EXPLAINING OUTPUT GROWTH WITH A HETEROSCEDASTIC NON-NEUTRAL PRODUCTION FRONTIER: THE CASE OF SHEEP FARMS IN GREECE

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This paper extends the primal decomposition of TFP changes to the case of non-neutral production frontiers. Output growth is decomposed into input growth (size effect), changes in technical efficiency, technical change, and the effect of returns to scale. Within the proposed formulation, however, technical efficiency changes are attributed not only to autonomous changes (i.e., passage of time) but also to changes in input use and in the not-so-fixed farm characteristics. The empirical model is based on a heteroscedastic non-neutral production frontier and an unbalanced panel data set of sheep farms in Greece for the period 1989-92. The technical efficiency change effect is found to be the main source of TFP growth, followed by technical change and the scale effect, which has caused a 0.35% output slowdown The not-so-fixed farm characteristics have been the most important determinant of technical efficiency changes, followed by changes in input use.

Introduction

By using a stochastic production frontier approach, a number of empirical studies (e.g., Fan, 1991; Ahmad and Bravo-Ureta, 1995; Wu, 1995; Kalirajan, Obwona and Zhao, 1996; Kalirajan and Shand, 1997; Giannakas, Tran and Tzouvelekas, 2000; and Giannakas, Schoney and Tzouvelekas, 2001) have provided evidence on the sources of output growth in agriculture.[1] These studies have two features in common: *first*, they have considered only two potential sources of total factor productivity (TFP) growth, namely technical change and technical efficiency changes, and *second*, they have been based on a neutral production frontier. In the light of Bauer (1990), Lovell (1996) and Kumbhakar (2000) theoretical results, the former implies that potentially important sources of TFP growth, such as scale economies and allocative efficiency, have been inadequately omitted from the analysis.[2] On the other hand, the use of a neutral production frontier implicitly assumes that technical efficiency changes are either autonomous (i.e., passage of time) or induced by changes in the not-so-fixed farm-specific characteristics (i.e., socioeconomic and demographic), but in any case are independent of changes in input use.

Bauer (1990), Lovell (1996) and Kumbhakar (2000) provided a theoretical model highlighting the importance of the scale economies as a source of growth, but all the aforementioned studies on agricultural output growth have neglected their impact even though most of them reported evidence of non-constant returns to scale.[3] This certainly provides misleading results concerning the sources of output growth as the scale effect can be omitted in the decomposition of TFP growth only in the case of constant returns to scale (Lovell, 1996). Specifically, Fan (1991), Ahmad and Bravo-Ureta (1995), and Giannakas, Schoney and Tzouvelekas (2001) have most likely underestimated the portion of output growth attributed to TFP by not accounting for the scale effect associated with increasing returns to scale in Chinese agriculture, US dairy farms, and Saskatchewan wheat farms, respectively. On the other hand, Wu (1995), and Giannakas, Tran and Tzouvelekas (2000) have most likely overestimated the portion of output growth attributed to TFP by omitting the scale effect associated with decreasing returns to scale in Chinese agriculture and Greek olive oil production, respectively. Since the range of scale economies is not known *a priori*, it seems appropriate to proceed by statistically testing the hypothesis of constant returns to scale. If this hypothesis is rejected, the scale effect is present and should be taken into account.

More importantly, all previous studies have paid relatively little attention to technical efficiency changes *per se* and its determinants in particular. The former involves two aspects, namely formal statistical testing and appropriate measurement. It has been shown that technical efficiency makes no contribution to TFP changes if it is time invariant (Lovell, 1996; Kumbhakar, 2000). However, with the exceptions of Ahmad and Bravo-Ureta (1995) and Giannakas, Schoney and Tzouvelekas (2001), previous studies have not tested statistically for the presence of time-varying technical efficiency, even though they have explicitly incorporated technical efficiency changes into TFP measurement.[4] Whenever technical efficiency is in fact time-varying, the measurement of technical efficiency changes becomes a crucial issue. Nevertheless, all but one (Wu, 1995) of previous studies have computed the rate of technical efficiency change as the average of the differences of farm-specific estimates between sequential periods instead of using directly the functional representation of the temporal pattern model. This could yield inaccurate estimates of the effect of technical efficiency changes.

On the other hand, it should be recognized in considering the determinants of technical efficiency changes that time-varying technical efficiency may not only be due to autonomous changes (i.e., passage of time), but it could also be related to changes in the not-so-fixed farm-specific socioeconomic and demographic factors as well as changes in input use.[5] In analytical terms, identifying the determinants of technical efficiency changes is perhaps as important as decomposing the technical change effect into a neutral and a bias component. However, considering explicitly the impact that changes in input use may have on technical efficiency changes requires moving away from the conventional neutral production frontier model and using instead a non-neutral formulation. In the latter, technical inefficiency stems from farm-specific characteristics and the intensity of input use (Huang and Liu, 1994). That is, the degree of technical efficiency depends on the method of applications as well as the quantity of inputs used. Consequently, technical efficiency changes may be attributed to changes in the factors determining the methods of applications (i.e., time-specific factors and farm-specific socio-economic and demographic variables) and to changes in input use.

The main objective of this paper is to extent Bauer (1990), Lovell (1996) and Kumbhakar (2000) primal decomposition of output growth to the case of non-neutral production frontiers. Thus output growth is decomposed into input growth, technical efficiency changes, technical change and the scale effect. However, apart from autonomous changes (i.e., passage of time) only, technical efficiency changes are also attributed to changes in input use and to changes in the not-so-fixed farm-specific characteristics. Separate estimates of these components of output growth are obtained from the estimated parameters of the underlying non-neutral production frontier function. The empirical model is based on a heteroscedastic non-neutral production frontier that allows the variance of the one-sided error term to be function of farm-specific characteristics, and an unbalanced panel data set of 51 Greek sheep farms over the period 1989-92. To the best of our knowledge this is the first attempt to formulate and estimate a heteroscedastic non-neutral production frontier.

A restructuring of the sheep sector started after Greece's accession to the European Union (EU) that involved a transition from an extensive (nomadic) towards a more intensive production system, with the aid of the provided structural funds. At present, the major production system may be characterized as semi-extensive with or without transhumance, where sheep graze throughout the year but herbage intake is sufficient to meet the nutritional requirements only for 3-5 months (March-April to June-July) and the rest is covered with concentrates and roughage.[6] On the other hand, EU price support policies, implemented on a flock size base, induced farmers to rely more on the increase of flock size in order to sustain their income, rather than to improve their productive efficiency (Hadjigeorgiou *et al.*, 1999). Indeed the average flock size increased significantly from 45 in 1982 to 70 in 1993 but the total number of sheep rose only slightly as the number of sheep farms decreased from the 1980s to the 1990s. It is hypothesized that these changes have affected the productive performance of sheep farms and our empirical results attempt to shed some light on their impact on the sources of output growth.

The rest of this paper is organized as follows: the theoretical model using a non-neutral production frontier is presented in the next section. The empirical model based on a heteroscedastic non-neutral production frontier function is discussed in the third section. The data employed in the empirical model are described in the fourth section and the empirical results are analyzed in the fifth section. Concluding remarks follow in the last section.

