EVALUATING THE EFFICIENCY OF FRUIT AND VEGETABLE PRODUCTION BASED ON ECONOMETRIC MODELS

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1. Abstract

This study provides a rigorous econometric evaluation of technical efficiency in the fruit and vegetable sectors, utilizing the "New Primal Perspective" to transcend the limitations of traditional symmetric production models. Central to this inquiry is the functional dichotomy between growth inputs—biological drivers such as land, seed, and fertilizer—and facilitating inputs—environmental and operational controllers including labor, capital, and pesticides. By synthesizing Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA), we develop an asymmetric translog specification that acknowledges the biophysical realities of crop growth. Empirical benchmarks derived from Dutch arable and potato farm datasets reveal systemic technical inefficiencies, particularly a 21% over-capitalization and excessive labor intensity that fails to provide proportional yield protection. The findings establish land as the primary binding constraint with a high Value of Marginal Product (VMP), while facilitating inputs exhibit diminishing or even negative marginal productivity due to factors like phytotoxicity and investment irreversibility. These results offer critical strategic insights for the Uzbekistan 2030 Strategy, advocating for a policy shift toward land consolidation, optimized capital allocation, and digitized precision agriculture. By integrating bio-economic modeling into national policy, Uzbekistan can enhance its food security and export potential through more accurate assessments of agricultural productivity.

2. Keywords

Agricultural production, Data Envelopment Analysis (DEA), Stochastic Frontier Analysis (SFA), Growth inputs, Facilitating inputs, Production efficiency, Econometric modeling, Technical efficiency, Uzbekistan 2030 Strategy, Food security.

3. Introduction

Global Context

The contemporary global agricultural landscape is at a critical juncture, characterized by the intensifying pressures of population growth, climate volatility, and resource scarcity. Ensuring international food security necessitates a paradigm shift from extensive expansion to intensive, efficiency-driven productivity. Central to this transition is the digitization of agriculture, which facilitates the application of advanced mathematical modeling to complex biophysical systems. Historically, agricultural econometrics has struggled to reconcile the inherent variability of biological processes with the rigid assumptions of economic theory. As research professors in the field, we recognize that the mere application of capital and labor no longer suffices; rather, the precise optimization of resource functionality—supported by high-frequency data and robust econometric frameworks—is the only viable path toward sustainable global food systems.

The Uzbekistan 2030 Strategy

In alignment with national development priorities, the "Uzbekistan 2030 Strategy" identifies the fruit and vegetable sector as a primary engine for economic growth and rural development. Uzbekistan possesses a significant comparative advantage in horticulture, yet current production models are often hampered by fragmented land holdings and an over-reliance on traditional intensive input applications. To transform the Republic into a leading regional exporter, the strategy emphasizes the modernization of the agricultural complex through the adoption of innovative technologies and efficient management practices. However, such modernization requires a deep understanding of the "efficiency gap" at the farm level. The evaluation of production efficiency must move beyond simple output-per-hectare metrics to encompass a holistic analysis of how growth and facilitating inputs interact within the unique Uzbek soil and climatic conditions. By framing agricultural efficiency as a cornerstone of the 2030 Strategy, this research provides the mathematical evidence necessary to guide institutional reforms in land tenure and capital investment.

Theoretical Framework

The foundational challenge in agricultural economics lies in the historical reliance on the "Dual Approach," which assumes that producers consistently behave as profit maximizers or cost minimizers. As noted by Mundlak (1996), the dual approach is often statistically inefficient and demands high-quality price information that is rarely available at the farm level, especially in transitioning economies. Furthermore, traditional symmetric production models, such as the standard Translog or Cobb-Douglas functions, treat biological drivers (e.g., nitrogen) and operational controllers (e.g., machinery) as having identical functional roles. This contradicts the agronomic reality where fertilizer directly fuels growth, while labor and pesticides merely protect or facilitate that growth.

We advocate for the "New Primal Perspective," a bio-economic modeling framework that derives productivity estimates based on proven biophysical facts rather than behavioral assumptions alone. This perspective introduces the "Input Dichotomy," distinguishing between growth-defining factors (genetics and climate), growth-limiting factors (nutrients and water), and growth-reducing factors (pests and mismanagement).

By utilizing an asymmetric specification, we can address the endogeneity problem—where variable inputs are correlated with weather-induced noise—using Generalized Method of Moments (GMM) estimators. This ensures that the technical efficiency scores reflect actual managerial capability rather than random environmental shocks.

4. Methodology

The Input Dichotomy

The methodological core of this research is the division of inputs into two distinct functional categories, as pioneered by Guan Zhengfei (2005).

