Input interactions and structural dynamics in Greek agriculture productivity

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ABSTRACT

This study examines the impact of fixed capital, variable inputs, and labor on agricultural output in Greece from 1981 to 2021 using a Cobb-Douglas equation. It also investigates changes over time through the Bai-Perron structural changes method, confirming a structural break in 2006. From 1981 to 2005, labor and fixed capital had positive elasticities, contributing positively to agricultural production but with decreasing returns to scale. Post-2006, labor and fixed capital exhibited negative elasticities, indicating inefficiencies, while variable inputs retained positive elasticity. This shift suggests an increased influence of variable inputs on production after 2006. The findings highlight the need for continuous monitoring and analysis of agricultural factors to enhance sector competitiveness and sustainability, providing insights for policy design and implementation aimed at agricultural development.

Keywords: Agriculture productivity growth; input-output analysis; Cobb - Douglas function, Greek agriculture

1. INTRODUCTION

Agricultural production processes require not only the optimal use and combination of inputs, but also the effective utilization of other aspects such as technological innovations, the experience and ability of those employed in the agricultural sector, and consideration of elements related to the economic circumstances that characterize economies both individually and globally. Moreover, unprecedented economic, social, and environmental conditions, particularly financial crises, income inequalities among farmers and consumers, and climate change, have shaped a complex environment for agricultural production. Based on the above reasoning, decisions are formulated regarding the appropriate quantities and types of production factors, with the ultimate goal of achieving economic efficiency in the agricultural sector. Decisions about input use are not purely technical; they also reflect agriculture's continuous endeavors to adapt strategically to shifting economic, environmental, and technological conditions. As farmers face extensive changes in market conditions, technological capabilities, and political regulations, the selection of production factors must be performed while considering their interaction.

In this context, capital is a decisive factor for agricultural production, fulfilling a dual role as a source of financing and as a shaper of production processes. Technological progress and innovation require frequent investments in fixed capital, such as equipment and machinery. These investments aim to improve efficiency along with the use of and promote sustainable production methods (Crespi & Zuniga, 2012; Gann, 2000) in most sectors, hence also in including agriculture. In addition, labor productivity is a fundamental determinant for the efficient implementation of agricultural activities, influencing output quantity and quality, as well as the associated production costs. The latter are also affected by the quality of inputs utilized (Akram et al., 2019), such as fertilizers, pesticides and seeds, as well as land rental expenses, payments to dependent labor (Jayachandran, 2006), and intermediate consumption elements in general. The selection of the amount of labor and variable inputs used in the production process, is influenced by the potential provided by existing fixed capital, highlighting the interaction between these elements.

The Cobb-Douglas production function is considered a useful tool for modeling the interaction between factors of production, as it expresses the relationship between the quantity of production outputs and the inputs used in it. The efficiency of the Cobb-Douglas function, lies in its ability to reliably represent the production process. It estimates the contribution of each input to the total output, the returns to scale, the marginal productivity of production factors, and their marginal rate of substitution (Fuss & McFadden, 1978). The application of the Cobb-Douglas function to agricultural production has been intensely researched, as it captures the relationship between inputs and output, while simultaneously offering simplicity and flexibility in modeling.

To better understand the suitability of the Cobb-Douglas production function for analyzing agricultural productivity and the influence of different production factors on output, a number of empirical studies are reviewed. Within this framework, Armagan & Ozden (2007) argue that the Cobb-Douglas production function estimation is suitable for the efficient analysis of agricultural activities, as it is characterized by ease of calculations and the capability of statistical testing of production flexibilities, pointing out that this approach addresses the concept of productivity and efficient use of inputs, through the integration of the output function based on the inputs used. Faruq-Uz-Zaman (2021) further endorses the Cobb-Douglas production function, highlighting its practical value in estimating marginal productivity and assessing input efficiency. Using data related to crop production in Bangladesh, the author employed inputs such as land area under cultivation, the proportion of the population engaged in agriculture, household spending as a proxy for capital input, fertilizer usage per hectare, and total cultivated land under irrigation to estimate impacts on agricultural output. The results indicated inefficiency in input use, with negative returns to scale (elasticity of -0.977), primarily due to the negative marginal productivity of cultivated land and labor, highlighting the non-rational use of the aforementioned production factors.

Echevarria (1998) confirmed the negative effect of labor growth on agricultural production using data from 1971 to 1991 for Canada. By employing the Cobb-Douglas equation, she compared the agricultural sector with services and industry, determining a reduced need for labor in agriculture and the particular importance of using technological innovations, as they positively affect productivity. Mundlak et al. (1999) used panel data from 1967 to 1992 for 57 countries, suggesting that agricultural production should rely to a greater extent on its extensive industrialization. They argued that output is relatively less influenced by labor changes than by capital, and that efficient production methods reduce labor needs, indicating a shift towards labor-reducing technology.

Yuan (2011) used data from 1999 to 2008 for Hebei Province, China. The study estimated a Cobb-Douglas production function with independent variables including cultivated land area, effective irrigation area, chemical fertilizer usage, agricultural machinery power, rural electricity consumption, and manpower. Effective irrigation area was identified as the most significant contributor to agricultural output, exerting a positive sign, followed by chemical fertilizer usage and farm labor. Cultivated land area, electricity consumption, and farm machinery power also showed a positive impact on output, though to a lesser extent, with overall input elasticity indicating decreasing returns to scale, with a value of 0.56.