Theoretical Framework

Consider that farms use inputs $x = (x_1, x_2, ..., x_J)$ to produce a single output y through a technology described by a well-behaved production function $f(x;t)$, where t is a time index. Since farms may not necessarily be technically efficient, $y \leq f(x;t)$ or equivalently $y = f(x;t)TE^O(x;z,t)$, where $TE^O(x;z,t)$ is the output-oriented measure of technical inefficiency defined over the range $(0,1]$ and $z = (z_1, z_2, ..., z_M)$ is a vector of farm-specific characteristics.[7] The above formulation corresponds to the Huang and Liu (1994) non-neutral production frontier model, which assumes that technical efficiency depends on both the method of application of inputs and the intensity of input use. The former is related to the managerial and organizational ability of farmers, which is assumed to depend on farm-specific characteristics and learning by doing (i.e., passage of time).

After taking logarithms of both sides of $y = f(x;t)TE^O(x;z,t)$ and totally differentiating with respect to time results in:

$$\dot{y} = T_t(x;t) + \sum_{j=1}^{J} \varepsilon_j(x;t)\dot{x}_j + \dot{TE}^O(x;z,t) + \sum_{j=1}^{J} \frac{\partial TE^O(x;z,t)}{\partial \ln x_j}\dot{x}_j + \sum_{m=1}^{M} \frac{\partial TE^O(x;z,t)}{\partial \ln z_m}\dot{z}_m \quad (1)$$

where a dot over a function or a variable indicates a time rate of change, $\varepsilon_j(x;t) = \partial \ln f(x;t)/\partial \ln x_j$ is the output elasticity of the j^{th} input, and $T_t(x;t) = \partial \ln f(x;t)/\partial t$ is the primal rate of technical change. Substituting the *Divisia index* of TFP growth, $\dot{TFP} = \dot{y} - \sum_{j=1}^{J} s_j \dot{x}_j$, into (1) yields:

$$\dot{TFP} = T_t(x;t) + \sum_{j=1}^{J} \{\varepsilon_j(x;t) - s_j\}\dot{x}_j + \dot{TE}^O(x;z,t) + \\ + \sum_{j=1}^{J} \frac{\partial TE^O(x;z,t)}{\partial \ln x_j}\dot{x}_j + \sum_{m=1}^{M} \frac{\partial TE^O(x;z,t)}{\partial \ln z_m}\dot{z}_m \quad (2)$$

where $s_j = (w_j x_j)/C$, w_j is the price of the j^{th} input and C is the (observed) total cost. Under profit maximization and allocative efficiency $w_j = p(\partial f(x;t)/\partial x_j)$ and thus $s_j = \varepsilon_j(x;t)/E$ (Chan and Mountain, 1983). Then, (2) may be rewritten as:

$$\dot{TFP} = T_t(x;t) + (E-1)\sum_{j=1}^{J} \left\{\frac{\varepsilon_j(x;t)}{E}\right\}\dot{x}_j + \dot{TE}^O(x;z,t) + \\ + \sum_{j=1}^{J} \frac{\partial TE^O(x;z,t)}{\partial \ln x_j}\dot{x}_j + \sum_{m=1}^{M} \frac{\partial TE^O(x;z,t)}{\partial \ln z_m}\dot{z}_m \quad (3)$$

where $E = \sum \varepsilon_j(x;t)$ is the scale elasticity that is greater than, equal to, or less than one under increasing, constant, or decreasing returns to scale, respectively.

In (3), TFP changes may be attributed to three sources: *first*, into the technical change effect (first term), which is positive (negative) under progressive (regressive) technical change. This term, which can be decomposed further into a neutral and a biased component, vanishes when there is no technical change. *Second*, into the scale effect (second term), the sign of which depends on both the magnitude of the scale elasticity and the changes of the aggregate input over time. It is positive (negative) under increasing (decreasing) returns to scale as long as input use increases and *vice versa*. This term vanishes when either the technology is characterized by constant returns to scale (i.e., E=1) or the aggregate input quantity remains unchanged over time. *Third*, into the technical efficiency changes effect (the sum of the last three terms), which contributes positively (negatively) to TFP growth as long as efficiency changes are associated with movements towards (away from) the production frontier.[8] These changes may be due to three factors: (a) the passage of time (i.e., autonomous changes) (third term), (b) changes in input use (fourth term), and (c) changes in the not-so-fixed farm-specific characteristics (fifth term). These three terms are closely related to the form of the production frontier. If it is specified as non-neutral, which is the most general formulation, all of these terms are relevant and should be taken into account. If instead a neutral production frontier is assumed, the fourth term vanishes and then there are two alternatives. If TE^O is specified as a technical inefficiency effect model (see Kumbhakar, Ghosh and McGuckin (1991) and Battese and Coelli (1995)), both the third and the fifth term should be considered, but if TE^O is modeled as a pure time-varying process, following the specifications of Cornwell, Schmidt and Sickles (1990), Kumbhakar (1990), Battese and Coelli (1992) or Cuesta (2000), only the third term in (3) should be taken into account.[9]

The above decomposition encompasses those developed previously by Bauer (1990), Lovell (1996) and Kumbhakar (2000) as special cases. In particular, (2) and (3) are nested to the decompositions of TFP proposed respectively by Bauer (1990) and Lovell (1996) when the last two terms in these two equations are both set equal to zero. In addition, if the last two terms in (2) are both set equal to zero, then it degenerates Kumbhakar's (2000) decomposition by noticing that the second term in (2) may be written as $(E-1)\sum(\varepsilon_j(x;t)/E)\dot{x}_j + \sum(\varepsilon_j(x;t)/E - s_j)\dot{x}_j$.[10] Finally, under the additional assumption that constant returns to scale prevails, the third term in (3) also vanishes, and then it provides the decomposition developed by Nishimizu and Page (1982).

For the purposes of this study, (3) is converted into an output growth format, by using the *Divisia index* of TFP growth and $s_j = \varepsilon_j(x;t)/E$, i.e.:

$$\dot{y} = T_t(x;t) + (E-1)\sum_{j=1}^{J}\left\{\frac{\varepsilon_j(x;t)}{E}\right\}\dot{x}_j + \dot{TE}^O(x;z,t) + \\ + \sum_{j=1}^{J}\frac{\partial TE^O(x;z,t)}{\partial \ln x_j}\dot{x}_j + \sum_{m=1}^{M}\frac{\partial TE^O(x;z,t)}{\partial \ln z_m}\dot{z}_m + \sum_{j=1}^{J}\left\{\frac{\varepsilon_j(x;t)}{E}\right\}\dot{x}_j \quad (4)$$

where the last term refers to the size effect that captures the contribution of aggregate input growth (factor accumulation) on output changes. Output increases (decreases) are associated with increases (decreases) in the aggregate input, *ceteris paribus*. Also, the more essential an input is in the production process the higher its contribution is on the size effect.