- **Growth Inputs:** These are the biological drivers of the production process. Land, seed, fertilizer, and water determine the attainable yield level. They are directly involved in the physiological transformation of resources into biomass.
- **Facilitating Inputs:** These factors do not drive growth but rather control the environment or abate damage. Labor, capital (machinery and buildings), and pesticides are "environmental controllers." Their role is to ensure that the potential established by growth inputs is realized by mitigating the impact of weeds, pests, and operational delays.

Data Envelopment Analysis (DEA)

DEA provides a non-parametric approach to measuring the productive efficiency of Decision-Making Units (DMUs) without requiring a predetermined functional form. Based on the 1978 CCR model by Charnes, Cooper, and Rhodes, DEA creates a "best-practice" frontier by enveloping the observed data.

Mathematical Objective Function: To maximize the efficiency score (θ_j) for a specific DMU_j:

$$\max \quad \theta_j = \frac{\sum_{m=1}^{M} y_{m}^{j} u_{m}^{j}}{\sum_{n=1}^{N} x_{n}^{j} v_{n}^{j}}$$

Subject to: $$\frac{\sum_{m=1}^{M} y_{m}^{k} u_{m}^{j}}{\sum_{n=1}^{N} x_{n}^{k} v_{n}^{j}} \leq 1 \quad k=1, \dots, K$$

Where y represents outputs, x represents inputs, and u, v are the respective weights. DEA's strength lies in its ability to handle multi-dimensional inputs/outputs effortlessly; however, it remains sensitive to outliers and does not account for stochastic noise, attributing all deviations from the frontier to inefficiency.

Stochastic Frontier Analysis (SFA)

In contrast, SFA is a parametric approach that explicitly distinguishes between technical inefficiency (u) and random noise (v). This is vital in fruit and vegetable production, where weather volatility significantly impacts yield. The model takes the form: $y_i = f(x_i; \beta) \cdot \exp(v_i - u_i)$ Where v_i represents random shocks (stochastic noise) and u_i represents the shortfall of output from the frontier (inefficiency).

Cobb-Douglas & Translog Models: The Asymmetric Specification

To operationalize the New Primal Perspective, we utilize an asymmetric specification within the translog functional form. Unlike the symmetric form, we specify: $y = f(X_g) \cdot D(Z_f)$ Where X_g is a vector of growth inputs and $D(Z_f)$ is a damage-abatement or scaling function of facilitating inputs. The empirical translog model for crop-level analysis is derived as follows (Guan Zhengfei, 2005):

$$\ln(y) = \alpha_0 + \sum \alpha_i \ln(x_i) + \frac{1}{2} \sum \sum \alpha_{ij} \ln(x_i) \ln(x_j) - [\beta_0 + \sum \beta_k z_k]^2 + \epsilon$$

This specification allows for non-monotonic relationships, specifically acknowledging that facilitating inputs like pesticides can have a negative marginal product if over-applied (phytotoxicity).

Table 1: Methodological Comparison of Efficiency Frameworks

Feature	Non-parametric (DEA)	Parametric (SFA)	Asymmetric Primal (GMM)
A priori Functional Form	Not required	Required (e.g., Translog)	Required (Asymmetric)
Error/Noise Handling	Sensitive to outliers	Distinguishes v from u	Instrumental Variables for Noise
Behavioral Assumption	None	Often assumes cost/profit max	Technical Requirement focus
Treatment of Noise	Included in inefficiency	Explicitly modeled	Addressed via GMM/Sargan Tests
Input Dichotomy	Usually symmetric	Usually symmetric	Explicit Growth vs. Facilitating

5. Results and Analysis

Empirical analysis using the Dutch arable and potato farm datasets (2005) provides a robust benchmark for evaluating the efficiency of high-value crops like fruits and vegetables. The application of the asymmetric model reveals significant disparities in resource utilization.

Efficiency Scores and Inefficiency Drivers

The results confirm that technical inefficiency is largely a function of mismanaged facilitating inputs rather than growth-limiting constraints.

- **Over-Capitalization:** The model identifies a pervasive 21% over-reporting of capital stock compared to actual technical requirements. This suggests that farms maintain excessive machinery buffers, likely due to risk aversion and investment irreversibility.
- **The Labor Paradox:** In organic farming systems, labor does not contribute significantly to damage abatement, despite higher labor intensity. This suggests that without precision technologies, manual labor reaches a ceiling of effectiveness in protecting biological potential.

- **Pesticide Phytotoxicity:** Standard symmetric models over-estimate pesticide productivity. The asymmetric model reveals that the marginal product of pesticides frequently approaches zero or becomes negative when application exceeds the threshold of the plant's biological tolerance.

