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Capital Investment, Financial Viability, and Sustainable Regional Agricultural Performance: Evidence from a Verified Regional Panel

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Abstract

Capital investment and the financial viability of agricultural producers are central to the economic pillar of sustainable agricultural development, yet regional evidence from verified administrative data remains limited. This study examines regional agricultural production performance in 20 Ukrainian oblasts over 2020–2025 using a balanced panel of 120 region-year observations. Performance is measured as the log geometric mean of five physical outputs: grain, oilseeds, milk, livestock liveweight for slaughter, and eggs. A pre-estimation data-consistency audit excluded agricultural land area and the number of agricultural producers, whose annual values were largely interpolated and strongly collinear. Fixed Effects estimates show that capital investment ($\beta = 0.131$, $p < 0.001$) and the share of profitable enterprises ($\beta = 0.005$, $p < 0.05$) are positively associated with production performance, while the 2022–2025 period is associated with an average conditional reduction of approximately 7.0%. Event-study estimates reveal a non-monotonic trajectory, with the largest reduction in 2024 (approximately −9.9%). The results remain stable under year fixed effects, Driscoll–Kraay standard errors, leave-one-regressor-out tests, cluster bootstrap intervals, dynamic specifications, structural-break validation, and placebo tests. The investment association also holds across alternative constructions of the composite indicator and in all macro-regions, whereas the association with financial viability is weaker, depends mainly on livestock outputs, and is absent in the central grain-producing oblasts. Because reverse causality cannot be excluded in this observational design, the estimates are interpreted as robust within-region associations rather than causal effects. The findings identify investment capacity as a robust correlate, and enterprise financial viability as a regionally conditioned correlate, of the economic-productive dimension of sustainable

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regional agricultural development and highlight data-quality auditing as a prerequisite for evidence-based policy.

Keywords: sustainable agricultural development; regional agricultural performance; capital investment; financial viability; fixed effects panel model; data-consistency audit; structural break; food security; regional development

1. Introduction

Sustainable agricultural development requires that regional farming systems maintain and expand their productive capacity while remaining economically viable and resilient to external disturbances. This objective is embedded in the 2030 Agenda for Sustainable Development, particularly in the targets related to food security, sustainable food production systems, and inclusive rural growth [1]. Recent global assessments emphasize that the economic sustainability of agri-food systems depends not only on natural resource endowments but also on the capacity of producers to invest, modernize, and absorb shocks [2]. In this context, the economic pillar of sustainability—productive capacity, investment, and financial viability—constitutes a necessary condition for achieving environmental and social objectives in agriculture.

The concept of sustainable intensification highlights that increases in agricultural output should be achieved primarily through more efficient use of existing resources, technological renewal, and improved organization of production rather than through the expansion of cultivated area [3,4]. At the sectoral level, productivity growth is closely associated with technological change and with more efficient use of productive inputs [5]. Capital accumulation is therefore a fundamental mechanism through which productive capacity and efficiency can expand [6,7]. In agriculture, capital investment supports machinery renewal, production infrastructure, storage facilities, and technological modernization, all of which affect the ability of regional agricultural systems to sustain output over time.

Regional economic theory provides a broader framework for understanding why similar national conditions generate different agricultural outcomes across territories. Regions differ in their productive structure, market accessibility, infrastructure, resource endowments, and capacity to adjust to changes in the operating environment [8,9]. Agricultural policy research further emphasizes that investment capacity and structural adjustment are essential for maintaining productive potential and facilitating modernization [10,11]. Competitiveness and productive efficiency also depend on the capacity of agricultural enterprises to transform available resources into economically viable output [12], while financial resilience affects the ability of producers to maintain operations, absorb adverse shocks, and preserve productive capacity under unstable conditions [13]. Land and soil resources define basic production opportunities [14,15], but resource availability alone does not guarantee stronger economic performance.

Ukraine provides a relevant empirical setting for examining these relationships. Agriculture is an important component of the national economy, contributing to food security, exports, rural employment, and regional development, and its regional production structure is highly heterogeneous across crop and livestock specializations [16]. During 2020–2025, Ukrainian agriculture also experienced a pronounced common structural shift in its operating environment, which makes it possible to examine whether investment and financial determinants of production performance remain stable when general conditions change substantially.

Empirical evidence on the investment–performance link is, however, less unequivocal than the theoretical argument suggests. Farm-level studies from Central and Eastern Europe based on Farm Accountancy Data Network microdata have estimated the net effects of pro-investment instruments of the Common Agricultural Policy on farm performance [17] and examined how investment changes the economic efficiency of production factors [18]; at the same time, this literature documents overinvestment, in which additional fixed assets are not matched by proportional growth in output [19]. Analyses at the level of the European Union show that the assessment of agricultural performance depends on which determinants are considered in addition to output [20], and that the financial structure of farms—debt, liquidity, and current assets—is related to profitability in ways that differ across regions and farm types [21]. Two questions therefore remain open: whether investment translates into growth of physical output or mainly into capital deepening with weak returns, and whether the financial viability of producers is associated with production performance independently of investment.

For Ukraine, the evidence base is dominated by two strands. The first quantifies losses of crop production with satellite and statistical data and concentrates on the most affected territories [22–24]; the second evaluates the international market consequences of disrupted exports [25] or documents losses, policy responses, and clusters of regions at the national level [26,27]. Enterprise-level analyses show that the financial and economic performance of agricultural enterprises has been destabilized by market and operating conditions despite their resource capacity [28]. Recent evidence also shows that development opportunities depend on regional agricultural and livestock production structures [29]. Comparatively little work has examined, on regional panel data covering the territories where production remained statistically observable, whether the economic determinants of physical output—investment and financial viability—remained stable when the operating environment changed, and whether these relationships differ across regions.

These relationships require an empirical framework capable of distinguishing changes occurring within regions from persistent differences between them. Panel-data methods provide such an opportunity by exploiting both cross-sectional and temporal variation while controlling for time-invariant regional heterogeneity [30–33]. At the same time, identification from within-region variation places strong requirements on data quality: interpolated or reconstructed annual observations may create artificial within-region changes and weaken the interpretation of estimated coefficients. This problem is rarely addressed explicitly in regional agricultural studies that rely on administrative statistics.

Against this background, several limitations of the existing evidence persist. Most regional studies rely on monetary output measures that are sensitive to inflation and price volatility, include structural scale variables without verifying the quality of their annual measurement, and assume that the relationships between investment, profitability, and production remain constant across periods. Consequently, there remains a need for an analytical framework that combines physical output measures, explicit screening of regressors for genuine within-region variation, and systematic tests of the temporal stability of the estimated relationships.

The aim of this study was to assess the association of capital investment and enterprise financial viability with regional agricultural production performance, as a key dimension of sustainable regional agricultural development, using a verified balanced panel of 20 Ukrainian oblasts for 2020–2025. The analysis addresses the economic-productive dimension of regional agricultural sustainability—productive capacity and the financial viability of producers—and does not provide a comprehensive measure of sustainability in its environmental, social, and economic sense. Accordingly, the study addresses three research questions:

RQ1. How strongly is capital investment associated with regional agricultural production performance?

RQ2. What relationship exists between enterprise financial viability and regional agricultural production performance?

RQ3. How is the common structural shift in the operating environment associated with regional production performance, and how robust are the estimated relationships across alternative specifications?

Relative to the literature reviewed above, the principal contribution of this study is threefold. First, it constructs a composite physical measure of agricultural production performance that limits dependence on monetary output indicators. Second, it introduces a pre-estimation data-consistency audit that screens candidate regressors for interpolation-generated variation before Fixed Effects estimation. Third, it combines the core Fixed Effects specification with a comprehensive set of inference, dynamic, temporal-identification, and measurement-validity checks within a unified analytical framework. In addition, the study examines the sensitivity of the results to the construction of the composite indicator and translates the estimated coefficients into region-specific contributions, linking the panel estimates to the regional dimension of agricultural policy.

2. Materials and Methods

Assessing the determinants of regional agricultural production performance requires analytical methods capable of separating persistent regional differences from within-region changes, while ensuring that the estimated relationships are not driven by measurement artefacts. This study therefore combines a data-consistency audit with Fixed Effects panel estimation and a structured set of robustness and identification checks.

Figure 1 presents the integrated analytical architecture developed for this study. The framework illustrates the compilation and auditing of the regional panel, the core estimation stage, the complementary robustness and identification checks, and the final synthesis used to formulate policy implications. The analytical framework is structured into four distinct phases.