A quite different relationship has been used in previous studies to decompose agricultural output growth, namely:

$$\dot{y} = \dot{TE}^{0}(x;z,t) + T_t(x;t) + \sum_{j=1}^{J} \varepsilon_j(x;t)\dot{x}_j \tag{5}$$

This can be seen as a restrictive version of (4) in the sense that it implicitly assumes (a) a neutral production frontier, (b) a pure time-varying specification for the technical inefficiency function, and (c) a constant returns to scale technology.[11] Besides these, the measurement of the size effect consists another notable difference between (4) and (5). In particular, Fan (1991), Ahmad and Bravo-Ureta (1995), Giannakas, Tran and Tzouvelekas (2000), and Giannakas, Schoney and Tzouvelekas (2001) have measured the size effect using the last term in (5), which is different from the last term in (4).[12] They are equal only under constant returns to scale. Given however that Fan (1991), Ahmad and Bravo-Ureta (1995), and Giannakas, Schoney and Tzouvelekas (2001) have reported evidence of increasing returns to scale, they have overestimated the relative contribution of the size effect, while Giannakas, Tran and Tzouvelekas (2000) have underestimated it since they have found decreasing returns to scale.[13] Thus, (4) and (5) would yield quite different results concerning the sources of output growth. Specifically, the relative contribution of TFP into output growth is overestimated (underestimated) when (5) is employed and decreasing (increasing) returns to scale prevail, while the opposite is true for the size effect.

Apart of analytical reasons, appropriately quantifying the sources of output growth is also important for analyzing sectors' long-term prospects and policy related issues. The greater the portion of output growth attributed to TFP is, the better the long-term prospects for farm income are, since the size effect (i.e., input growth) is considered as a costly source of growth while TFP as a costless, at least from farmers' point of view. In addition, the relative importance of each TFP component is by itself informative as the factors (and presumably the policies) affecting the various sources of TFP growth are not necessarily the same. For example, R&D has a considerable impact on the technical change effect but it rarely affects technical efficiency changes. In contrast, extension may affect both through its impact of the rate of diffusion and by improving the managerial and organizational ability of farmers. A similar argument could be made for education. On the other hand, the scale effect is usually related to farm size, land fragmentation, rules governing farm successors, capital and borrowing constraints, which are prompt to structural and institutional changes. As long as the driving forces of growth are taken into account in shaping development policies, the decomposition analysis could provide some useful insights.

Empirical Model

Consider the stochastic production frontier $y_{it} = f(x_{it}; \beta) exp(v_{it} - u_{it})$, where $f(\bullet)$ is approximated by the translog function, i.e.,

$$\ln y_{it} = \beta_0 + \sum_{j=1}^{J} \beta_j \ln x_{jit} + \frac{1}{2} \sum_{j=1}^{J} \sum_{k=1}^{J} \beta_{jk} \ln x_{jit} \ln x_{kit} + \beta_T t + + \frac{1}{2} \beta_{TT} t^2 + \sum_{j=1}^{J} \beta_{Tj} \ln x_{jit} t + e_{it} \qquad (6)$$

with symmetry imposed ($\beta_{jk} = \beta_{kj}$), the subscript i is used to index farms, β is a vector of parameters to be estimated, $e_{it} = v_{it} - u_{it}$ is a stochastic composite error term, and $-u_{it} = \ln TE_{it}^{O}$. The term v_{it} depicts a symmetric and normally distributed error term (i.e., statistical noise), which represents those factors that cannot be controlled by farmers, measurement errors in the dependent variable, and omitted explanatory variables. It is further assumed that v_{it} and u_{it} are independently distributed from each other.

In modelling u_{it}, it is assumed that the mean of the pre-truncated distribution depends on both input use and farm-specific characteristics while the variance of the pre-truncated distribution depends only on farm-specific characteristics. These result in a heteroscedastic non-neutral production frontier model.[14] Specifically, by using Huang and Liu (1994) formulation for the mean and Reifschneider and Stevenson (1991) additive formulation for the variance of the pre-truncated distribution, the following specification is obtained:

$$\mathrm{u}_{\mathrm{it}} = \delta_o + \sum_{j=1}^{J} \delta_j \ln x_{jit} + \sum_{m=1}^{M} \delta_m z_{mit} + A(t) \quad (7a)$$

$$\sigma^2_{(u)it} = exp\left(\theta_o + \sum_{m=1}^{M} \theta_m z_{mit} \right) \quad (7b)$$

where $A(t) = \sum_{t=1}^{T} \delta_T D_t$ with D_t being time dummies, and δ and θ are vectors of parameters to be estimated.[15] In the above set-up, both the mean and the variance are farm-specific parameters of the distribution of u_{it}. This allows for non-monotonic inefficiency effects with respect to factors included in both (7a) and (7b).

The above specification is quite general and encompasses several of previous models as special cases. *First*, if $\theta_m = 0$ (for all *m*) then (7a)-(7b) are nested to the Huang and Liu (1994) non-neutral production frontier model. *Second*, if $\theta_m = \delta_j = 0$ (for all *m* and *j*) then (7a)-(7b) are reduced to the conventional technical inefficiency effect model. *Third*, if $\theta_m = \delta_j = \delta_m = \delta_T = 0$ (for all *m*, *j*, and *T*) then (7a)-(7b) result in the Stevenson (1980) model. *Fourth*, if $\theta_m = \delta_j = \delta_m = \delta_T = \delta_0 = 0$ (for all *m*, *j* and *T*) then the Aigner, Lovell and Schmidt (1977) model is obtained. *Fifth*, if $\delta_j = 0$ (for all *j*) then (7a)-(7b) degenerate the Wan (2002) heteroscedastic technical inefficiency effect model. *Sixth*, if $\delta_j = \delta_m = \delta_T = 0$ (for all *j*, *m* and *T*) then (7a)-(7b) yield the heteroscedastic frontier model used by Christopoulos, Lolos and Tsionas (2002).

The frontier model (6), (7a) and (7b) is estimated by the maximum likelihood method using the Gauss (Version 3.2.26) computer program and TE^O_{it} is computed by the conditional expectation of $exp(-u_{it})$ given e_{it} as:

$$TE^O_{it} = \exp\left[-\mu^0_{it} + 0.5\left(\sigma^0_{it}\right)^2 \right] \left[\frac{\Phi\left(\rho^0_{it} - \sigma^0_{it}\right)}{\Phi\left(\rho^0_{it}\right)} \right] \quad (8)$$

where $\mu^0_{it} = \frac{\sigma^2_v \mu_{it} - \sigma^2_{(u)it} e_{it}}{\sigma^2_v + \sigma^2_{(u)it}}$, $\sigma^0_{it} = \frac{\sigma_{(u)it}\sigma_v}{\sqrt{\sigma^2_{(u)it} + \sigma^2_v}}$, $\rho^0_{it} = \frac{\mu^0_{it}}{\sigma^0_{it}}$, and $\Phi(\bullet)$ represents the cumulative distribution function of the standard normal random variable. In addition, following Wan (2002), the components of the technical efficiency changes effect are computed as:[16]

$$\dot{TE}_{it}^{O} = -[A(t) - A(t-1)]\xi_{it}\left(\sigma_{it}^{0}\right)^{-2} \tag{9a}$$

$$\frac{\partial \ln TE_{it}^{O}}{\partial \ln x_{jit}} = -\delta_j\left[\xi_{it}\left(\sigma_{it}^{0}\right)^{-2}\right] \tag{9b}$$