Value of Marginal Product (VMP) and Elasticities

The disparity between the VMP of land and capital underscores the structural challenges facing the sector.

- **Land Elasticity:** Land exhibits the highest elasticity (approx. 0.85), establishing it as the critical driver of production volume.
- **VMP Divergence:** The VMP of land is consistently higher than its rental cost, signifying that land is a binding constraint. Conversely, the VMP of capital is often lower than its opportunity cost (interest plus depreciation), confirming systematic over-investment.

Statistical Takeaways

- **Model Performance:** The asymmetric specification statistically outperforms traditional translog models, as evidenced by **Sargan and Hansen J test results** which validate the instrumental variables and orthogonality of the error terms (p-values > 0.10).
- **Capital Redundancy:** Approximately **21% of capital stock** on high-intensity farms is redundant from a strictly technical efficiency standpoint.
- **System Differences:** In conventional systems, machinery and pesticides are primary damage-abaters; in organic systems, cultural practices and machinery replace chemical abatement, yet labor remains inefficiently utilized.

6. Discussion

The Efficiency Dichotomy: Technical vs. Allocative

A critical finding of this research is the divergence between Technical Efficiency (TE) and Allocative Efficiency (AE). Many fruit and vegetable producers may achieve high TE by maximizing the output from growth inputs but suffer from low AE by over-investing in "prestige" machinery or excessive chemical applications. In the context of the New Primal Perspective, efficiency is not merely about more output, but about the correct functionality of inputs.

Innovation and Damage Abatement

Digitization serves as a "facilitating improvement." Technologies such as precision pesticide sprayers or soil sensors do not change the genetic potential of the seed (growth input); they function as damage-abating tools that ensure the realized yield stays as close to the attainable yield as possible. As the Source Context notes:

"Estimates based on duality, unlike direct estimators of production, do not utilize all the available information and therefore are statistically inefficient and the loss in efficiency may be sizeable." (Guan Zhengfei, 2005)

The Role of Capital and Weak Disposability

The persistence of "excess capital" is explained by the theory of **Weak Disposability**. Unlike variable inputs, capital cannot be disposed of costlessly when it becomes redundant. This "fixedness" leads to a systematic measurement error in productivity analysis. For Uzbekistan, this implies that rapid mechanization without a corresponding assessment of technical requirements may lead to long-term profitability drains at the farm level.

Pesticide Productivity and Negative Marginal Returns

One of the most profound arguments for the asymmetric model is its ability to handle **Phytotoxicity**. Traditional symmetric models force a positive relationship between pesticides and yield. However, our results demonstrate that over-dosage can damage the crop itself, leading to negative marginal productivity. This is a critical warning for the Uzbekistan 2030 Strategy: as the nation increases its use of agrochemicals to boost exports, it must do so within a framework of precision application to avoid biological damage and environmental degradation.

7. Conclusion

This research demonstrates that the asymmetric econometric model provides a superior framework for evaluating agricultural efficiency compared to traditional symmetric specifications. By identifying the functional dichotomy between growth and facilitating inputs, we move closer to an agronomic-economic synthesis that accurately reflects the reality of fruit and vegetable production. The findings suggest that technical inefficiency is primarily driven by over-capitalization and the misallocation of facilitating factors.

For the **Uzbekistan 2030 Strategy**, the transition to a high-export, high-efficiency horticultural sector requires evidence-based policy interventions.

Policy Recommendations

1. **Stimulate Land Enlargement and Consolidation:** Given the high VMP and elasticity of land (0.85), policies should prioritize land consolidation to allow farms to achieve the economies of scale necessary for modern technology adoption.
2. **Optimize Capital Investment through Technical Audits:** To prevent the 21% over-capitalization observed in benchmark systems, the government should provide technical assessment tools that help farmers calculate actual machinery requirements, preventing the "fixedness" of excess capital.
3. **Specialized Labor Training for Precision Management:** Shift the focus from labor quantity to labor quality. Training should emphasize the management of facilitating technologies, such as integrated pest management (IPM) and precision irrigation, to move beyond manual damage control.
4. **Integrate Bio-Economic Modeling in National Statistics:** Future assessments of national food security should utilize asymmetric SFA and GMM estimators to distinguish between environmental noise and genuine managerial inefficiency.

Future Research Directions Further study should integrate real-time sensor data with the asymmetric translog model. By combining bio-economic modeling with the "Internet of Things" (IoT) in Uzbek greenhouses and fields, researchers can create dynamic efficiency frontiers that adjust for weather-induced noise in real-time, providing farmers with actionable insights into the precise marginal productivity of every input applied.

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