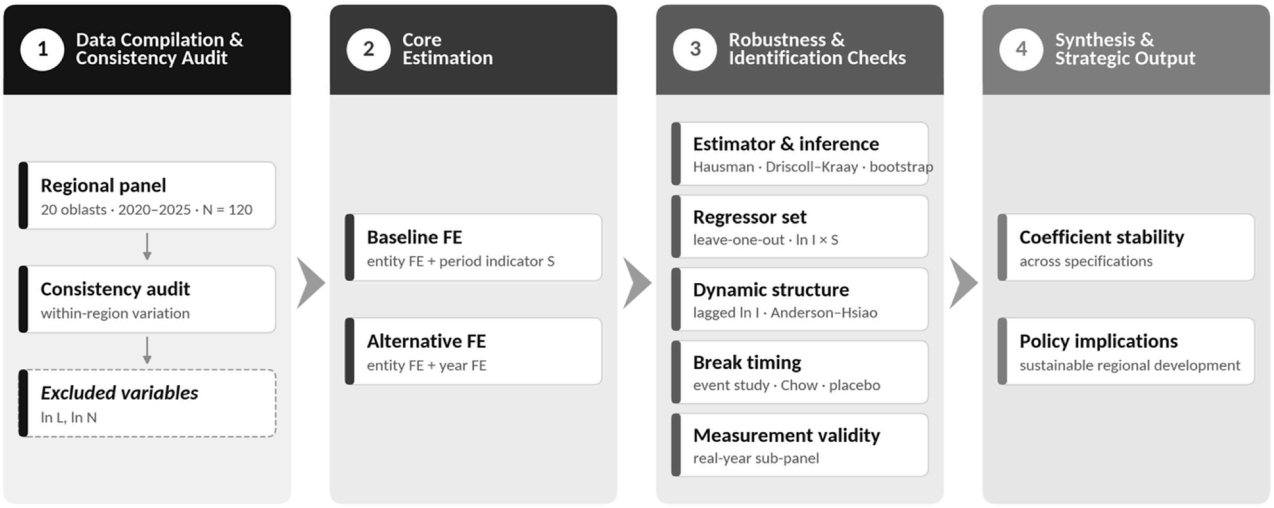


Figure 1. Analytical framework of the study: data compilation and consistency audit (Phase 1), core estimation (Phase 2), robustness and identification checks (Phase 3), and synthesis (Phase 4). Source: authors' elaboration.

Phase 1. Data Compilation and Consistency Audit. The process begins with the construction of a balanced regional panel comprising the dependent variable and all candidate explanatory variables. Each candidate regressor is screened for genuine within-region

annual variation. Variables whose year-to-year changes are predominantly generated by interpolation are excluded from the core specification.

Phase 2. Core Estimation. The baseline model is a Fixed Effects specification with region-specific intercepts and a common period indicator. An alternative specification replaces the period indicator with a complete set of year fixed effects.

Phase 3. Robustness and Identification Checks. The stability of the core estimates is assessed with respect to the choice of estimator and inference procedure, the composition of the regressor set, the dynamic structure of the investment–performance association, the timing of the structural break, and the measurement quality of the excluded variables.

Phase 4. Synthesis and Strategic Output. The final phase synthesizes the investment coefficients obtained across all specifications and derives evidence-based implications for sustainable regional agricultural development.

2.1. Study Area, Data Collection, and Data-Consistency Audit

The empirical analysis is based on a balanced panel covering 20 Ukrainian oblasts over 2020–2025, yielding 120 region-year observations. The panel framework enables the joint analysis of temporal dynamics and regional heterogeneity while controlling for unobservable, time-invariant region-specific characteristics [30,31]. Ukraine's first-level administrative structure comprises 24 oblasts, the Autonomous Republic of Crimea, and two cities with special status (Kyiv and Sevastopol). The national aggregate and the cities of Kyiv and Sevastopol were excluded because they do not represent comparable regional agricultural systems. Donetsk, Luhansk, Zaporizhzhia, and Kherson oblasts, together with the Autonomous Republic of Crimea, were excluded because consistent longitudinal regional statistics were not available for them over the full study period: for these territories, which were wholly or largely temporarily occupied or within the zone of active hostilities during part of 2020–2025, annual regional series for the variables used in this study are either missing or not comparable with pre-2022 values. The sample therefore comprises all 20 oblasts for which complete and consistent annual series exist for every variable over 2020–2025, which also keeps the panel balanced. Several retained oblasts (Chernihiv, Sumy, Kharkiv, and Mykolaiv) were directly affected by hostilities in 2022 but have complete annual series; their production disruptions are therefore reflected in the data rather than removed from the sample. Because the excluded regions are among those most exposed to the disruption of agricultural activity, the estimated period effect refers to the territories where agricultural production remained statistically observable and is likely to be a conservative estimate of the national shift.

The dataset was compiled from official statistical sources, including the State Statistics Service of Ukraine, regional statistical offices, and complementary official publications [34–42]. Table 1 presents the variables, their measurement, and the institutional data sources used in the study.

Every candidate explanatory variable was subjected to an internal consistency audit, comparing its year-to-year variation within each region against the pattern expected of independently measured annual statistics. Two candidate structural variables—agricultural land area and the number of agricultural producers—failed this audit. Their within-region annual series followed arithmetic-progression patterns indicative of interpolation, which was corroborated by spot-verification against regional statistical office publications. In addition, a leave-one-regressor-out test showed that the statistical significance of neither variable is robust to the exclusion of the other (Appendix A, Table A1). Both variables were therefore excluded from the core specification. The remaining explanatory variables—capital investment and the share of profitable agricultural enterprises—passed the same audit. One

component of the dependent variable (livestock liveweight for slaughter) showed a narrower, single-year version of the same artefact, which is discussed in Sections 3.7 and 4.7.

Table 1. Characterization of variables, indicators, and institutional data sources used in the study (2020–2025).

Code	Indicator	Unit/Transformation	Primary Institutional Source	Reference
Y	Agricultural Production Performance	Log of geometric mean of 5 outputs	State Statistics Service of Ukraine	[34,36,37]
ln I	Capital Investment in Agriculture	ln (million UAH)	Regional statistical offices	[35]
P	Share of Profitable Agricultural Enterprises	%	State Statistics Service of Ukraine	—
S	Period Indicator	0 = 2020–2021; 1 = 2022–2025	Constructed by the authors	—
ln L	Agricultural Land Area (candidate, excluded)	ln (thousand ha)	State Statistics Service of Ukraine	[36]
ln N	Number of Agricultural Producers (candidate, excluded)	ln (units)	Regional statistical offices	[42]

Note: ln, natural logarithm; UAH, Ukrainian hryvnia; — no separate bibliographic reference (the share of profitable agricultural enterprises is taken from the official annual financial-results statistics of the State Statistics Service of Ukraine; the period indicator is constructed by the authors). Source: authors' elaboration based on official statistical sources [34–42].

2.2. Variable Selection and Measurement

Continuous variables exhibiting substantial positive skewness were transformed into natural logarithms to reduce heteroskedasticity, improve distributional properties, and facilitate elasticity-based interpretation of the estimated coefficients [31,33].

Dependent variable. Regional Agricultural Production Performance (Y) is constructed as the logarithm of the geometric mean of five production components:

$$Y_{it} = \frac{1}{5}\sum_{k=1}^{5} lnQ_{kit}\,, \tag{1}$$

where

Y_{it} denotes the integrated agricultural production performance of oblast i in year t;

Q_{kit} denotes production component k: grain production, oilseed production, milk production, livestock liveweight for slaughter, and egg production.

This transformation places heterogeneous production components within a common analytical framework without mechanically summing quantities measured in different physical units, and it reduces the direct influence of inflation and price volatility on the dependent variable. By combining crop and livestock outputs, the indicator reflects the overall productive capacity of regional agricultural systems, which is a core component of the economic-productive dimension of agricultural sustainability. Because equal weighting of the five components is itself a modelling choice [43], the sensitivity of the results to the construction of the indicator is examined in Section 2.7.

Explanatory variables. Capital investment (ln I) is measured as the natural logarithm of capital investment in agriculture (million UAH); a positive association is expected [5,10,11]. The share of profitable agricultural enterprises (P, %) is retained in its original scale as a measure of enterprise financial viability; a positive association is expected [12,13].

Period indicator. The period indicator S takes the value of 0 for 2020–2021 and 1 for 2022–2025. It captures a common structural shift in the national operating environment for agriculture—including changes in input and output markets, logistics, and production conditions—that affected all regions simultaneously. Because S varies only over time, it is interpreted as a common period effect rather than as the effect of any single cause; its

role is to prevent the investment and profitability coefficients from absorbing this shift. A negative coefficient is expected.