$$\frac{\partial \ln TE_{it}^{O}}{\partial \ln z_{mit}} = -z_{mit}\left\{\delta_m\left[\xi_{it}\left(\sigma_{it}^{0}\right)^{-2}\right] + \theta_m\left[0.5\sigma_{it}^{0}\zeta_{it}\right]\right\} \tag{9c}$$

where $\xi_{it} = \left(\sigma_{it}^{2}\right)^{2}\left\{1 - \rho_{it}^{0}\frac{\varphi\left(\rho_{it}^{0}\right)}{\Phi\left(\rho_{it}^{0}\right)} - \left[\frac{\varphi\left(\rho_{it}^{0}\right)}{\Phi\left(\rho_{it}^{0}\right)}\right]^{2}\right\}$, $\zeta_{it} = \left[1 + \left(\rho_{it}^{0}\right)^{2}\right]\frac{\phi\left(\rho_{it}^{0}\right)}{\Phi\left(\rho_{it}^{0}\right)} + \rho_{it}^{0}\left[\frac{\phi\left(\rho_{it}^{0}\right)}{\Phi\left(\rho_{it}^{0}\right)}\right]^{2}$

and $\varphi(\bullet)$ is the density function of the standard normal distribution. On the other hand, the primal rate of technical change for (6) is measured as:[17]

$$T_{it}(x;t) = \beta_T + \beta_{TT}t + \sum_{j=1}^{J}\beta_{Tj}x_{jit} \tag{10}$$

and the scale elasticity is calculated as follows:

$$E_{it} = \sum_{j=1}^{J}\varepsilon_{jit} = \sum_{j=1}^{J}\left(\beta_j + \sum_{k=1}^{J}\beta_{jk}x_{kit} + \beta_{Tj}t\right) \tag{11}$$

Then, the relationships (9), (10) and (11) are used to implement the decomposition of output growth through (4).

Data Description

Sheep farming consists the largest livestock sector in Greece accounting for 43% of the total value of livestock product. Sheep milk and meat are also among the major agricultural commodities with a share of around 13% in the total value of agricultural production. In the early 1990s (the period considered in this study), sheep milk and meat production were around 640 and 82 thousands tonnes, respectively. In that period, there were almost 130,000 farms, with varying degrees of specialization, most of which were located in less-favored and mountain areas where employment opportunities outside farming were limited. The major production system was (and still is) characterized as semi-extensive (with or without transhumance) and mainly utilized dual-purpose (milk and meat) local breeds. Production is labor intensive and mainly uses family labor. Greece is the fourth largest EU producers of sheep milk and meat accounting for a 10% of the total EU production.

The data for this study are taken from a questionnaire survey conducted by the Institute of Agricultural Economics and Rural Sociology of the National Agricultural Research Foundation of Greece. The objective of the survey, financed by the Greek Ministry of Agriculture, was to provide information on the total cost of production for the major agricultural commodities during the period 1989-92. The sample of farms included in the survey consists a rotating panel that fulfils certain stratification criteria. In particular, the sample was stratified according to the orientation of production, geographical regions, the total number of farms in each region, and farm size in order to reflect national averages. Production orientation is determined according to the sources of revenue, using the two thirds of farm revenue as a relevant benchmark figure.

Our analysis is based on a total of 51 sheep farms that received more than 95% of their revenue from sheep meat, milk and wool products. The data set used is an unbalanced panel of 178 observations, which means that on average each farm is observed three to four times during the period 1989-92. Although a larger number of farms had been classified as sheep farms, we have focused only on those highly specialized sheep farms (with no or very limited number of goats) to ensure that the underlying assumption of the best practice frontier approach (i.e., that the sample farms operate under a common technology) is met to a great extent. Consequently, a number of farms that combine sheep and goat production were excluded from the analysis, even though more than two thirds of their revenue came from sheep products, as it was suspected that their production technology may differ from that of highly specialized sheep or goat farms. In addition, using the portion of graze, and concentrates and roughage cost on total feed expenses (see Table 1), we may infer that the sample of the sheep farms used is rather homogeneous in terms of the technology employed, namely the semi-extensive production system.

For the purposes of the present study, output is measured in terms of total gross revenue from farm produce (i.e., meat, milk and wool) measured in value terms. Summary statistics of this and the following variables are given in Table 1. The inputs considered are: *first*, labor (including family and hired workers) measured in full-time annual working days. *Second*, flock size measured by the number of animals. *Third*, expenses for feed (including graze and concentrates and roughage), measured in value terms;[18] and *fourth*, other cost expenses, consisting of fuel and electric power, depreciation, interest payments, veterinary expenses, fixed assets interest, taxes and other miscellaneous expenses, measured in value terms. All value term variables have been converted into 1990 constant prices.

The following variables have been included in the *z*-vector: *first*, the age of the farm owner, measured in years. *Second*, farm owner's education, measured in years of schooling.[19] *Third*, outstanding farm debt, measured in value terms. *Fourth*, total direct income payments received, measured in value terms. *Fifth*, a location dummy variable, which takes the value of one if the farm locates in less-favored areas (LFA) and zero otherwise.[20] *Sixth*, a dummy variable determining the type of operation, which takes the value of one for family farming and zero otherwise. *Seventh*, a dummy variable indicating whether an improvement plans is taking place in the farm, which takes the value of one if such a plan is in place and zero otherwise. *Eighth*, time dummies to capture the temporal pattern of technical inefficiency.

Empirical Results

The estimated parameters of (6) and (7) are reported in Table 2.[21] The first-order parameters (β_j) have the anticipated (positive) sign and magnitude (being between zero and one), and the bordered Hessian matrix of the first and second derivatives is found to be negative semi-definite implying that all regularity conditions (namely, positive and diminishing marginal products) are valid at the point of approximation (i.e., the sample mean). The computed pseudo-R^2 (Greene, 1993; p. 651) is 0.856 indicating that the proposed model is a good representation of the data-generation process.

Several hypotheses concerning model specification are presented in Table 3.[22] *First*, the null hypothesis that $\theta_0 = \theta_m = \delta_0 = \delta_j = \delta_T = 0$ (for all *m*, *j* and *T*) is rejected at the 5% level of significance, indicating that the technical inefficiency effects are in fact stochastic and present in the model. Moreover, Schmidt and Lin's (1984) test for the skewness of the composed error term also confirms the existence of technical inefficiency.[23] Consequently, the traditional average production function does not represent adequately the input-output relationship of the farms in the sample. It was found that the majority of farms in the sample operated below the production frontier and thus, differences in the degree of technical efficiency explain a significant part of output variability across farms.

Second, we test the proposed formulation against several nested alternatives. In particular, the null hypothesis that $\theta_m = 0$ (for all *m*) is rejected at the 5% level of significance, implying that the homoscedastic Huang and Liu (1994) model is rejected in favor of the more general heteroscedastic non-neutral production frontier model (see Table 2). In addition, the hypotheses that $\theta_m = \delta_j = 0$ (for all *m* and *j*) and that $\delta_j = 0$ (for all *j*) are both rejected at the 5% level of significance, indicating that neither the homoscedastic nor the heteroscedastic technical inefficiency effects model are supported by the data. Lastly, the hypothesis that $\delta_j = \delta_m = \delta_T = 0$ (for all *j*, *m* and *T*) is also rejected at the 5% level of significance, implying that the heteroscedastic truncated normal specification of the production frontier model (e.g., Christopoulos, Lolos and Tsionas, 2002) could not be degenerated by the data.