Dawson & Lingard (1982), investigate the relationship between various input factors and total revenue in agricultural output using a Cobb-Douglas production function. The study employs Ordinary Least Squares and covariance analysis to estimate the elasticities and marginal productivity of labor, total wage-bill, machinery costs, livestock costs, crop costs, general farming costs, rent, and land area, which are set as independent variables, using total revenue as the dependent variable. The results emphasize the special role of labor and raw materials, as their increase leads to improved productivity, while a similar but less important effect is observed with investments in fixed capital. Nevertheless, decreasing returns on the scale of variable inputs are observed, indicating a relatively reduced efficiency in the use of production factors.

A study by Ghoshal & Goswami (2017), referring to the efficiency of agricultural production in regions of India using Stochastic Frontier Analysis with the use of the Cobb-Douglas production function, in panel data for the period from 2005 to 2014, found matching results. The average annual efficiency ranged from 0.376 to 0.882 across different regions of the country, also indicating inefficiency in the use of production inputs, with the fertilizers and pesticides being the most important variable inputs for increasing output. Additionally, the presence of a comprehensive public infrastructure network, specifically the total state road length per unit of cultivated area, had a positive impact on output. This finding is consistent with that of Mamatzakis (2003), who studied the Greek agricultural sector from 1960 to 1995 using the I3SLS method to estimate a translog cost function. The study indicated that improvements in public infrastructure, reduce marginal variable costs and positively impact productivity advancement.

The present study investigates how the main production factors, namely, fixed capital, variable inputs and labor, have jointly shaped the growth of Greek agricultural output over the past four decades amid evolving technological advances, macroeconomic shocks, and Common Agricultural Policy regimes. To this end, a modified Cobb-Douglas specification, incorporating capital-labor and capital-intermediate input interactions, is estimated and subjected to sequential structural-break analysis to identify and date any endogenous shifts in factor productivity. At the second level, the resulting factor elasticities are compared to chart the evolution of input returns over time, to derive evidence-based insights into how structural shifts reallocate productivity patterns, which can inform the design of policy measures to strengthen sectoral efficiency and resilience.

The paper is organized as follows. Section 2 discusses the evolution of Greek agriculture in relation to CAP Common Agricultural Policy reforms and macroeconomic shocks. Section 3 provides an overview of the data employed and details the empirical methodology adopted. Section 4 summarizes the estimation results derived from the empirical analysis. Section 5 derives policy implications from the results, and section 6 presents concluding comments.

2. COMPETITIVENESS AND PRODUCTIVITY CHALLENGES IN GREEK AGRICULTURE

Greece's entry into the European Economic Community in 1981 and the immediate adoption of the Common Agricultural Policy, is widely credited with transforming Greek agriculture. Previously characterized by small-scale, family subsistence farming, the Greek rural economy began shifting towards market-oriented production after the accession (Caraveli, 2000). Tangible improvements in farm incomes and rural development were evident by the late 1970s following Greece's EU membership, as CAP price guarantees initially boosted agricultural revenues (Christou & Sarris, 1980). Today, the CAP continues to shape and control the framework of operation and activity in the agricultural sector. Over approximately four decades of CAP implementation, significant changes have been observed in the Greek rural economy. The most noteworthy of these changes concern employment, production structure, prices, and rural incomes. Common Agricultural Policy implementation resulted in substantial improvements in producer incomes through subsidies and played a key role in rural development. However, according to Haniotis

(2024), CAP revisions have often exacerbated structural issues in Greek agriculture, including uneven distribution of subsidies, a lack of a functional Farm Advisory System, and slow adaptation to market-oriented reforms, which have limited Greece's ability to align production with market demands and compete internationally.

The 1980s, according to historical data from the Hellenic Statistical Authority (ELSTAT, 1980–2006), stand out as the most prosperous decade for Greek agriculture, marked by high real producer prices and strong overall production value. Following this prosperous period, production volumes stabilized in the 1990s, while real prices gradually and steadily declined. Building on the changes, the 2003 reform of the Common Agricultural Policy, which decoupled subsidies from actual output, brought a significant shift to the Greek agricultural landscape by weakening the link between support and production. As noted by Psaltopoulos et al. (2006), policy adjustments altered the rural economic environment and had uneven effects across regions, adding a layer of instability to production outcomes. The global financial crisis of 2008 compounded these challenges, and by 2011, the value of agricultural production had fallen to its lowest level in decades (Eurostat, 2024). At the same time, falling consumer demand and financial pressure on households caused a deeper contraction in agricultural output, revealing the level that agricultural sector was exposed to wider economic disruptions (Konstantinidis, 2016).

As reported by the Greek GSEE-ADEDY Labor Institute (2002), labor productivity during the 1980s increased at an annual rate of 4.9%. In the 1990s, it stabilized at slightly higher levels, despite a significant reduction in the workforce from 31.6% of the total personnel in Greece in 1980 to 18.0% in 2000. Between 2000 and 2010, the agricultural labor force in Greece experienced a cumulative decline of 22.1%, equivalent to a compound annual decrease of 2.5%. Over the same period, the branch's gross value added receded from €7.49 billion to €6.52 billion, a drop of 13.0% (1.4% per year) (ELSTAT, 2024). Simultaneously, the 2007 financial shock, coupled with the decrease in private investments in agriculture, resulted in low overall performance of the primary sector. Although agriculture still absorbed 11.0% of national employment, it generated barely 3.5% of GDP, a mismatch that steadily eroded its competitiveness (Kassimis & Papadopoulos, 2013). These challenges have persisted in the long term, leading the country to exhibit a consistent trade deficit in agricultural products, which ranged from -1.5 to -2.8 billion euros annually throughout the mid-2010s and up to date (ELSTAT, 2014-2023). As a result, in 2024, Greek agriculture contributes only 3.8% to the country's national GDP, with an average of approximately 3.6% for the 2020s, which is significantly lower than the 6.9% contribution recorded in 1995 and the average of around 4.6% during the 2000s (Eurostat, 2024), suggesting the sector's reduced competitiveness within the national economy.