Fixed effects. Regional fixed effects control for time-invariant regional characteristics [30,31]. Year fixed effects are employed in an alternative specification in place of S, since S is itself defined exclusively by temporal variation.

2.3. Fixed Effects Model Specification

The core relationship is estimated using the following Fixed Effects specification:

$$Y_{it} = \alpha_i + \beta_1 \, ln \, I_{it} + \beta_2 \, P_{it} + \beta_3 \, S_t + \varepsilon_{it}, \quad (2)$$

where

α_i denotes the region-specific fixed effect;

$\ln I_{it}$ represents the logarithm of capital investment in agriculture;

P_{it} denotes the share of profitable agricultural enterprises;

S_t is the period indicator;

ε_{it} is the idiosyncratic error term.

The coefficients β_1, β_2, and β_3 measure the within-region relationship between changes in the corresponding explanatory variables and changes in agricultural production performance. Specification and residual diagnostics follow standard panel-data practice [44]. The choice between Fixed and Random Effects is evaluated using the Hausman test [45]. Residual diagnostics include the Modified Wald test for groupwise heteroskedasticity, the Wooldridge test for first-order serial correlation [46], and the Pesaran CD test for cross-sectional dependence [47]. Given these diagnostics, inference is based on heteroskedasticity-robust standard errors, complemented by Driscoll–Kraay standard errors [48] and region-level cluster bootstrap confidence intervals (1000 replications) [49].

2.4. Dynamic Specifications

To test whether the association between capital investment and production performance is contemporaneous or delayed, Equation (2) is re-estimated with $\ln I_{it}$ replaced by its one-year lag:

$$Y_{it} = \alpha_i + \beta_1 \, ln \, I_{i,t-1} + \beta_2 \, P_{it} + \beta_3 \, S_t + \varepsilon_{it}, \quad (3)$$

In a nested specification, both terms are entered jointly to test whether the contemporaneous association persists after conditioning on its own lag.

To assess the persistence of production performance while addressing the endogeneity that a lagged dependent variable introduces under Fixed Effects, Equation (2) augmented with $Y_{i,t-1}$ is first-differenced to eliminate α_i [50]:

$$\Delta Y_{it} = \rho \Delta Y_{i,t-1} + \beta' \Delta X_{it} + \Delta \varepsilon_{it}, \quad (4)$$

where

Δ denotes the first-difference operator;

ρ is the persistence parameter;

X_{it} is the vector of explanatory variables.

Because $\Delta Y_{i,t-1}$ is mechanically correlated with $\Delta \varepsilon_{it}$, it is instrumented with the twice-lagged level $Y_{i,t-2}$, which is uncorrelated with $\Delta \varepsilon_{it}$ under the assumption of no serial correlation in ε_{it}, and Equation (4) is estimated by two-stage least squares. Because the cross-sectional dimension (20 regions) limits attainable instrument strength, the first-stage F-statistic is reported, and the results are treated as corroborative rather than as the primary source of identification [51,52].

2.5. Temporal Identification Checks: Event Study, Structural Break, and Placebo Test

To trace the year-by-year trajectory of the period effect rather than imposing a constant average, S_t in Equation (2) is replaced with separate year indicators relative to the 2020–2021 reference period:

$$Y_{it} = \alpha_i + \beta_1 \ln I_{it} + \beta_2 P_{it} + \sum_{\tau} \delta_\tau D_{\tau,it} + \varepsilon_{it}, \quad \tau \in \{2022, 2023, 2024, 2025\} \tag{5}$$

where $D_{\tau,it} = 1$ if $t = \tau$ and 0 otherwise, so that each δ_τ measures the deviation of year τ from the reference period.

The choice of 2022 as the break date defining S_t was validated using a Chow-type comparison [53]. Equation (2) was re-estimated with the break year k alternately set to 2021, 2022, 2023, and 2024, defining $S_t(k) = 1\{t \geq k\}$, and the resulting within-R^2 and residual sums of squares were compared:

$$k^* = \underset{k}{\operatorname{argmin}} RSS(k), \quad k \in \{2021, 2022, 2023, 2024\} \tag{6}$$

In addition, a permutation-based placebo test [54] was conducted. The observed indicator was randomly reshuffled across all region-year observations to generate $B = 500$ placebo assignments. Equation (2) was re-estimated on each, and the empirical permutation p-value was computed as follows:

$$p = \frac{1}{B} \sum_{b=1}^{B} 1\left[\left|\hat{\beta}_3^{(b)}\right| \geq \left|\hat{\beta}_3\right|\right] \tag{7}$$

where $\hat{\beta}_3$ is the coefficient obtained using the correctly dated indicator.

2.6. Real-Year Reconstruction of Agricultural Land Area and the Number of Agricultural Producers

To verify that the exclusion of agricultural land area and the number of agricultural producers is not solely an artefact of interpolation, both variables were reconstructed using only the years for which regional statistical reference tables report genuinely observed values (2022, 2023, and 2025). This yields an unbalanced three-year sub-panel on which Equation (2) is re-estimated with $\ln L_{it}$ and $\ln N_{it}$ restored, together with a leave-one-regressor-out check.

2.7. Sensitivity of the Composite Indicator and Regional Heterogeneity

Three checks address the construction of the dependent variable. First, Equation (2) was re-estimated five times, each time excluding one component from the geometric mean (leave-one-component-out). Second, separate crop (grain and oilseeds) and livestock (milk, liveweight for slaughter, and eggs) sub-indices were used as dependent variables. Third, an alternative composite was computed as the mean of standardized (z-score) log outputs, which removes the implicit weighting of components by their variability [43]. In addition, the baseline composite was re-estimated on 2020–2024 to exclude the 2025 liveweight values, which follow a linear extrapolation pattern (Section 4.7).

To examine regional heterogeneity, the 20 oblasts were grouped into three macro-regions: West (8 oblasts), Centre (6), and North, East and South (6). Equation (2) was re-estimated with region-group-specific slopes on ln I and P, and the equality of the slopes was tested with Wald tests. The economic significance of the baseline coefficients for each oblast was assessed by computing the contribution of within-region changes in investment and in the share of profitable enterprises between 2020–2021 and 2024–2025, $\hat{\beta}_1 \Delta \ln I + \hat{\beta}_2 \Delta P$, expressed relative to the cross-regional average change; this relative form removes the common nominal price component of investment, which is measured in current prices.

3. Results

3.1. Descriptive Statistics and Multicollinearity Diagnostics

Table 2 presents descriptive statistics for the dependent variable and the variables retained in the verified specification.

Table 2. Descriptive statistics of variables (N = 120).

Variable	Description	Mean	Std. Dev.	Min	Max
Y	Log Agricultural Production Performance	6.21	0.50	5.05	7.13
ln I	Log Capital Investment	7.68	0.93	4.12	8.98
P	Share of Profitable Enterprises (%)	73.75	5.17	55.10	87.60
S	Period Indicator (2022–2025 = 1)	0.67	0.47	0.00	1.00

Note: Y, log of the geometric mean of grain, oilseed, milk, liveweight-for-slaughter, and egg production; ln I, log of capital investment in agriculture (million UAH, current prices); P, share of profitable agricultural enterprises; S, period indicator. Source: authors' calculations.

Table 3 reports Variance Inflation Factors (VIFs) for the retained explanatory variables, alongside the values obtained for the excluded variables (agricultural land area and the number of agricultural producers) for comparison.

Table 3. Multicollinearity diagnostics.

Variable	VIF	Status
ln I—Capital Investment	1.03	Acceptable
P—Share of Profitable Enterprises	1.21	Acceptable
S—Period Indicator	1.21	Acceptable
ln L—Agricultural Land Area (for reference)	4.58	Excluded
ln N—Number of Agricultural Producers (for reference)	3.97	Excluded

Note: VIF, variance inflation factor; ln L and ln N are reported for comparison only and are not included in the core specification. Source: authors' calculations.

VIF values for the retained regressors range from 1.03 to 1.21, indicating no multicollinearity concerns. The excluded variables (agricultural land area and the number of agricultural producers) have considerably higher VIF values (4.58 and 3.97) and unstable coefficients when modelled jointly (Appendix A, Table A1).

3.2. Baseline Fixed Effects Estimates

Diagnostic testing indicated groupwise heteroskedasticity in the model residuals (Modified Wald test, $\chi^2(20) = 142.24$, $p < 0.001$). The Wooldridge test did not indicate statistically significant first-order serial correlation ($F(1,19) = 1.21$, $p = 0.285$), while the Pesaran CD test provided borderline evidence of cross-sectional dependence (CD = 1.85, $p = 0.064$). The preferred specification was therefore estimated with heteroskedasticity-robust standard errors, and Driscoll–Kraay standard errors are reported as a robustness check (Section 3.3). The Hausman test rejects the Random Effects estimator ($\chi^2(3) = 595.49$, $p < 0.001$), supporting the Fixed Effects specification. Table 4 presents the baseline estimates.