From the above it is evident that both conventional inputs and farm-specific characteristics have a significant role in explaining differences in the mean and the variance of the technical efficiency distributions. Given that the effect of some of these variables are non-monotonic in the proposed specification, their impact is more accurately determined by the corresponding marginal effects, reported in Table 4, rather than the relevant estimated parameters presented in Table 2. From Table 4, it follows that the impact of all conventional inputs on technical efficiency is negative for the whole period under consideration. That is, technical efficiency decreases as the quantity of input used increases. On the other hand, all but one (i.e., location) of farm-specific characteristics have positive mean and variance effects, with farm debts being the only exception with respect to its variance effect which was negative.

Regarding some of these effects in particular, it is worth mentioning that *first*, the magnitude of the mean effect of farmer's age decreases significantly in the fourth quartile of the distribution lending support to the hypothesis of decreasing returns to experience (Makary and Rees, 1981; Tauer, 1995).[24] *Second*, the result for education is in accordance with Welch's (1970) "worker effect", stating that education leads to better utilization of given inputs as it enables farmers to use technical information more efficiently. *Third*, the result for the direct income payments indicates that, in order to remain in business, farmers tend to become more efficient as their exposure to market pressure increases. *Fourth*, the finding with respect to farm debts supports

Jensen's (1986) hypothesis that greater reliance on debts to finance farm operation stimulates considerable effort by farmers to improve their performance in order to meet cash obligations. *Fifth*, family farming tends to result in higher efficiency due to stronger incentives as well as absence of monitoring and screening effort.

Estimates of technical efficiency scores in the form of frequency distributions are reported in Table 5. During the period 1989-92, mean technical efficiency is estimated at 67.92% implying that output could have increased on average by 32.08% if inefficiency was eliminated. Mean technical efficiency follows a slightly increasing trend over time as it has increased from 67.50% in 1989 to 68.30% in 1992. This is also confirmed from the estimates of the relevant parameters in the mean inefficiency function (see Table 2) and the fact that the hypothesis of time-invariant (due to autonomous changes) technical inefficiency (i.e., $\delta_T = 0$ for all *T*) is rejected at the 5% level of significance (see Table 3). Thus it can be argued that, for most farms in the sample, the pattern of technical efficiency indicates movements towards the production frontier over time.

As far as the structure of production technology is concerned, the hypothesis that the production frontier has a Cobb-Douglas form (i.e., $\beta_{jk} = 0$ for all *j* and *k*) is rejected at the 5% level of significance (see Table 3). In addition, the hypotheses of no technical change (i.e., $\beta_{\mathrm{T}} = \beta_{TT} = \beta_{Tj} = 0$ for all *j*) as well as that of Hicks-neutral technical change (i.e., $\beta_{Tj} = 0$ for all *j*) are rejected at the 5% level of significance (see Table 3).[25] Thus technical change has been a significant source of output growth and it should be taken into account in (4). The neutral component of technical change is found to be progressive at a constant rate as the estimates for the parameters β_T and β_{TT} are both positive, but the latter is statistically insignificant at the 5% level of significance (see Table 2). Regarding biases, technical change is found to be feed-saving, flock size-using, and labor- and other cost-neutral as the relevant estimated parameters are not statistically different than zero (see Table 2).

On the other hand, the null hypothesis of a linearly homogeneous production technology (i.e., $\sum \beta_j = 1$ and $\sum \beta_{jk} = \sum \beta_{Tj} = 0$ for all *j* and *k*) is also rejected at the 5% level of significance, implying the existence of non-constant returns to scale. Thus, the scale effect is a significant source of output growth and it should be taken into account in (4). According to our empirical results, production was characterized by decreasing returns to scale, which on average was 0.904 during the period 1989-92. This means that the policy-induced increase of flock size went beyond the potential capabilities of the semi-extensive production system. That is, the average flock size of 174 sheep (see Table 1) was, for the semi-extensive system, greater than that maximizing the ray average productivity. Moreover, due to the continued increase in average flock size, returns to scale were following a declining trend over time (see Table 6). At 1989 the relevant point estimate of returns to scale was 0.943, while at 1992 it decreased to 0.838.

The decomposition analysis results are presented in Table 7, where the first two columns are based on (4) and the last two on (5). In both cases, the magnitude of the average annual rate of change during the period under consideration is reported first, followed by the relative contribution of the corresponding effect into the observed output growth. Notice that in computing the technical efficiency change effect in (4), we have considered only those farm-specific characteristics that have changed over time (i.e., the not-so-fixed farm characteristics). It turns out that the type of farming (i.e., family or not), farm location (i.e., in LFA or anywhere) and formal education had no impact on the technical efficiency change effect. On the other hand, following most of previous studies, we have used discrete changes based on the results reported in Table 5 to compute the technical efficiency change effect in (5).

From Table 7 it is clear that (4) and (5) yield quite different results regarding the sources of output growth. This is rather expected as the hypothesis of constant returns to scale has been rejected and the computation of the size and the technical efficiency change effects has been done differently. Since evidence of decreasing returns to scale has been found, the relative contribution of TFP into output growth is overestimated when (5) is employed, while the opposite is true for the size effect, as long as the technical efficiency change and the size effects are measured in the same way. In this case, part of output growth would be falsely attributed to TFP changes whereas it is in fact associated with increases in input use. However, this is not reflected in the results reported in the last two columns of Table 7 because different measures of both the technical efficiency change and the size effects have been used. Besides these differences, it should be noticed that the portion of unexplained residual is greater when the decomposition of output growth is based on (5).

Given that the hypotheses of constant returns to scale and of a neutral production frontier have been rejected, we proceed by using (4). During the period 1989-92, the average annual output growth was 3.94%. The empirical results in Table 7 indicate that a greater portion of the observed output growth (60.2%) is attributed to the size effect and a smaller portion (32.9%) to TFP growth. Specifically, the aggregated input increased with an average annual rate of 2.37% while the average annual rate of TFP growth is estimated at 1.30%. Most of the aggregated input growth is associated with flock size and feed whereas a smaller portion is due to increases in labor and other cost. This is a rather expected result given the ongoing then increase in the average flock size and the required increase in feed.

Technical efficiency change is found to be the main source of TFP and output growth. In particular, during the period under consideration, 87.7% of TFP growth and 28.8% of the observed output growth have been attributed to changes in technical efficiency (see Table 7). The effect of technical efficiency changes is positive since the pattern of technical efficiency indicated movements towards the production frontier over time. Moreover, additional insights on the sources of technical efficiency changes can be drawn from the proposed model. Specifically, the not-so-fixed farm characteristics have been the most significant determinants of technical efficiency changes, while only a small portion is due to pure autonomous changes (i.e., passage of time). From the *z*-variables, farm debts and direct income payments have been the most important, with the latter canceling entirely the negative impact of inputs. Concerning the impact of inputs, it should be noticed that, in contrast to the size effect, labor and other cost have been far more important in explaining changes in technical efficiency.