As productivity trends downward and a significant portion of the workforce departs the agricultural sector, further contraction of production is likely. Kalfas et al. (2024) emphasize that addressing productivity and workforce challenges requires substantial investment in infrastructure, supportive policies, and farmer education to facilitate the adoption of modern practices and enhance sector performance. Hence, enhancing competitiveness in the agricultural sector remains a key challenge for the future of Greek agriculture, as these factors determine its ability to penetrate international markets.

3. MATERIALS & METHODS

Data were collected from the European Commission's Directorate General for Economic and Financial Affairs (AMECO) database on an annual basis, covering the period 1981–2021. The regression model used is based on a production function that reflects the impact of labor and production cost on agricultural output. These factors interact separately with capital, allowing for a detailed analysis of their combined effects on the production process. This relationship is formulated as a modified Cobb–Douglas production function, expressed by the following equation:

$$Y = A \cdot (LK)^{\alpha_L} \cdot (CK)^{\alpha_C} \quad (1),$$

where Y defines agriculture output in real prices, L represents labor in terms of employed persons, C defines agricultural sector's variable costs as the aggregate of land rental expenses, hired-labor wages and intermediate consumption, K stands for the agriculture sector fixed capital in real prices and A captures total factor productivity.

The above functional form implies that capital acts not as an isolated input but as a productivity amplifier, influencing the effectiveness of labor and cost via the LK and CK interaction terms. The parameters α_L and α_C therefore represent the output elasticities with respect to the labor–capital and cost–capital interactions respectively, as specified below:

$$\varepsilon_L = \frac{\partial Y}{\partial L} \cdot \frac{L}{Y} = A\alpha_L \cdot (LK)^{\alpha_L - 1} \cdot (CK)^{\alpha_C} \cdot K \cdot \frac{L}{A \cdot (LK)^{\alpha_L} \cdot (CK)^{\alpha_C}} = \alpha_L \quad (2)$$

$$\varepsilon_C = \frac{\partial Y}{\partial C} \cdot \frac{C}{Y} = A\alpha_C \cdot (LK)^{\alpha_L} \cdot (CK)^{\alpha_C - 1} \cdot K \cdot \frac{C}{A \cdot (LK)^{\alpha_L} \cdot (CK)^{\alpha_C}} = \alpha_C \quad (3)$$

Since (1) can be rewritten as:

$$Y = A \cdot L^{\alpha_L} \cdot C^{\alpha_C} \cdot K^{\alpha_L + \alpha_C} \quad (4),$$

the output elasticity with respect to capital ε_K is presented as the aggregate of the interaction elasticities:

$$\varepsilon_K = \frac{\partial Y}{\partial K} \cdot \frac{K}{Y} = A \cdot L^{\alpha_L} \cdot C^{\alpha_C} \cdot (\alpha_L + \alpha_C) \cdot K^{\alpha_L + \alpha_C - 1} \cdot \frac{K}{AL^{\alpha_L} \cdot C^{\alpha_C} \cdot K^{\alpha_L + \alpha_C}} = \alpha_L + \alpha_C \quad (5)$$

To estimate the impact of labor, production cost and capital on agricultural output via Ordinary Least Squares, the modified Cobb–Douglas production function is transformed to a log-linear model:

$$\ln(Y) = \beta_0 + \beta_1 \cdot (lnL + lnK) + \beta_2 \cdot (lnC + lnK) + u \quad (6),$$

where u is the disturbance term, $\beta_1 = \alpha_L$, $\beta_2 = \alpha_C$ and $\beta_1 + \beta_2 = \alpha_L + \alpha_C$.

Hence, the parameter estimates directly reflect the output elasticities of the labor–capital and cost–capital interactions, illustrating how shifts in capital intensity condition the productivity of both labor and intermediate inputs and thus affect overall output.

To accommodate non-constant elasticities and endogenous complementarity, the specification follows Thompson (2014) in treating capital as a productivity amplifier. In the form given in (1), this entails that both the marginal product of labor, $\frac{\partial Y}{\partial L}$, and the marginal product of intermediate inputs, $\frac{\partial Y}{\partial C}$, are functions of the capital stock K, thereby endogenizing substitution elasticities and capturing evolving input complementarities.

The traditional Cobb–Douglas form imposes two restrictive assumptions that are crucial for understanding its limitations: (i) unit elasticity of substitution (σ=1) between every input pair; and (ii) full separability, meaning the marginal product of each factor does not depend on the level of any other factor (Arrow et al., 1961). Induced-innovation theory, however, challenges these assumptions by predicting that when relative factor prices change, firms will direct technical change toward the now-cheaper factor, thereby endogenously altering the productivity of both capital and labor (Acemoglu, 2002). Thus, a standard Cobb–Douglas cannot capture complementarity or allow its intensity to adjust, which is necessary to account for economic changes such as mechanization, CAP-subsidy regimes, and rising production costs that have fundamentally transformed agriculture over the past decades.

By contrast, the CES specification of Arrow et al. (1961) relaxes the unit-substitution assumption by permitting $\sigma \neq 1$, yet it still constrains that elasticity to remain constant over time. The translog function, as introduced by Christensen et al. (1973), affords full flexibility, but at the expense of estimating $\frac{n(n+3)}{2}$ parameters, a complexity that induces high covariance among regressors, leading to multicollinearity and unstable estimates (Berndt & Christensen, 1973).