Capital investment is positively associated with production performance ($\beta = 0.131$, $p < 0.001$): a 1% within-region increase in investment corresponds to an estimated 0.131% increase in the production index (the geometric mean of the five outputs). The share of profitable enterprises is also positively associated with production performance ($\beta = 0.005$, $p = 0.040$), implying that a one-percentage-point increase in the share of profitable enterprises corresponds to an increase in the production index of approximately 0.5%. The coefficient on the period indicator is -0.072 ($p < 0.001$), equivalent to an average conditional reduction of approximately 7.0% during 2022–2025 relative to 2020–2021. Figure 2

illustrates the raw relationship between capital investment and production performance in the two periods.

Table 4. Fixed Effects panel regression results (dependent variable: Y).

Variable	Coefficient	Robust Std. Err.	*t*-Stat	*p*-Value
ln I—Capital Investment	0.131	0.031	4.19	< 0.001
P—Share of Profitable Enterprises	0.005	0.0024	2.08	0.040
S—Period Indicator	−0.072	0.020	−3.68	< 0.001
R^2 (within)	0.398			
N/Regions	120/20			

Note: Regional (entity) fixed effects are included; standard errors are heteroskedasticity-robust; N, number of region-year observations. Source: authors' calculations.

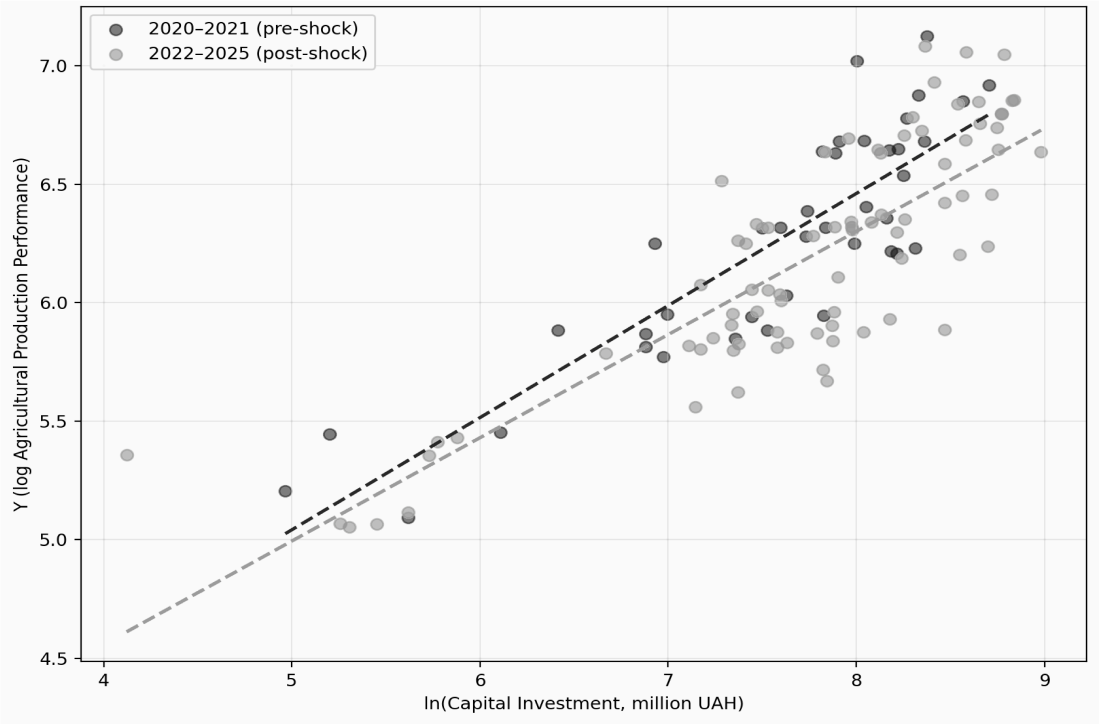


Figure 2. Raw relationship between log capital investment and agricultural production performance, by period. Fitted lines are simple bivariate OLS trends shown for visual reference and do not correspond to the Fixed Effects estimates in Table 4. Source: authors' calculations.

The bivariate pattern shows a strong positive association between investment and production performance in both periods, with the post-2021 trend line shifted downward. This visual pattern is consistent with the Fixed Effects results, in which the investment slope remains positive while the level of production performance declines in the second period.

3.3. Robustness of the Core Specification

Table 5 reports the alternative temporal specification in which the period indicator is replaced with year fixed effects.

Table 5. Baseline versus year-fixed-effects specification.

Specification	ln I	P	S/Year FE	Note
Baseline (Entity FE + S)	0.131 ***	0.005 *	−0.072 ***	Preferred specification
Entity FE + Year FE (S omitted)	0.143 ***	0.006 *	Year effects	Coefficients stable

Note: *** $p < 0.001$; * $p < 0.05$;. Entity FE, regional fixed effects; Year FE, year fixed effects. Source: authors' calculations.

With year fixed effects, the coefficients on capital investment (0.143) and the share of profitable enterprises (0.006) remain positive and statistically significant, indicating that the core results do not depend on the specific parameterization of the common temporal shift. Driscoll–Kraay inference, which is robust to cross-sectional dependence, leaves all core coefficients significant ($p < 0.001$ for ln I, P, and S).

A leave-one-regressor-out test was then applied to the three retained variables, mirroring the diagnostic applied to the excluded variables (Table 6).

Table 6. Leave-one-regressor-out test for the verified specification.

Specification	ln I	P	S
Full model (baseline)	0.131 ($p < 0.001$)	0.005 ($p = 0.040$)	−0.072 ($p < 0.001$)
ln I dropped	—	0.006 ($p = 0.032$)	−0.049 ($p = 0.020$)
P dropped	0.136 ($p < 0.001$)	—	−0.096 ($p < 0.001$)
S dropped	0.109 ($p < 0.001$)	0.009 ($p = 0.003$)	—

Note: All specifications include regional fixed effects; *p*-values are based on heteroskedasticity-robust standard errors; — variable excluded from the specification. Source: authors' calculations.

All retained regressors preserve their signs and statistical significance when any other regressor is removed, in contrast to the excluded variables (agricultural land area and the number of agricultural producers). Region-level cluster bootstrap confidence intervals (1000 replications) exclude zero for all core coefficients: ln I [0.060, 0.231], P [0.001, 0.011], and S [−0.126, −0.025]. Finally, the ln I × S interaction term is not statistically significant (0.00003, $p = 0.999$), providing no evidence that the investment coefficient differs between the two periods.

3.4. Dynamic Structure of the Investment–Performance Association

Table 7 compares the contemporaneous investment specification with a one-year-lagged alternative, estimated on the same reduced sample (N = 100, since one year is lost to lagging).

Table 7. Contemporaneous versus lagged investment specifications.

Specification	Coefficient on Investment	*p*-Value	R^2 (Within)
Contemporaneous ln I (same N = 100 sample)	0.104	0.006	0.477
Lagged ln I (t − 1) only	0.060	0.223	0.364
Both included: ln I	0.099	0.004	0.481
Both included: ln I (t − 1)	0.029	0.453	

Note: All specifications include regional fixed effects, the share of profitable enterprises, and the period indicator, and are estimated on the same sample ($N = 100$; 2021–2025); *p*-values are based on heteroskedasticity-robust standard errors. Source: authors' calculations.

The lagged coefficient is not statistically significant on its own ($p = 0.223$) and becomes negligible when the contemporaneous term is included ($p = 0.453$), whereas the contemporaneous coefficient remains significant throughout. This pattern indicates that the estimated investment–performance relationship is predominantly contemporaneous in the present data. This is consistent with the possible interpretation that investment functions partly through current-season inputs, machinery maintenance, and working capital—a mechanism that the model does not identify directly—although longer adjustment lags cannot be ruled out given the short panel.

Table 8 reports the Anderson–Hsiao dynamic-panel estimate.

Table 8. Anderson–Hsiao dynamic-panel estimate (exploratory).

Specification	Key Coefficients	First-Stage F	Interpretation
Anderson–Hsiao (ΔY_{t-1} instrumented by Y_{t-2})	ln I: 0.086 (p = 0.022); ρ: 0.705 (p = 0.617)	0.53	Weak instrument for the persistence term; investment coefficient corroborates the baseline direction

Note: $\Delta Y_{(t-1)}$ is instrumented with $Y_{(t-2)}$; the equation is estimated in first differences by two-stage least squares (Equation (4)); first-stage F, *F*-statistic of the excluded instrument. Source: authors' calculations.