On the other hand, the average annual rate of technical change is estimated at 0.50% and accounts for 12.7% of the observed output growth and for 38.5% of TFP growth (see Table 7). Concerning the sources of technical change, it can be seen from Table 7 that 94% is due to its neutral component and only 6% to its biased component. Technical change is found to be the second more important source of output and TFP growth. This finding contradicts however with previous results of Fan (1991), Ahmad and Bravo-Ureta (1995), Wu (1995), Kalirajan, Obwona and Zhao (1996), Kalirajan and Shand (1997), Giannakas, Tran and Tzouvelekas (2000), and Giannakas, Schoney and Tzouvelekas (2001), who found technical change to be the main source of TFP growth. Since there are no differences in computing the effect of technical change, this result may due to differences in computing the size and the technical efficiency changes effects as well as the treatment of the scale effect, which indirectly affect the relative contribution of technical change into TFP growth.[26]

The scale effect is negative as sheep farms in the sample exhibited decreasing returns to scale and the aggregated input increased over time. During the period 1989-92, diseconomies of scale have slowed down annual output growth at an average rate of 0.35% (see Table 7). This is a rather significant figure that would have been omitted if constant returns to scale were falsely assumed. In such a case, TFP growth would have been overestimated. Specifically, the estimated average annual rate of TFP growth would have been 1.65% instead of 1.30%. Consequently, there would have been significant differences in TFP growth by not accounting simultaneously for the scale effect.

The above empirical results indicate that at the beginning of the 1990s the long-term prospects of sheep farming in Greece did not seem very promising, as only one third of the observed output growth during the period 1989-92 were attributed to TFP. Afterwards these have been reflected in the evolution of the sector during the 1990s, when the number of farms continued to decrease steadily and the income from sheep farming declined relative to other agricultural products. The policy-induced increase of flock size, within the frame of the semi-extensive production system still in use, had resulted in a negative scale effect that squeezed TFP growth. The estimated slow rate of technical change, on the other hand, indicates very limited attempts to modernize the existing production system or to adopt a better one. On possible reason for this is that the semi-extensive system had not exhausted yet its production potential at the beginning of the 1990s. This is reflected in our estimates of the degree of technical efficiency, which imply that there were still opportunities for improvement at that time. Consequently, it is not surprising that technical efficiency change was found to be the main driving force of TFP growth.

Taking these findings at face value, it would suggest that in the 1990s emphasis should have been placed into measures enhancing technical efficiency. In particular, our empirical results indicate that the intensity of input use was the main source of deterioration for technical efficiency. In this instant, the role of extension services may be important, as one of their tasks is to disseminate information on optimal input use and best practice instructions. Another task is to consult directly with farmers on specific production problems, thus facilitating a better understanding of the potentials as well as the limitations surrounding the semi-extensive production system. These could have eventually helped farmers to improve technical efficiency. However, since

Greece's accession to EU, public extension personnel have almost exclusively dealt with the practical implementation of CAP price support policies, absorbing their main role.[27] Perhaps the failure to provide farmers with means to improve their productive performance is one of the reasons that lead to the stagnation of the Greek sheep sector in the 1990s.

Concluding Remarks

This paper extends the primal decomposition of TFP changes, developed by Bauer (1990), Lovell (1996) and Kumbhakar (2000), to the case of non-neutral production frontiers. Output growth is decomposed into input growth (size effect), changes in technical efficiency, technical change, and the effect of returns to scale. Within the proposed formulation, however, technical efficiency changes are attributed not only to autonomous changes (i.e., passage of time) but also to changes in input use and in the not-so-fixed farm characteristics. These provide additional insights for understanding TFP and output changes. The empirical model is based on a heteroscedastic non-neutral production frontier, which integrates the Reifschneider and Stevenson (1991) heteroscedastic frontier model with the Huang and Liu (1994) non-neutral frontier model.

This methodology is applied to an unbalanced panel data set of sheep farms in Greece, during the period 1989-92. The empirical findings indicate that the scale effect, which has not been taken into account by previous studies, had a significant role in explaining output growth; it was found that, on average, it caused a 0.35% output slowdown annually. Thus, there would have been significant differences in TFP growth by not accounting simultaneously for the scale effect. Further, despite any errors that may arise by not accounting for the scale effect when parametrically measuring TFP growth, misconceptions also arise concerning the potential sources of TFP and output growth. In contrast to most previous studies, the technical efficiency change effect is found to be the main source of TFP growth, followed by technical change and the scale effect.

Even though the decomposition analysis of output growth used in this study is more complete than those used previously, a portion of the observed annual output growth still remains unexplained. In the present case, this unexplained residual refers to 7.1% of the observed annual output growth. This may be due to the assumption of allocative efficiency. Unfortunately, within the primal framework it is impossible to separate the scale from the allocative efficiency effect without information on input prices. If input price data were available, a system-wide approach (Kumbhakar, 1996) could be a potential alternative, but at the cost of complicating a lot the estimation procedure. Another potential alternative could be the use of the dual approach with similar complications and data requirements.

Table 1: Summary Statistics of the Variables

Variable	1989	1990	1991	1992	Average Period Values Mean	Min	Max	St. Deviation
Output (in €)	12,857	13,587	14,075	14,625	13,786	1,677	44,958	7,099
Labor (in days)	179	182	187	190	184	18	700	99
Flock Size (Number of animals)	163	171	179	186	174	21	549	92
Feed Expenses (in €)	5,074	5,564	5,963	6,330	5,733	164	35,934	4,559
Graze	4,262	4,563	4,949	5,064	4,710	138	29,825	3,974
Cocnentrates and Roughage	812	1,001	1,014	1,266	1,023	26	6,109	4,762
Other Costs (in €)	1,280	1,398	1,598	1,705	1,495	93	5,961	1,110
Age (in years)	52	53	51	54	53	22	83	14
Education (in years)	4.8	5.2	4.9	5.3	5.1	1	12	3.1
Debts (in €)	647	754	642	596	660	0	2,125	405
Direct Income Payments (in €)	502	567	612	654	584	0	1,162	222
Location in LFA (% of farms)					61.2			
Family Farming (% of farms)					54.2			
Improvement Plan (% of farms)					64.0			

Table 2: Parameter Estimates of the Translog Production Frontier for a Sample of Sheep Farms in Greece, 1989-1992.