Semi-flexible, interaction-augmented specifications provide a balanced alternative to the rigid Cobb–Douglas and the overly complex translog forms. Thompson (2014) evaluated three competing models: a log-linear Cobb–Douglas, a full translog, and a two-interaction 'physical production function', which is specified as follows:

$$Y = A \cdot (LK)^{a_L} \cdot (EK)^{a_E} \quad (7),$$

where L denotes labor, K capital, E energy, and A total factor productivity, demonstrating that this specification outperforms both the log-linear Cobb–Douglas and the translog by treating capital as a productivity amplifier, thereby introducing spill-over effects to labor and energy that vary with the level of the capital stock.

Based on the above, the study adopts Thompson's (2014) specification by replacing the energy term (E) with sector-specific variable costs (C). This approach preserves log-linearity, allows for the direct interpretation of each exponent as an output elasticity, endogenizes substitution elasticities, and captures evolving capital–input complementarities.

Additionally, given the frequent complex changes in the relationship between agricultural outputs and production inputs in the agricultural sector, due to factors such as rapid technological progress, climate change, and other environmental factors, as well as the application of differentiated policies and changing demand needs, it is necessary to study and detect the presence of structural changes in this sector. In this direction, the Bai-Perron Multiple Structural Changes Linear Estimation (Bai & Perron, 2003) is applied, which detects the presence of endogenous structural breaks, under the following model specification:

$$y_t = x_t'\beta_j + z_t'\delta + u_t, \text{for } t = T_{j-1} + 1, \dots, T_j, j = 1, \dots m + 1 \quad (8),$$

where y_t denotes the dependent variable at time t, x_t represents a vector of covariates with regime-specific coefficients β_j, z_t comprises covariates with time-invariant coefficients δ and the error term u_t captures stochastic disturbances. The model partitions the data into $m + 1$ distinct regimes, defined as intervals $(T_{j-1}, T_j]$ between structural breakpoints, where each regime j maintains constant parameters β_j, while allowing coefficients to shift across regimes.

Initially, the hypothesis of zero versus a fixed number of up to five breaks, and zero versus an undetermined number of up to five breaks (Bai & Perron, 1998) is tested, followed by testing l versus $1 + l$ breaks (Bai & Perron, 2003), a procedure that is particularly suitable for small samples, as outlined in detail by Antoshin et al. (2008). The test statistics are calculated as follows:

$$Test\ statistic: \frac{RSS_0 - RSS_1}{\sigma^2} \quad (9),$$

where RSS_0 is the residual sum of squares under the null hypothesis (fewer breaks), RSS_1 is the residual sum of squares under the alternative hypothesis (more breaks) and σ^2 is the variance of the residuals.

For sequential testing of breaks, the approach involves two steps. In the first stage, the null hypothesis of no structural breaks versus the alternative of m breaks is tested, using the $supF(m)$ test, defined as the maximum F-statistic across all possible break points T_1 through T_m:

$$supF(m) = max\{F_{T_1}, F_{T_{2,\ldots,}} F_{T_m}\} \quad (10)$$

Subsequently, the hypothesis of l versus the alternative of $l + 1$ structural breaks is examined using the $supF(l + 1|l)$ statistic, which evaluates whether the inclusion of an additional break significantly improves the model fit, defined as:

$$supF(1 + l|l) = \frac{T - l(p+q)}{q} \cdot \frac{RSS_l - RSS_{1+l}}{RSS_{1+l}} \quad (11),$$

where p is the number of parameters in β, q is the number of parameters in δ, T is the sample size, RSS_l is the residual sum of squares with l breaks and RSS_{1+l} is the residual sum of squares with $1 + l$ breaks.

The structural change points were detected using the Bayesian Information (BIC) (Yao, 1998) and modified Schwarz (LWZ) (Liu, 1997) criteria, in order to achieve the optimal choice of the number of structural changes incorporated in the regression model. The final selection of the optimal model is achieved based on the criterion that provides the lowest critical value threshold, and then the linear regression model is estimated for each possible period of structural change.