The investment coefficient retains its positive sign and statistical significance (β = 0.086, p = 0.022) under this alternative identification strategy. The persistence term is imprecisely estimated because of the weak first stage, which is expected given the short time dimension and the limited number of cross-sectional units [51]. The dynamic estimate is therefore interpreted as directional corroboration of the baseline result rather than as a more credible point estimate.

3.5. Temporal Identification: Event Study, Structural Break, and Placebo Test

Table 9 reports the event-study specification, which replaces the pooled period indicator with separate year effects relative to the 2020–2021 reference period.

Table 9. Event-study estimates of the period effect by year.

Year	Coefficient (Relative to 2020–2021)	*p*-Value
2022	−0.062	0.009
2023	−0.064	0.006
2024	−0.104	<0.001
2025	−0.058	0.019

Note: Year-indicator coefficients from Equation (5), which includes ln *I*, *P*, and regional fixed effects; reference period 2020–2021; *p*-values are based on heteroskedasticity-robust standard errors. Source: authors' calculations.

The period effect does not decline monotonically after 2022. The year 2024 shows the deepest reduction in the panel (−0.104 log points, or approximately −9.9%), while 2025 returns only to a magnitude similar to 2022–2023 rather than to the reference level (Figure 3).

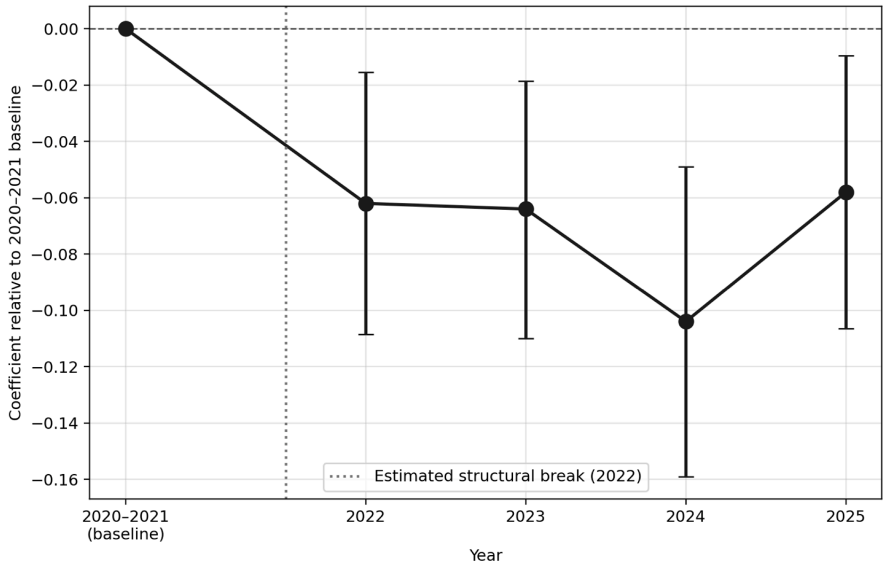


Figure 3. Event-study estimates of the period effect on agricultural production performance relative to the 2020–2021 reference period, with 95% confidence intervals. Source: authors' calculations.

Table 10 reports the Chow-type comparison of candidate break years and the permutation-based placebo test.

Table 10. Structural-break validation and placebo test.

Break Year (k)	R^2 (Within)	Coefficient on $S(k)$	p-Value
2021	0.310	−0.035	0.322
2022 (best fit)	0.398	−0.072	<0.001
2023	0.358	−0.050	0.010
2024	0.340	−0.043	0.014

Note: Each row re-estimates Equation (2) with the break year k defining $S(k) = 1$ for $t \geq k$ and 0 otherwise. Placebo test (500 random permutations of S): mean placebo coefficient ≈ 0.000 (SD = 0.019) versus the true coefficient of −0.072; permutation $p = 0.002$. Source: authors' calculations.

The model achieves its highest within-R^2 and lowest residual sum of squares when the break year is set to 2022, indicating that the break date is supported by the data rather than imposed by assumption. The permutation test confirms that a coefficient of the observed magnitude is highly unlikely to arise from a randomly assigned indicator ($p = 0.002$), indicating that the period effect reflects a genuine feature of the data rather than an artefact of the panel structure.

3.6. Restoring Agricultural Land Area and the Number of Agricultural Producers Using Verified Real-Year Data

To verify that the exclusion of agricultural land area (L) and the number of agricultural producers (N) reflects a substantive limitation rather than only the interpolation artefact, both variables were reconstructed using exclusively the years for which genuinely observed values are reported: 2022, 2023, and 2025. Depending on the availability of the restored variables, this yields an unbalanced sub-panel of 58–60 observations. Because all observations fall within the 2022–2025 period, the period indicator has no variation here and is omitted (Table 11).

Table 11. Verified real-year sub-panel with agricultural land area and the number of agricultural producers restored (2022, 2023, 2025).

Specification	ln L	ln N	ln I	P
Both L and N included	0.535 ($p = 0.044$)	−0.244 ($p = 0.047$)	0.066 ($p = 0.007$)	0.0059 ($p < 0.001$)
L excluded, N retained	—	−0.087 ($p = 0.587$)	0.064 ($p = 0.010$)	0.0063 ($p = 0.001$)
N excluded, L retained	0.379 ($p = 0.083$)	—	0.059 ($p = 0.023$)	0.0058 ($p < 0.001$)

Note: Unbalanced sub-panel of the years with genuinely observed values (2022, 2023, and 2025), N = 58–60 depending on the availability of the restored variables; regional fixed effects are included; the period indicator is omitted because it has no variation within the sub-panel; — variable excluded from the specification. Source: authors' calculations.

Even when verified, non-interpolated values are used, agricultural land area and the number of agricultural producers remain highly collinear (VIF = 6.98 and 4.63, respectively), and their statistical significance is not robust to one another's exclusion. This confirms that the difficulty in separating these two variables reflects genuine multicollinearity between two proxies for the general scale of a region's agricultural sector, and not only the interpolation problem. The exclusion of both variables from the core specification is therefore justified on econometric as well as data-quality grounds. Capital investment and the share of profitable enterprises remain stable and significant across all three sub-panel specifications.

Figure 4 summarizes this robustness evidence. The investment coefficients obtained from the baseline model, the year-fixed-effects alternative, the same-sample contemporaneous specification, the Anderson–Hsiao estimator, and the verified real-year sub-panel

cluster between approximately 0.06 and 0.14, with overlapping confidence intervals that exclude zero in every case.

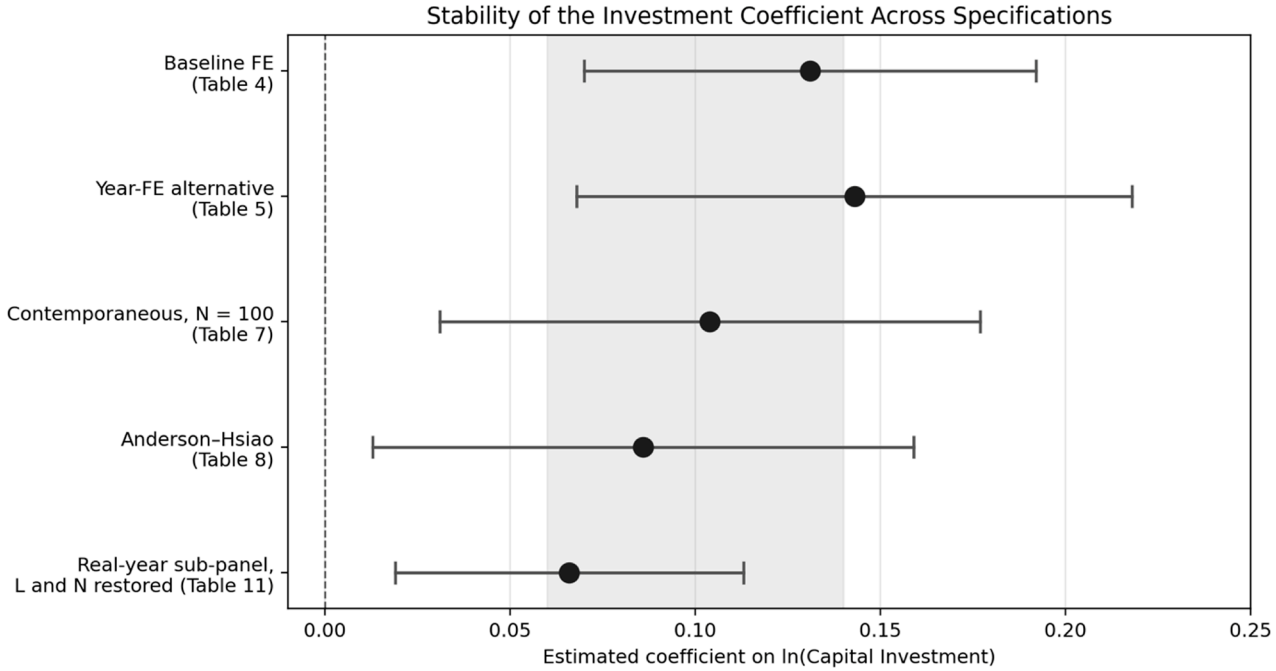


Figure 4. Stability of the estimated coefficient on ln(Capital Investment) across specifications, with 95% confidence intervals. The shaded band marks the range 0.06–0.14. Source: authors' calculations.