Parameter	*Estimate*	*t-ratios*	Parameter	*Estimate*	*t-ratios*
Stochastic Frontier Model					
β_0	-0.037	(6.56)*			
β_H	0.587	(6.30)*	β_{LL}	0.140	(3.08)*
β_L	0.067	(2.32)**	β_{FC}	-0.089	(2.07)**
β_F	0.127	(3.53)*	β_{FF}	0.094	(2.54)**
β_C	0.014	(2.62)*	β_{CC}	-0.002	(0.05)
β_{HL}	-0.266	(2.06)**	β_T	0.020	(4.39)**
β_{HF}	-0.223	(2.76)*	β_{TT}	-0.008	(1.97)**
β_{HC}	0.028	(0.40)	β_{TH}	0.241	(2.35)*
β_{HH}	0.195	(1.17)	β_{TL}	-0.094	(0.68)
β_{LF}	0.155	(2.12)**	β_{TF}	-0.153	(2.85)*
β_{LC}	-0.092	(0.99)	β_{TC}	-0.004	(0.561)
Inefficiency Effects Model					
Mean Function					
δ_0	-0.255	(3.01)*			
δ_H	0.254	(2.11)**	δ_{IMP}	-0.007	(0.41)
δ_L	0.151	(0.16)	δ_{LFA}	0.038	(0.16)
δ_F	0.052	(2.26)**	δ_{EDU}	-0.106	(4.26)*
δ_C	0.085	(2.91)*	δ_{DIP}	-0.047	(0.09)
δ_{FMG}	-0.148	(2.18)**	δ_{T90}	-0.288	(3.42)*
δ_{DBT}	0.025	(4.10)*	δ_{T91}	0.102	(0.28)
δ_{AGE}	-0.073	(2.63)*	δ_{T92}	-0.090	(2.11)**
Variance Function					
θ_0	-0.464	(3.69)*	θ_{IMP}	-0.006	(0.30)
θ_{FMG}	-0.130	(2.27)**	θ_{LFA}	0.036	(1.56)
θ_{DBT}	-0.099	(1.72)**	θ_{EDU}	-0.097	(3.84)*
θ_{AGE}	0.122	(2.60)*	θ_{DIP}	-0.039	(2.59)*
$\ln L$	-202.175		σ_v	0.848	(4.16)*

Notes: (1) *L* stands for labor, *H* for flock size, *F* for feed, *C* for other cost, *T* for time, *FMG* for family farms, *DBT* for farm's total debts, *AGE* for farmer's age, *IMP* for the existence of improvement plan in the farm, *LFA* for farms location in less-favored areas, *EDU* for farmer's education, *DIP* direct income payments and *T90-T92* for time dummies.

(2) in parentheses are the absolute t-ratios.

(3) * (**) indicate statistical significance at the 1 (5)% level.

Table 3: Model Specification Tests

Hypothesis	lnL	Calculated χ^2-statistic	Critical Value (α=0.05)
$\theta_0 = \theta_m = \delta_0 = \delta_j = \delta_T = 0$ for all *m*, *j* and *T*	-222.30	40.25	$\chi^2_{16} = 26.32$
$\theta_m = 0$ for all *m*	-215.22	26.08	$\chi^2_7 = 14.07$
$\theta_m = \delta_j = 0$ for all *m* and *j*	-219.26	34.17	$\chi^2_{11} = 19.68$
$\delta_j = 0$ for all *j*	-211.65	18.95	$\chi^2_4 = 9.49$
$\delta_j = \delta_m = \delta_T = 0$ for all *j*, *m* and *T*	-219.78	35.21	$\chi^2_{14} = 23.69$
$\delta_T = 0$ for all *T*	-209.62	14.89	$\chi^2_3 = 7.81$
$\beta_{jk} = 0$ for all *j* and *k*	-218.39	32.42	$\chi^2_{10} = 18.31$
$\beta_{\mathrm{T}} = \beta_{TT} = \beta_{Tj} = 0$ for all *j*	-213.23	22.10	$\chi^2_6 = 12.59$
$\beta_{Tj} = 0$ for all *j*	-212.55	20.74	$\chi^2_4 = 9.49$
$\beta_{\mathrm{jk}} = \beta_{\mathrm{T}} = \beta_{TT} = \beta_{Tj} = 0$ for all *j* and *k*	-222.59	40.83	$\chi^2_{16} = 26.32$
$\sum \beta_j = 1$ and $\sum \beta_{jk} = \sum \beta_{Tj} = 0$ for all *j* and *k*	-216.99	29.63	$\chi^2_6 = 12.59$

Table 4: Marginal Effects of the Variables Included in the Mean and the Variance Inefficiency Functions for Sheep Farms in Greece, 1989-1992.

Inefficiency Variable	1989	1990	1991	1992
Mean Inefficiency Function				
Labor	-0.001	-0.027	-0.032	-0.041
Flock Size	-0.002	-0.045	-0.054	-0.068
Feed	-0.001	-0.009	-0.011	-0.014
Other Cost	-0.001	-0.015	-0.018	-0.023
Age	0.016	0.025	0.027	0.030
Education	0.012	0.029	0.032	0.037
Income Payments	0.005	0.012	0.014	0.016
Debts	0.013	0.005	0.004	0.002
Family Farming	0.014	0.038	0.043	0.050
Improvement Plan	0.001	0.002	0.002	0.002
Less Favored Area	-0.004	-0.010	-0.011	-0.013
Variance Inefficiency Function				
Age	0.016	0.011	0.010	0.008
Education	0.026	0.016	0.014	0.011
Income Payments	0.012	0.007	0.006	0.005
Debts	-0.009	-0.005	-0.004	-0.003
Family Farming	0.037	0.024	0.021	0.016
Improvement Plan	0.002	0.001	0.001	0.001
Less Favored Area	-0.009	-0.006	-0.005	-0.004

Table 5: Frequency Distribution of Technical Efficiency Ratings for Sheep Farms in Greece, 1989-1992.

Efficiency (%)	1989		1990		1991		1992	
<40	0	(0.0)	0	(0.0)	0	(0.0)	0	(0.0)
40-50	3	(7.1)	1	(2.0)	2	(5.7)	3	(6.0)
50-60	11	(26.2)	18	(35.3)	11	(31.4)	12	(24.0)
60-70	22	(52.4)	21	(41.2)	14	(40.0)	19	(38.0)
70-80	5	(11.9)	9	(17.6)	7	(20.0)	13	(26.0)
80-90	1	(2.4)	2	(3.9)	1	(2.9)	3	(6.0)
90-100	0	(0.0)	0	(0.0)	0	(0.0)	0	(0.0)
N	42		51		35		50	
Mean	67.5		68.1		67.8		68.3	
Maximum	84.4		85.5		83.2		88.9	
Minimum	48.9		50.2		49.6		52.7	

Note: In parentheses are the corresponding percentage values.

Table 6: Production Elasticities and Returns to Scale Estimates for Sheep Farms in Greece, 1989-1992.

	1989		1990		1991		1992	
Production Elasticities								
Labor	0.026	(4.02)*	0.066	(3.75)*	0.106	(3.91)*	0.084	(3.32)*
Flock Size	0.716	(4.64)*	0.671	(4.02)*	0.611	(3.74)*	0.609	(3.70)*
Feed	0.112	(5.32)*	0.131	(5.40)*	0.165	(5.63)*	0.132	(4.32)*
Other Cost	0.089	(3.68)*	0.056	(3.02)*	0.028	(2.74)*	0.013	(2.33)*
Returns to Scale	0.943	(3.87)*	0.924	(3.38)*	0.910	(3.99)*	0.838	(3.63)*

Notes: (1) in parentheses are the absolute t-ratios.

(2) * (**) indicate statistical significance at the 1 (5)% level.