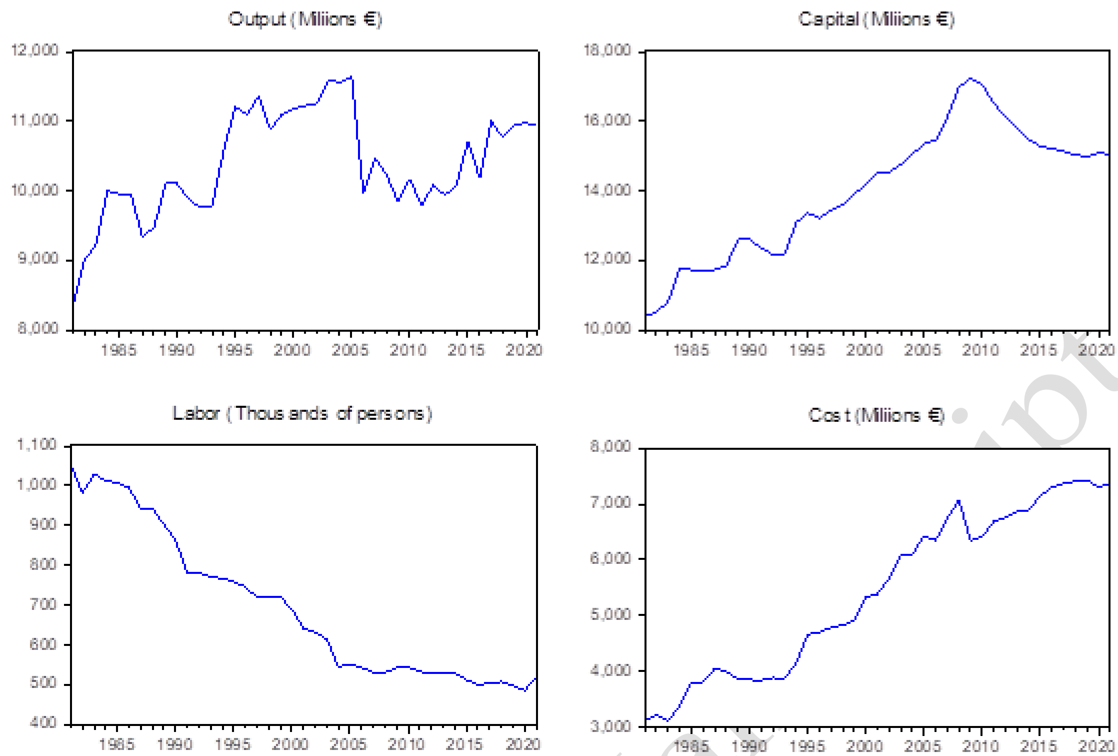
4. RESULTS

In Figure 1, time trends of output, fixed capital, employed persons, and variable costs for the Greek agriculture sector (1980–2020) are presented. Initially, a significant increase in agricultural output and fixed capital of the Greek agriculture sector occurred during the 1980s and up to 1995. This was likely related to the introduction of new technologies and improvements in the management of European resources, which indicate the adoption of strategies for the development of the agricultural sector and the industrialization of production, leading to the transformation of the capital/labor ratio. To provide more detail, the average growth rate of agricultural output for the period 1981–1995 is 2.24%, with an overall percentage change of 34.69% in 1995 compared to 1981. Additionally, the average and total increase in fixed capital for the same period is 1.84% and 28.21%, respectively. This suggests a potential relationship between invested capital and agricultural output, possibly indicating increasing returns to scale. The trend of increasing capital intensity and decreasing labor intensity in agricultural production is evident. This is confirmed by a decrease in the number of individuals employed in the agriculture sector at an average rate of 2.24% per year, resulting in an overall reduction of 27.80% in the total number of farmers, equivalent to 292,200 individuals. In contrast to the trends in output and capital, production costs increased significantly by 3.09% per year and 50.30% overall by 1995 compared to 1981.

During the 1996–2006 period, agricultural output growth reversed, resulting in a total decline of 10.22%. This was mainly due to a 14.41% reduction in agricultural product in 2006 compared to 2005, and an average negative change of 0.95%. In contrast, while capital experienced a decelerated average annual growth of 1.34% and a total growth of 16.95%, employment decreased significantly by 27.35% from 1996 to 2006, at a constant annual rate of 2.90%. On the contrary, production costs continued their upward trend, increasing by 35.11% in 2006 compared to 1996. In 2007, as the global economic crisis emerged, a decline in agricultural output to its average levels during the 1990s and a total reduction of 6.04% is observed. During the years 2007–2009, fixed capital increased by 11.52% compared to the pre-crisis period. However, variable costs decreased less proportionally than the reduction in output, reflecting the negative effects of the crisis on the agricultural sector.

After the crisis period, agricultural output is observed to recover with a slow growth rate of 0.95% per year, failing to reach pre-crisis levels. These recovery efforts are accompanied by a reduction in fixed capital by 11.66% in 2021 compared to 2009, with an annual decrease of 1.12%, and an average increase in production costs of 1.26% annually. Thus, the compensation of fixed capital and variable inputs of production is linked to the stabilization of agricultural output. Finally, the number of individuals employed in the agricultural sector shows relative stability after the negative economic conditions of the period 2007-2009, decreasing by 15,500 individuals in 2021 compared to 2007 at a rate of 2.92%, demonstrating the long-term effect of the economic crisis on employment.

Figure 1. Time trends



The Spearman correlation matrix (Table 1) reveals statistically significant linear relationships between agricultural production, fixed capital, employment, and variable costs, providing insights into the dynamics of agricultural productivity. The positive correlation between agricultural output and capital (rho = 0.338, $p = 0.031$) suggests that an increase in capital contributes to the growth of agricultural productivity. Nevertheless, it appears that the increase in agricultural output is also associated with an increase in variable production costs (rho = 0.447, $p = 0.003$) and a decrease in the number of individuals employed in the agricultural sector (rho = -0.432, $p = 0.005$). The negative correlation between capital and labor (rho = -0.663, $p < 0.001$) confirms the inversion of the capital-labor ratio. The results suggest that technological development and automation of the production process, bring about a steady increase in production. Moreover, improvements in equipment and know-how allow labor to be more productive, regardless of the number of workers, with production costs increasing given increased investment in equipment (rho = 0.653, p < 0.001). Simultaneously, as the number of people employed in the agricultural sector decreases, production costs increase (rho = -0.783, p < 0.001), as a result of changes in the production process, with the integration of more industrialized but also costly practices driving part of the rural population to abandon the agricultural sector.

Table 1. Spearman correlation matrix

	Output	Capital	Labor	Cost
Output	1			
Capital	0.338 (0.031)	1		
Labor	-0.432 (0.005)	-0.663 (<0.001)	1	
Cost	0.447 (0.003)	0.653 (<0.001)	-0.783 (<0.001)	1

Numbers in parentheses denote p-values

Stationarity must be established as a prerequisite in time-series analysis to avoid spurious regression relationships (Granger & Newbold, 1974; Phillips, 1986) and ensure consistent parameter estimates (Phillips & Perron, 1988). Thus, ADF and Phillips-Perron unit root tests are applied, using the MacKinnon critical values of -3.441 and -2.866 for a 1% and 5% significance level with a constant term, and -3.974 and -3.417 for a 1% and 5% significance level with both a constant term and trend (MacKinnon, 1996). As observed at Table 2, for all the variables, the assumption of stationarity is accepted at levels.