3.7. Sensitivity of the Composite Indicator and Regional Heterogeneity

Table 12 reports the core specification re-estimated with alternative constructions of the dependent variable.

Table 12. Sensitivity of the core estimates to the construction of the composite indicator (Entity FE, robust standard errors).

Dependent Variable	ln I	P	S	R^2 (Within)
Baseline (five components)	0.131 ($p < 0.001$)	0.005 ($p = 0.040$)	−0.072 ($p < 0.001$)	0.398
Without grain	0.106 ($p < 0.001$)	0.007 ($p = 0.010$)	−0.052 ($p = 0.009$)	0.359
Without oilseeds	0.111 ($p < 0.001$)	0.004 ($p = 0.104$)	−0.130 ($p < 0.001$)	0.487
Without milk	0.151 ($p < 0.001$)	0.007 ($p = 0.026$)	−0.045 ($p = 0.054$)	0.358
Without liveweight for slaughter	0.134 ($p < 0.001$)	0.005 ($p = 0.052$)	−0.073 ($p < 0.001$)	0.378
Without eggs	0.155 ($p < 0.001$)	0.004 ($p = 0.149$)	−0.061 ($p = 0.005$)	0.328
Crop sub-index (grain, oilseeds)	0.223 ($p = 0.001$)	0.004 ($p = 0.354$)	0.003 ($p = 0.938$)	0.252
Livestock sub-index (milk, liveweight, eggs)	0.070 ($p = 0.046$)	0.007 ($p = 0.046$)	−0.122 ($p < 0.001$)	0.421
Standardized (z-score) composite	0.181 ($p < 0.001$)	0.007 ($p = 0.067$)	−0.150 ($p < 0.001$)	0.430
Baseline composite, 2020–2024 (N = 100)	0.166 ($p < 0.001$)	0.007 ($p = 0.097$)	−0.075 ($p < 0.001$)	0.443

Note: z-score coefficients are expressed in standard-deviation units of the standardized composite and are not directly comparable in magnitude with the other rows. Source: authors' calculations.

The investment coefficient is positive and statistically significant in all ten variants (0.070–0.223), including both sub-indices and the 2020–2024 sample that excludes the extrapolated 2025 liveweight values. The coefficient on the share of profitable enterprises keeps its positive sign in every variant but is less precisely estimated: it is significant at the 5% level in four of the ten variants and at the 10% level in seven, and it is not significant for the crop sub-index ($p = 0.354$). The common period effect is concentrated in livestock outputs (−0.122, $p < 0.001$), whereas the crop sub-index shows no significant common shift once investment and profitability are controlled for (0.003, $p = 0.938$). No single

output drives the investment result: when any one of the five components is excluded, the investment coefficient remains within 0.106–0.155 and significant at the 0.1% level (Table 13).

Table 13. Region-group-specific slopes on capital investment and the share of profitable enterprises (Entity FE, robust standard errors).

Macro-Region	Oblasts	Slope on ln I	Slope on P
West	Volyn, Rivne, Lviv, Ternopil, Ivano-Frankivsk, Zakarpattia, Chernivtsi, Khmelnytskyi	0.087 ($p < 0.001$)	0.007 ($p < 0.001$)
Centre	Vinnytsia, Cherkasy, Kirovohrad, Poltava, Kyiv, Zhytomyr	0.117 ($p = 0.016$)	−0.002 ($p = 0.340$)
North, East and South	Chernihiv, Sumy, Kharkiv, Dnipropetrovsk, Mykolaiv, Odesa	0.221 ($p = 0.001$)	0.010 ($p = 0.009$)

Note: Model includes regional fixed effects and the period indicator S (−0.064 ($p < 0.001$)); R^2 (within) = 0.517; N = 120. Wald test of equal slopes: ln I, $\chi^2(2) = 4.11$, $p = 0.128$; P, $\chi^2(2) = 13.92$, $p = 0.001$. Source: authors' calculations.

The investment slope is positive and significant in all three macro-regions, ranging from 0.087 in the West to 0.221 in the North, East and South, and the hypothesis of equal slopes is not rejected ($p = 0.128$). By contrast, the slopes on the share of profitable enterprises differ significantly across macro-regions ($p = 0.001$): the association is positive and significant in the West (0.007) and in the North, East and South (0.010) but absent in the Centre (−0.002, $p = 0.340$), where the main grain-producing oblasts are located.

The regional contributions implied by the baseline coefficients are reported in Appendix A (Table A3). Relative to the cross-regional average, changes in investment and profitability between 2020–2021 and 2024–2025 imply contributions ranging from −11.5% (Kharkiv) to +11.4% (Lviv). On average, the implied contribution is +4.3% in the West, −0.7% in the Centre, and −5.0% in the North, East and South, compared with actual relative changes in the production index of +8.4%, +4.9%, and −16.1%, respectively. The implied contributions are positively correlated with the actual relative changes across oblasts ($r = 0.67$), although in the most affected oblasts (Kharkiv, Sumy, Mykolaiv) the actual decline substantially exceeds the part attributable to investment and profitability.

4. Discussion

The results obtained in this study indicate that, once measurement-unreliable variables are excluded, regional agricultural production performance is consistently associated with two economic determinants: capital investment and enterprise financial viability. The investment relationship remains stable across alternative temporal specifications, inference procedures, dynamic structures, data subsets, constructions of the composite indicator, and macro-regions; the financial-viability relationship is positive throughout but weaker and regionally conditioned. Both persist despite a pronounced common shift in the operating environment after 2021. Because the dependent variable measures physical output, the discussion refers to the economic-productive dimension of regional agricultural sustainability rather than to sustainability in its comprehensive environmental, social, and economic sense.

Because the Fixed Effects estimates identify associations from within-region co-movement, the discussion below distinguishes three levels: empirically established findings, plausible explanatory mechanisms that the model does not identify directly, and policy interpretations, which are presented separately in Section 4.6. Table 14 summarizes this distinction; the interpretations are hypotheses consistent with the estimates rather than findings demonstrated by them.

Table 14. Statistically established results versus plausible mechanisms.

Topic	Statistically Established (This Study)	Plausible Mechanism (Not Identified by the Model)
Capital investment	Positive within-region association with the production index (β = 0.131); robust across all specifications, sub-indices, and macro-regions; predominantly contemporaneous	Capacity, post-harvest/livestock-infrastructure, and liquidity channels; reverse causality from current harvests to investment cannot be excluded
Financial viability	Positive association (β = 0.005); significant in the West and in the North, East and South, absent in the Centre; sensitive to the composition of the indicator	Internal financing of working capital and herd maintenance; profitability may also respond to output
Period effect	Average conditional reduction ≈ 7.0% in 2022–2025, deepest in 2024; best-fitting break in 2022; concentrated in livestock outputs	Combined common shift in operating conditions; individual causes are not identified by the model
Scale variables	Land area and the number of agricultural producers do not provide reliable within-region variation	Need for transparent documentation of observed versus estimated annual values

Source: authors' elaboration.

4.1. Capital Investment and Sustainable Agricultural Performance

Capital investment has the largest and most stable retained coefficient: β = 0.131 in the baseline model and 0.143 with year fixed effects, with the alternative estimates clustering between approximately 0.06 and 0.14 (Figure 4). This result is consistent with previous evidence linking investment and technological renewal to agricultural productivity and performance [5,10,11]. From a sustainability perspective, the finding supports the logic of sustainable intensification: growth in physical output is associated with the renewal of productive capital rather than with the expansion of land use [3,4]. The predominantly contemporaneous nature of the association (Table 7) is compatible with the interpretation that part of agricultural investment operates through current-season capacity—machinery maintenance, inputs, and working capital—rather than exclusively through long-term asset accumulation; this mechanism is plausible but not directly identified by the model.

