against Ukraine caused a deconcentration of production; in particular, in crop farming the resource-oriented model deepened, with a maximisation of the cultivation of export-oriented crops with a potentially stable positive sales margin. Traditionally, these include soya, sunflower and maize. Within the framework of this study, trends in the concentration of agricultural output were analysed and compared with the principal development trends of sector enterprises. To deepen the conclusions, the specific features of the formation of agricultural enterprise performance at the regional level were determined through a cluster analysis of the structure of Ukraine's agricultural production operating under wartime conditions. The results of the study demonstrate that in 2014-2021 the agricultural sector of Ukraine showed high growth rates: exports of agricultural products reached USD 27.7 billion with an average annual increase of 12.6%, while the structure of production was characterised by a high level of concentration, with up to 85% of exports accounted for by cereals, oilseeds and products of their processing. At the same time, the full-scale war caused losses to the sector's resource base: in 2023, compared with the average level of 2019-2021, sown areas decreased by 16.3%, the number of enterprises by 16.8%, and employment fell to 22.7 thousand workers. The relative resilience of enterprises across clusters under crisis economic conditions was assessed by estimating their calculated losses resulting from changes in the production volumes of wheat, maize and sunflower during the crisis caused by the onset of the acute phase of military aggression. The development of competitiveness in the agricultural sector slowed due to the decline in domestic demand for foodstuffs and the intensification of the polarisation of the socio-economic development of rural territories, characteristic of all natural-economic zones. The prospects for further research lie in conducting a structural analysis of competitiveness across agricultural enterprises of various organisational and legal forms and sizes.

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▸ Conflict of Interest

None.

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Структурний аналіз розвитку конкурентоспроможної сільськогосподарської діяльності в Україні за впливу умов воєнного часу

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▸ **Анотація.** Актуальність дослідження зумовлена необхідністю ідентифікації структурних змін в аграрному секторі, що відбулися в умовах війни, а також пошуком ефективних управлінських рішень, здатних забезпечити конкурентоспроможність аграрного підприємництва в нових економічних реаліях змінного інституційного середовища. Метою дослідження стало здійснення структурного аналізу ефективності сільськогосподарських підприємств у регіональному розрізі для визначення просторових закономірностей розвитку та ступеня впливу воєнного фактору на економічну результативність аграрного виробництва. У дослідженні використано метод кластерного аналізу, що дозволив згрупувати регіони України за рівнем економічної ефективності підприємств сільського господарства на основі багатовимірних статистичних показників, зокрема валової продукції, доходу, прибутковості, рівня рентабельності та інвестиційної активності у розрахунку на один гектар сільськогосподарських угідь. Результатом проведеного аналізу стало виокремлення чотирьох кластерів регіонів, які продемонстрували суттєві відмінності в рівні результативності діяльності підприємств, ресурсному забезпеченні та адаптації до воєнних умов. Встановлено, що найбільшої шкоди зазнали регіони з високим рівнем концентрації рослинницького виробництва, тоді як території з більш диверсифікованою структурою продемонстрували відносно вищу стійкість. У результаті дослідження в розрізі сформованих кластерів було проаналізовано ресурсну базу та результативність виробничої діяльності сільськогосподарських підприємств. Підтверджено гіпотезу дослідження щодо значного впливу спеціалізації виробництва на стійкість господарств в несприятливих інституційних умовах. Проаналізовано особливості актуальної територіальної зональності сільськогосподарського виробництва та ідентифіковано стратегії розвитку підприємств у розрізі відповідних кластерів. Визначено економічні ефекти функціонування сільськогосподарських підприємств, які розподілені за відповідними кластерами та встановлено зв'язок між рівнем спеціалізації і втратами сільгосппідприємств від погіршення умов господарювання в 2022 році. Практична цінність дослідження полягає у можливості використання отриманих результатів для розроблення цільових програм підтримки аграрного підприємництва, планування заходів з просторового розвитку галузі та формування політики відновлення сільського господарства в післявоєнний період

▸ **Ключові слова:** формування конкурентоспроможності; економічна ефективність; воєнний вплив; аграрне підприємництво; структурні зміни; просторовий розвиток

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