Table 2. Unit root tests

	ADF		Phillips-Perron	
	Constant without trend	Constant with trend	Constant without trend	Constant with trend
lnY	-2.897*	-2.928*	-2.958*	-3.421*
lnL+lnK	-4.514*	-4.652**	-3.724**	-3.962*
lnC+lnK	-3.358*	-3.639*	-4.787**	-5.105**

* Denotes stationarity at 5%
** Denotes stationarity at =1%

The confirmed stationarity of all variables ensures that the modified Cobb–Douglas elasticities can be interpreted without the risk of invalidating standard inference procedures due to stochastic trends. The estimation results (Table 3) show that the coefficient β_1 is statistically significant with a value of 0.105 ($p = 0.025$), indicating a positive combined effect of capital and labor on agricultural output. Additionally, the interaction between fixed and variable cost signifies a positive impact on agricultural output (β_2=0.103, $p = 0.038$). Based on the estimated coefficients, output elasticity to labor equals 0.105 and the elasticity of output with respect to variable inputs equals to 0.103, with the output elasticity to capital being equal to 0.208. Consequently, a 1% increase in fixed capital raises agricultural output by 0.208%, while equivalent increases in labor and variable inputs lead to 0.105% and 0.103% increases in agricultural production, respectively, underscoring the relatively greater importance of fixed capital., the production function exhibits decreasing returns to scale.

The modest R^2 of 0.282 reflects that the modified Cobb–Douglas specification—by design—captures only the elasticities of labor, fixed capital, and variable inputs, excluding broader determinants of output such as policy subsidies, climatic shocks, or technological change. Consequently, while the estimated coefficients are informative about input-output relationships, the low goodness-of-fit underscores the need to interpret the results within the context of an inherently multifaceted agricultural system in which many important drivers lie outside the production-function framework.

Table 3. OLS estimation results

Dependent Variable: lnY					
	b	s.e	t	p	
Constant	6.972	3.121	2.234	0.031	*
lnL+lnK	0.105	0.046	2.333	0.025	*
lnC+lnK	0.103	0.048	2.142	0.038	*
R^2		0.282			
F (p)		7.673 (0.002)			

* Significant at 5%

In Table 4, structural breaks testing is presented. The initial test examines the hypothesis of no structural breaks against the alternative of up to 5 separate breaks in the relationship between production inputs and agricultural output. The corresponding sup F_{T}s signal the presence of structural changes, as the null hypothesis of no structural breaks is in any case rejected. The Wald-Wolfowitz Test, using the WD max criterion, also rejects the null hypothesis, supporting the presence of up to five structural breaks.

Having established the presence of structural breaks in the relationship between production inputs and agricultural output, the determination of their exact number follows by testing the null hypothesis of *l* versus the alternative of *l + 1* breaks. This procedure identified one significant break based on the $\sup F_T(1|0)$ statistic, while all other $\sup F(l+1|l)$ were insignificant. The presence of a structural break is confirmed by the BIC and LWZ information criteria, which identify one break occurring in 2006.

Table 4. Estimated structural breaks

0 vs unknown number of breaks	0 vs fixed number of breaks		l versus the alternative of $l + 1$		Information criteria			Estimated break dates
WDmax	Number of Breaks	sup F_T	Number of Breaks	Sup $F_T(l+1\|l)$	Number of Breaks	BIC Criterion	LWZ Criterion	
134.226* (15.590)	1	44.741* (13.980)	*1|0*	44.741* (13.980)	1	-6.479*	-6.123*	2006
	2	30.056* (11.990)	*2|1*	3.972 (15.720)	2	-6.433	-5.856	1990, 2006
	3	26.732* (10.390)	*3|2*	2.882 (16.830)	3	-6.408	-5.591	1987, 1994, 2006
	4	20.230* (9.050)	*4|3*	0.970 (17.610)	4	-6.152	-5.072	1987, 1994, 2006, 2015
	5	14.800* (7.460)	*5|4*	0.219 (18.140)	5	-5.820	-4.442	1987, 1993, 1999, 2006, 2015

* Significant at 5%
Numbers in parentheses denote Bai-Perron critical values

Given the presence of a structural break dated in 2006, the regression model is re-estimated using standard regression techniques, after dividing the sample of observations into two sub-periods with the first covering the 1981 to 2005 and the second 2006 to 2021. The results presented in Table 5, show the existence of significant dissimilarities in the relationship between production inputs and agricultural output for the two sub-periods.

Table 5. OLS estimation results under structural breaks

Dependent Variable: lnY					
1981 - 2005					
	b	s.e	t	p	
Constant	1.225	0.450	2.722	0.011	*
lnL+lnK	0.161	0.077	2.090	0.044	*
lnC+lnK	0.304	0.024	12.461	0.000	**
2006 - 2021					
	b	s.e	t	p	
Constant	10.161	0.931	10.903	0.000	**
lnL+lnK	-0.411	0.059	-6.996	0.000	**
lnC+lnK	0.304	0.056	5.429	0.000	**
R^2		0.852			
F (p)		40.514 (<0.001)			

* Significant at 5%
** Significant at 1%

Regarding the 1981-2005 period, the coefficient of capital and labor is statistically significant (p = 0.044), equal to 0.161. For the combination of capital and variable inputs, the corresponding coefficient is 0.304 ($p < 0.001$). Therefore, it is indicated that the combined increase of fixed capital and labor and fixed capital and variable inputs of production by 1% implies an increase in agricultural output by approximately 0.161% and 0.304% respectively, expressing the contribution of combined efficiency to productivity. The presence of decreasing returns to scale, with scale is evident, as the elasticities the labor and variable cost are equal to 0.161 and 0.304, respectively, while the capital elasticity attributed to the sum of the aforementioned elements is 0.465.