The absence of a significant ln I × S interaction indicates that the investment–performance relationship did not change between the two periods. This stability is important for policy: the investment–performance association appears to be a stable characteristic of regional agricultural systems rather than a feature of a specific economic environment.

In economic terms, a 10% within-region increase in capital investment corresponds to an approximately 1.3% higher production index, and a change of one within-region standard deviation in ln *I* (0.32) corresponds to approximately 4.3%. Several plausible economic channels are consistent with this association; they are possible interpretations rather than demonstrated mechanisms, because the model does not identify them directly and the data do not allow them to be separated. A capacity channel may operate through machinery and equipment that improve the timeliness of sowing and harvesting and reduce field losses within the same season; this is consistent with the strongest association being observed for the crop sub-index (0.223; Table 12). A post-harvest and livestock-infrastructure channel may operate through storage, drying, and livestock housing, which reduce losses and support herd maintenance. A liquidity channel may arise where investment relies largely on internal funds, so that years of higher investment are also years in which enterprises can finance current inputs. The contemporaneous timing also admits a reverse channel: enterprises that realize larger harvests have more internal resources to invest in the same year. The coefficient should therefore be read as the strength of the joint movement of investment and output within regions, not as a causal return on investment. The positive investment slopes in all macro-regions (Table 13) indicate that the association is not confined

to a particular regional production structure, which also distinguishes the present evidence from farm-level findings of overinvestment in parts of Central and Eastern Europe [19].

4.2. Financial Viability and Economic Resilience

The share of profitable enterprises is positively associated with production performance ($\beta = 0.005$, $p < 0.05$) and remains positive across all specifications, including the verified real-year sub-panel, but it is less precisely estimated when the composite indicator is altered and is absent in the central oblasts (Tables 12 and 13). This is consistent with research showing that competitiveness and productive efficiency depend on the capacity of enterprises to convert resources into economically viable output [12] and that financial resilience supports the maintenance of operations and productive capacity under unstable conditions [13]. Financial viability can therefore be interpreted as a component of the economic resilience of regional agricultural systems: regions in which a larger share of producers operates profitably are better positioned to maintain output, finance current production, and undertake further investment.

In economic terms, a 5-percentage-point increase in the share of profitable enterprises—roughly one within-region standard deviation (4.6 p.p.)—corresponds to an approximately 2.5% higher production index. Two plausible mechanisms, which are not directly identified by the model, could account for this association. Where access to external credit is constrained, retained earnings are a principal source of working capital, so a larger share of profitable enterprises expands the regional capacity to purchase fertilizers, plant protection products, fuel, and feed in time for the production cycle [12,21]. Profitability also sustains livestock herds, whose maintenance requires continuous expenditure that unprofitable enterprises tend to cut first; this is consistent with the association being concentrated in livestock outputs (Table 12). In the central oblasts, where grain and oilseed production plays a leading role, the share of profitable enterprises is not associated with physical output, which suggests that financial viability matters most where production depends on continuous current expenditure. As with investment, the association may be bidirectional, because favourable harvests raise profitability in the same year.

4.3. The Common Period Shift and the Non-Monotonic Trajectory

The period indicator is associated with an average conditional reduction in production performance of approximately 7.0% during 2022–2025. The annual estimates (approximately −6.0% in 2022, −6.2% in 2023, −9.9% in 2024, and −5.6% in 2025) show no monotonic recovery pattern, and the 2022 break provides the best fit among the tested candidate years. Because the indicator varies only over time, it captures the combined effect of all changes in the national operating environment that affected regions simultaneously and should not be interpreted as the effect of a single factor. The deepest reduction in 2024 suggests that adverse conditions may accumulate over time—for example, through delayed adjustment of livestock herds, deferred asset renewal, and persistent pressure on input costs—rather than dissipating after an initial shock [16]. Importantly, the investment and profitability coefficients remain virtually unchanged when the period effect is parameterized differently, which indicates that the core economic relationships are robust to the common temporal shift.

The magnitude and timing of the period effect are statistically established; its causes are not identified by the model. Studies of the same period document several candidate channels—loss and abandonment of cropland and reduced crop output [22–24], disruption of export logistics with consequences for prices and farm incomes [25], and losses of agricultural enterprises together with changing policy responses [26,27]—which are consistent with a common shift but cannot be separated in a model in which S varies only over time.

The new evidence that the shift is concentrated in livestock outputs (Table 12) is consistent with the slower adjustment of herds noted above.

4.4. Economic Significance and Regional Specificities

The regional dimension of the results is visible in three respects. First, the investment slope is positive in every macro-region and largest in the North, East and South (0.221), where investment fell most sharply in several oblasts; in these oblasts, changes in investment are associated with larger changes in output per unit of investment. Second, the role of financial viability differs significantly across macro-regions: it is relevant in the West and in the North, East and South, but not in the central grain belt. Third, the implied regional contributions (Table A3) separate oblasts in which investment growth supported output—most western oblasts and Cherkasy and Poltava in the Centre—from oblasts in which falling investment (Kharkiv, Dnipropetrovsk, Chernivtsi) or a sharp fall in the share of profitable enterprises (Kirovohrad, Mykolaiv) implies a relative loss of production performance of 7–12%.

In the most affected oblasts, the actual decline of the production index exceeds the part attributable to investment and profitability several times over (for example, −45.4% versus −11.5% in Kharkiv), indicating that factors outside the model dominate there. For these regions, investment and financial support are likely to be necessary but not sufficient conditions for recovery of production performance.

4.5. Data Quality as a Prerequisite for Sustainability Monitoring

The explicit exclusion of interpolated structural scale variables demonstrates the importance of pre-estimation data-consistency audits in regional panels based on administrative statistics. Fixed Effects estimators identify relationships exclusively from within-region variation; when this variation is generated by interpolation, the resulting coefficients may reflect reporting practices rather than economic relationships. The real-year reconstruction (Table 11) further shows that land area and the number of agricultural producers remain collinear proxies for sectoral scale even when verified data are used. For sustainability monitoring, this finding implies that indicator systems used to track progress toward agricultural sustainability targets should be accompanied by transparent documentation of which annual values are observed and which are estimated.

4.6. Practical Implications and Recommendations for Development Policy

The robust associations identified in this study support several directions for policies aimed at sustainable regional agricultural development. These recommendations are policy implications derived from the associations established above; they are not themselves tested by the model.

Investment support. Since capital investment is the most stable correlate of production performance, support mechanisms should prioritize access to investment finance for machinery renewal, storage, processing, and technological modernization. Given the predominantly contemporaneous association, and to the extent that the current-season channel discussed in Section 4.1 operates, instruments that also support working capital and current-season inputs may yield more immediate production benefits than instruments focused solely on long-term assets.

Strengthening financial viability. Measures that improve the profitability and financial stability of agricultural enterprises—such as access to affordable credit, risk-management instruments, and stable market conditions—may support regional production performance, to the extent that the observed association reflects a causal channel, and strengthen the economic resilience of agricultural systems.

Region-specific approaches. The regional results indicate that the mix of instruments should differ across regions rather than follow national averages. In oblasts where investment fell (Kharkiv, Dnipropetrovsk, Chernivtsi), restoring investment capacity is the priority; in oblasts where the share of profitable enterprises fell sharply (Kirovohrad, Mykolaiv), instruments that support working capital and financial viability are likely to be more effective; in the central grain belt, where financial viability is not associated with output, investment support targeted at productivity-enhancing assets is more relevant than general support for profitability. In western oblasts with strong investment growth, monitoring whether additional assets are matched by output growth can help avoid overinvestment [19]. Recent evidence on the circular bioeconomy potential of regional agricultural and livestock production systems likewise shows that sustainable development opportunities depend on regional production structures and specializations [29].

Improving statistical reporting. The data audit indicates a need for more consistent annual regional reporting of agricultural land area and the number of agricultural producers before these variables are used for panel-based policy inference and for monitoring progress toward sustainable development objectives.

4.7. Limitations of the Study and Directions for Further Research

Despite the robustness of the core estimates, this study has several limitations that define directions for further research. First, the analysis covers 20 oblasts for which consistent longitudinal statistics were available; regions lacking such coverage were excluded, which limits the inferential scope to the analysed regions and, because the excluded regions are among the most affected, implies that the period effect is likely to be a conservative estimate (Section 2.1). Second, the period indicator captures the combined common shift in the operating environment and cannot separate the contributions of individual factors; future research could incorporate region-specific measures of input costs, labour productivity, market access, climatic conditions, and the intensity of disruptions to agricultural activity to decompose this effect. Consistent annual oblast-level series for these determinants were not available from official statistics for the full 2020–2025 period, so they could not be included in the present model. Third, the data-consistency audit led to the exclusion of scale variables such as land area; while this strengthens the reliability of the investment and profitability estimates, it narrows the scope of the analysis relative to a full structural-determinants framework. In addition, one component of the dependent variable (livestock liveweight for slaughter) showed a single-year interpolation pattern in 2025; the core results are unchanged when 2025 is excluded or when this component is omitted (Table 12), but the issue should be addressed as improved data become available. Fourth, the estimates are associations: the contemporaneous timing of the investment and profitability relationships is compatible with reverse causality, and the model does not provide causal identification. Fifth, the composite indicator measures physical production performance and the model therefore addresses the economic-productive dimension of sustainability only. Finally, the limited cross-sectional dimension restricts instrument strength in dynamic and instrumental-variable specifications; longer panels would enable fully powered dynamic causal identification and the integration of environmental indicators into a multidimensional assessment of agricultural sustainability.

From a methodological perspective, the proposed framework combines a pre-estimation data-consistency audit with Fixed Effects estimation and a structured set of inference, dynamic, temporal-identification, and measurement-validity checks. Unlike studies that rely on a single specification, this approach makes it possible to distinguish robust economic relationships from results that depend on measurement artefacts or on

the parameterization of temporal shifts, and it can be transferred to other regional panels based on administrative statistics.

5. Conclusions

This study examined whether capital investment and enterprise financial viability remain stable correlates of regional agricultural production performance when the operating environment changes sharply, using a verified panel of 20 Ukrainian oblasts for 2020–2025. The evidence supports three findings. First, within-region increases in capital investment are consistently associated with higher physical production performance across temporal specifications, inference procedures, dynamic structures, constructions of the composite indicator, and macro-regions. Second, the association with the share of profitable enterprises is positive but weaker: it is driven mainly by livestock outputs and is absent in the central grain-producing oblasts. Third, the investment–performance relationship did not change after 2021, even though the level of production performance shifted downward, most strongly in livestock outputs and in 2024.

The study contributes to the literature in three ways. It adds region-level evidence for Ukraine to a body of research that is dominated by farm-level studies in European Union member states [17–21] and by assessments of production losses in the most affected territories [22–24]; it shows that the association between investment and physical output is stable across a structural shift and across regional production structures, which is relevant to the open question of whether investment translates into output rather than into capital deepening; and it demonstrates that pre-estimation screening of administrative regressors changes which determinants can be credibly identified in Fixed Effects panels, since agricultural land area and the number of agricultural producers do not provide reliable within-region variation in official regional statistics.

These results imply, rather than demonstrate, that policies for the economic-productive dimension of sustainable agricultural development should combine investment finance with instruments that maintain the financial viability of producers, with a regionally differentiated balance: restoring investment capacity where investment has fallen, supporting working capital where profitability has deteriorated, and targeting productivity-enhancing assets in the central grain belt. Improving the annual regional reporting of land use and of the number of agricultural producers is a precondition for extending such analysis. Because the model captures productive and financial performance only, integrating environmental and social indicators into a multidimensional assessment of sustainability remains a task for further research.

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Data Availability Statement: The data used in this study were obtained from publicly available official statistics of the State Statistics Service of Ukraine and regional statistical offices [34–42]. The dataset comprises annual oblast-level indicators for 20 Ukrainian oblasts over 2020–2025 (120 region-year observations) and was used to construct the composite production performance indicator and to estimate the Fixed Effects panel models reported in this article. The compiled dataset and the Python (version 3.10) code used for the estimations are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. Data-Consistency Audit of the Excluded Variables

Table A1 reports the full-panel diagnostic that motivated the exclusion of agricultural land area (L) and the number of agricultural producers (N) from the core specification.

Table A1. Leave-one-regressor-out diagnostic for the excluded scale variables (full panel, N = 120).

Specification	ln I	P	S	Excluded Variables
Both L and N included	0.126 ***	0.004 †	−0.091 ***	L = 0.234 **; N = −0.449 **
L excluded, N retained	—	—	—	N = −0.083 (p = 0.254)
N excluded, L retained	—	—	—	L = −0.006 (p = 0.673)

Note: *** $p < 0.001$; ** $p < 0.01$; † $p < 0.10$; — not reported. Source: authors' calculations.

The coefficients on L and N change sign or lose significance depending on whether the other variable is included, which, together with the arithmetic-progression pattern of their annual within-region values, indicates that neither variable provides reliable within-region variation for Fixed Effects estimation.

Appendix A.2. Diagnostic Tests and Computational Configuration

Table A2 summarizes the specification and residual diagnostic tests applied to the baseline model.

Table A2. Specification and residual diagnostics for the baseline Fixed Effects model.

Test	Statistic	p-Value	Conclusion
Hausman test (FE vs. RE) [45]	$\chi^2(3) = 595.49$	<0.001	Fixed Effects preferred
Modified Wald test (groupwise heteroskedasticity)	$\chi^2(20) = 142.24$	<0.001	Heteroskedasticity present; robust SE used
Wooldridge test (first-order serial correlation) [46]	$F(1,19) = 1.21$	0.285	No significant serial correlation
Pesaran CD test (cross-sectional dependence) [47]	CD = 1.85	0.064	Borderline; Driscoll–Kraay SE reported

Note: FE, fixed effects; RE, random effects; SE, standard errors. Source: authors' calculations.

All estimations were performed in Python (version 3.10). Cluster bootstrap confidence intervals were obtained by resampling regions with replacement (1000 replications), and the permutation-based placebo test used 500 random reassignments of the period indicator.

Appendix A.3. Regional Contributions Implied by the Baseline Coefficients

Table A3 reports, for each oblast, the change in log capital investment and in the share of profitable enterprises between 2020–2021 and 2024–2025 and the implied contribution to the production index ($\hat{\beta}_1 = 0.131$, $\hat{\beta}_2 = 0.005$), expressed relative to the cross-regional average change. Oblasts are ordered by the predicted total contribution.

Table A3. Implied regional contributions of investment and financial viability to production performance, 2020–2021 to 2024–2025.

Oblast	Macro-Region	Δln I	ΔP (p.p.)	Investment Contribution (%)	Profitability Contribution (%)	Predicted Total (%)	Actual Relative Change in Y (%)
Lviv	West	0.9	1.8	+8.7	+2.7	+11.4	+13.2
Ivano-Frankivsk	West	1.0	−0.5	+9.4	+1.5	+11.0	+7.3
Ternopil	West	0.7	0.1	+6.0	+1.8	+7.8	+20.4
Volyn	West	0.6	0.2	+5.1	+1.9	+7.0	+4.6
Cherkasy	Centre	0.6	−1.1	+4.6	+1.2	+5.8	+8.5
Rivne	West	0.3	4.2	+1.4	+3.9	+5.2	+16.6
Poltava	Centre	0.6	−4.2	+4.4	−0.3	+4.1	+4.4
Vinnytsia	Centre	0.4	−2.8	+1.9	+0.4	+2.3	+6.0
Chernihiv	North, East and South	0.4	−4.7	+1.8	−0.6	+1.2	+6.3
Khmelnytskyi	West	0.5	−8.0	+3.4	−2.2	+1.1	+6.7
Odesa	North, East and South	0.3	−4.6	+0.4	−0.5	−0.1	+1.5
Sumy	North, East and South	0.3	−6.2	+0.8	−1.3	−0.5	−28.7
Zakarpattia	West	0.1	−3.6	−2.3	0.0	−2.3	−1.6
Kyiv	Centre	0.1	−5.1	−1.8	−0.8	−2.5	+3.3
Zhytomyr	Centre	0.0	−5.5	−3.0	−1.0	−3.9	+4.1
Chernivtsi	West	−0.7	7.1	−12.4	+5.3	−7.1	+0.5
Dnipropetrovsk	North, East and South	−0.4	−4.5	−8.1	−0.5	−8.6	−9.0
Kirovohrad	Centre	0.0	−16.5	−3.5	−6.5	−9.9	+3.0
Mykolaiv	North, East and South	−0.1	−15.6	−4.4	−6.0	−10.4	−21.7
Kharkiv	North, East and South	−0.7	−1.4	−12.6	+1.1	−11.5	−45.4

Note: Contributions are in log points × 100 (approximately %), relative to the cross-regional average; the relative form removes the common nominal price component of investment. Source: authors' calculations.

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