As for the 2006-2021 period, results are strongly differentiated compared to those of the 1981-2005 and even compared to those of the entire 1981-2021 period. The most significant result is the negative sign of the coefficient of capital and labor, which equals -0.411 ($p < 0.001$), indicating that their combined increase leads to a decrease in agricultural output. In contrast, the coefficient for the combination of capital and variable inputs remains at 0.304 and is significant ($p < 0.001$), indicating an increasing effect on agricultural production. The negative elasticity of labor indicates its detrimental effect on production, while capital also shows inelastic behavior with an elasticity of -0.107. In contrast, the positive elasticity of variable production inputs confirms their beneficial effect on agricultural output.

5. DISCUSSION

Analyzing agricultural production in Greece and examining its relationship with production factors opens new perspectives for understanding the driving forces that shape the agricultural economy of the country. The period after Greece's accession to the European Union in 1981 and the implementation of the Common Agricultural Policy marked an era of change in the agricultural sector, coinciding with an increase in productivity following the general European trend. However, this trajectory was not stable, as the present study clearly established certain distinct features, providing insight into the evolution of agricultural production and revealing consequent changes in output, employment, fixed capital, and variable inputs.

More specifically, the results highlight a pronounced shift in how labor, fixed capital, and intermediate inputs drive output, with a clear structural break around the mid-2000s. In the 1981–2005 sub-period, the log-linear estimates under the modified Cobb-

Douglas production function, reveal that labor services and variable inputs both made positive contributions to real output, alongside a robust role for fixed capital. The aggregate of the elasticities remained below unity, indicating decreasing returns to scale. This pattern is often seen in agrarian settings with small, family-run plots, where increasing inputs leads to coordination costs and underutilization rather than proportional production increases (Cornia 1985; Rizov et al. 2013). As Latruffe (2010) emphasizes, when scale elasticities lie below unity further productivity improvements must come from gains in technical efficiency, that is, from using the existing technology and resources more effectively.

The structural break in 2006, marks a radical reversal in factor contributions. Negative labor and capital elasticities are highly atypical, but may occur in cases of severe misallocation of production factors. For example, Zorya et al. (2003) and Bezlepkina & Oude Lansink (2003), document negative land and capital elasticities under transition-era credit schemes in post-Soviet republics, attributing these to mismanaged inputs. Additionally, rapid mechanization can lead to a labor surplus, which may depress output and cause marginal labor products to approach zero or become slightly negative (Echevarría, 1998). Moreover, when physical networks and advisory capacities do not expand in tandem with inputs, it can lead to coordination breakdowns and idle resources, further compounding misallocation and reversing marginal productivity (Yuan, 2011).

According to the above the Greek case can be considered an outlier. Two main mechanisms may explain this anomaly. First, CAP's area-based payments eased credit constraints for many smallholders, who often lacked the scale to justify such investments. This prompted them to acquire tractors and other machinery they could not fully employ, resulting in under-utilized capital assets as idle equipment failed to contribute to output

(O'Toole & Hennessy, 2015; Di Corato & Zormpas, 2022). Second, labor quality may have deteriorated as younger, more productive workers migrated to urban sectors due to the 2007 crisis (Cavounidis, 2013), leaving a workforce skewed toward older, part-time farmers. As Li & Sicular (2013) demonstrate, such demographic shifts can sharply erode the marginal productivity of those who remain, as older farmers tend to adopt new technologies and practices more slowly, which is relevant to the Greek case.

By contrast, variable inputs retain positive output elasticities throughout the full period. This pattern aligns with evidence from the Green Revolution, where greater use of fertilizers, irrigation water, and high-yielding seeds underpinned most of the dramatic yield increases of the late twentieth century (Tilman et al., 2002). For instance, adoption of modern agrochemicals and high-yield varieties can serve as a proxy for rapid productivity growth even as land and labor contributions flatten (Fan et al., 2012). Likewise, extension-supported fertilizer programs in Sub-Saharan Africa, have repeatedly demonstrated that well-targeted variable inputs can deliver positive returns despite systemic constraints on scale (Ricker-Gilbert & Jayne, (2012).

The 2006 structural break in Greek agriculture closely corresponds with the implementation effects of the 2003 CAP 'Fischler' reform, which Greece opted to apply in fully decoupled form immediately after its adoption. By converting subsidies into area-based entitlements, decoupling dismantled the incentive to deploy labor and capital efficiently, allowing farms—many of which were small, fragmented, and operated by aging farmers—to receive support irrespective of production (Konstantinidis, 2016). Consequently, agricultural output gains remained modest, as traditional inputs delivered diminishing returns within a structurally constrained production environment. EU evidence suggests that decoupling can enhance farm productivity in certain contexts (Rizov et al., 2013). However, Greece's structural limitations seem to have hindered effective resource reallocation when market signals replaced production-linked support. As a result, productivity gains failed to materialize, and after 2006, total factor productivity growth in Greece remained weak, reflecting the limited responsiveness of both labor and capital inputs.

Beyond decoupling, other CAP instruments likely reinforced the structural shift. The introduction of cross-compliance in 2005, obliged farmers to adhere to environmental and land-management standards, such as soil conservation, crop rotations, and buffer zones, to qualify for payments. While these measures aim to safeguard long-term productivity, they diverted labor toward non-productive compliance tasks, raising costs and constraining intensive practices (Barnes et al., 2013). Similarly, agri-environment schemes launched in 1992 and broadened in 2003, along with compulsory and later voluntary, set-aside payments, compensate for land withdrawal and low-input management, which have been shown to lower total-factor productivity (Mary, 2013) while sometimes prompting costly input re-allocation (Chakir & Thomas, 2022). In Greece, farm-level evidence shows that higher per-hectare organic-farming subsidies, granted without tying support to output, are associated with lower technical efficiency, implying that such payments can depress factor productivity rather than expand production (Nastis et al., 2012).

The 2013 CAP reform added a "greening" layer, implemented from 2015, that ties part of each farm's direct payment to compliance with crop-diversification rules, the establishment of ecological-focus areas, and the preservation of permanent grassland. Ciaian et al. (2018) show that these obligations can reduce land profitability and curb intensive cultivation, although the predicted output and productivity losses are limited and vary by region. In Greece, where most holdings cultivate fewer than five hectares (European Commission, 2024), the compliance with greening obligations leads to a shift from cash crops to set-aside and low-input uses, resulting in reduced farm income and a reallocation of labor and capital toward compliance measures rather than productivity-focused activities (Mantziaris et al., 2017).

Finally, the 2007-2013 and 2014-2020 Rural Development programmes channeled CAP Pillar II funds into on-farm modernization, training, advisory services, and agri-environmental measures. Dudu and Smeets Kristkova (2017) show that across EU regions, spending on physical-capital investments, human-capital support, and environmental actions raises total-factor productivity. However, in Greece, the absorption of the 2007-2013 Pillar II budget was only 41%, severely restricting opportunities to upgrade irrigation networks, acquire precision machinery, and expand extension services (Reziti & Zangelidis, 2019). Moreover, recurrent administrative fragmentation and ministerial turnover undermined strategic continuity (Karantininis, 2017). As a result, despite Pillar II's potential to restore labor and capital productivity, under-utilization of these funds left Greek agriculture trapped in an input-intensive, subsidy-driven equilibrium, reinforcing the negative elasticity observed after 2006.

Policy implications from our findings are clear. To address the decline in labor and capital productivity, Greece's agriculture policy must shift from general calls for technology uptake to specific actions for efficient use of Common Agricultural Policy (CAP) funds and strengthening national institutions. It is essential to allocate a substantial share of Rural Development (Pillar II) resources to productivity-enhancing activities, such as precision planting technology, drip-irrigated systems, cold-chain storage, and rural infrastructure upgrades, while adjusting co-financing rates based on farm size and business case viability.

Along with financial support for investment in capital, establishing an Agricultural Knowledge and Innovation System (AKIS) is essential for efficiently turning innovations into sustainable productivity improvements. Plans are underway to set up regional AKIS centers to bring universities, research institutes, extension networks, and producers' associations together into an organized system to provide field-relevant skills pertaining to precision agriculture methods, integrated management methods, and digital farm management materials. Through the creation of specific lines for AKIS budgeting within Pillar I and Pillar II, Greece is seeking to ensure continuity for advisory services despite ministerial leadership instability and to improve support for experienced producers in embracing intricate innovations.

Also, realigning Pillar I direct payments to include performance components is expected to enhance the link between subsidies and efficiency improvements. Linking a portion of basic payments to measurable improvement, for example, per labor unit yield increases or and rising return on invested capital, while ensuring compliance with environmental standards, will create a culture of continuous improvement without undermining income certainty. Finally, ongoing monitoring of input elasticities and returns to scale at the regional level can serve as an early-warning system for inefficiency, allowing policymakers to adapt support measures dynamically.

6. CONCLUSIONS

The present study was conducted to evaluate the joint contributions of fixed capital, labor and variable inputs to Greek agricultural output. A log-linear Cobb–Douglas production function, augmented with interaction terms for capital and labor and capital and variable inputs, was estimated through Ordinary Least Squares, and the Bai–Perron multiple-break procedure was employed to detect structural shifts in the input–output relationships. The results of the study demonstrate that the increase in capital and labor, and their interaction, contribute to the increase in agricultural production, aligning with classical production theory. The study also finds a two-way positive relationship between investments in fixed capital and the quality and quantity of production materials, enhancing the productivity of agricultural holdings. However, decreasing returns to scale indicate potential under-utilization of inputs or over-investment in productive factors. This result shows significant changes over time, particularly after 2006, when the efficiency of labor and capital decreased, possibly influenced by the economic crisis, signifying shifts in production patterns.

The negative elasticity of labor is intriguing and complex to explain, potentially attributed to factors such as technological progress and automation. As agricultural technology advances, less labor may be required, yet productivity can still increase. Conversely, the inelasticity of capital suggests diminished returns on investments in fixed equipment, poor management, or inadequate agricultural infrastructure. In contrast, the positive elasticity of variable production factors highlights their crucial role in agricultural output, especially when effectively combined with capital.

Given that Greek agriculture operates within the framework of the CAP, which emphasizes support for agriculture while enforcing compliance with environmental and quality standards, there is an opportunity for Greek agriculture to transition towards higher quality and environmentally friendly production methods. Achieving increased and sustainable agricultural production will require extensive research and innovation efforts across all levels, ensuring that significant innovations are implemented at the necessary scale.

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