Table 7: Decomposition of Output Growth of Sheep Farms in Greece, 1989-1992.

	Based on (4)		Based on (5)	
Output Growth	3.94	*(100)*	3.94	*(100)*
Size Effect:	2.37	*(60.2)*	2.12	*(53.8)*
Labor	0.25	*(6.5)*	0.22	*(5.6)*
Flock Size	1.00	*(25.5)*	0.90	*(22.8)*
Feed	1.10	*(28.1)*	0.99	*(25.1)*
Other Cost	0.01	*(0.2)*	0.01	*(0.1)*
TFP Growth:	1.30	*(32.9)*	0.61	*(15.6)*
Technical Change:	0.50	*(12.7)*	0.50	*(12.7)*
Neutral	0.47	*(12.0)*	0.47	*(12.0)*
Biased	0.03	*(0.7)*	0.03	*(0.7)*
Changes in Technical Efficiency:	1.14	*(28.8)*	0.11	*(2.8)*
Labor	-0.36	*(-9.1)*	-	-
Flock Size	-0.09	*(-2.2)*	-	-
Feed	-0.21	*(-5.3)*	-	-
Other Cost	-0.25	*(-6.3)*	-	-
Age	0.29	*(7.4)*	-	-
Direct Income Payments	0.92	*(23.4)*	-	-
Debts	0.71	*(18.0)*	-	-
Improvement Plan	0.01	*(0.3)*	-	-
Time	0.11	*(2.8)*		
Scale Effect	-0.35	*(-8.9)*	-	-
Unexplained Residuals	0.28	*(7.2)*	0.95	*(24.2)*

Note: In parentheses are the corresponding percentage values.

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Endnotes

[1] While these studies have used the primal approach, the dual decomposition analysis (Bauer, 1990) could have in principal been employed. However, farm-level input price data, necessary to implement the dual (cost function) decomposition analysis, are usually not available (as in the present study), but even if they do their variability in the cross-section dimension is limited in highly competitive industries, such as agriculture. This most likely will result in poor estimates of the production technology parameters.

[2] An exception is Karagiannis and Tzouvelekas (2001) who took into account the effects of returns to scale and of allocative inefficiency, but at the cost of relying on a self-dual (i.e., Cobb-Douglas) production frontier.

[3] Bauer (1990) and Lovell (1996) have shown that the effect of returns to scale on TFP growth can be identified within a parametric production function approach so long as allocative efficiency is assumed.

[4] Ahmad and Bravo-Ureta (1995) have incorporated the effect of technical efficiency changes into TFP measurement even though they have found technical efficiency to be time invariant. This raises concerns about the accuracy of their TFP estimates and consequently the sources of output growth.

[5] From the previous studies, only Giannakas, Schoney and Tzouvelekas (2001) could have proceed in such an analysis, considering though only the impact of farm-specific characteristics.

[6] Approximately the 80% of the Greek sheep farms may be characterized as semi-extensive (Hadjigeorgiou *et al*., 1999).

[7] This formulation implicitly assumes a deterministic frontier. We have adopted this formulation in order our results to be directly comparable with those of Bauer (1990), Lovell (1996), and Kumbhakar (2000). However, in implementing the proposed model empirically, it is necessary to take into account the stochastic nature of output and to make additional distributional assumption in order to obtain estimates of $TE^{O}(x;z,t)$. Without loss of generality, these elements are added into the model in the next section, where specific functional forms for $f(x;t)$ as well as the mean and the variance of $TE^{O}(x;z,t)$ are assumed.

[8] Thus, what really matters is not the degree of technical efficiency *per se*, but its changes over time. That is, even at low levels of technical efficiency, output gains

may be achieved by improving resource use. However, it is difficult to achieve substantial output growth gains at very high levels of technical efficiency. This is expected during the catching-up process.

[9] To some extent, the form of the technical inefficiency function can be deduced by formal statistical testing. In particular, Huang and Liu (1994) non-neutral production frontier is nested to Kumbhakar, Ghosh and McGuckin (1991) and Battese and Coelli (1995) model but neither of these is nested to Cornwell, Schmidt and Sickles (1990), Battese and Coelli (1992) or Cuesta (2000) specifications (Battese and Broca, 1997).

[10] The first of these terms captures the scale effect and the second captures either the deviations of input prices from the value of their marginal products or the departures of the marginal rate of technical substitution from the ratio of input prices.

[11] Ahmad and Bravo-Ureta (1995), Wu (1995), Giannakas, Tran and Tzouvelekas (2000), and Giannakas, Schoney and Tzouvelekas (2001) have assumed an explicit functional form for the technical inefficiency function while the rest of the aforementioned studies have computed the first term in (5) from the estimated values of the efficiency scores. Specifically, Ahmad and Bravo-Ureta (1995), Wu (1995), Giannakas, Tran and Tzouvelekas (2000) have used Cornwell, Schmidt and Sickles (1990) specification to model time-varying technical efficiency, while Giannakas, Schoney and Tzouvelekas (2001) have used the Battese and Coelli (1995) model. Based on these, Giannakas, Schoney and Tzouvelekas (2001) should have also taken into account in (5) the fifth term in (4).

[12] Notice however that sum of the second and the last term in (4) is equal to the last term in (5).

[13] On the other hand, if the size effect is measured residually, as in Kalirajan, Obwona and Zhao (1996) and Kalirajan and Shand (1997), its relative contribution to output growth is also incorrectly calculated in the absence of constant returns to scale.

[14] According to Kumbhakar and Lovell (2000), by neglecting heteroscedasticity in time-varying models results in biased estimates of the β parameters, especially when z and x are highly correlated (p. 129), and in downward (upward) biased estimates of technical efficiency for relatively small (large) producers (p. 119).

[15] Claudill, Ford and Gropper (1995) have considered a different specification of the variance function, which however is equivalent to (7b) if a constant is included in the z vector (Wang and Schmidt, 2002).

[16] These relationships corresponds respectively to the stochastic counterparts of the last three terms in (3), where the additional terms ξ, ς and σ^0 result from the distributional assumptions made for u_{it}. The second term in the bracket of (9b) would be equal to zero if a homoscedastic non-neutral production frontier had been used.

[17] According to Fare and Primont (1995, p. 39) and Forsund (1996), output and scale elasticities measures should be evaluated at the frontier. For this reason, the marginal effects of inputs (i.e., (9b)) are not included in the definitions of ε_j (for all *j*) and *E*. This is also true for the rate of technical change (Atkinson and Cornwell, 1998), which should be evaluated at the frontier, too.

[18] Grazing cost is estimated by using the grazing capacity standards of the grasslands in each region of the sample survey, as applied by the Greek Ministry of Agriculture (1998).

[19] It is debatable whether education should be considered as an input in the production function or as a *z*-variable increasing technical efficiency. Following Kumbhakar, Ghosh and McGuckin (1991), among others, we have adopted the latter view for the purposes of the present study.

[20] It is used to capture the effect that farming under disadvantaged conditions, in terms of poorly endowed infrastructure and extension services, may have on technical efficiency (Brummer, 2001).

[21] Before the estimation of the model we have statistically examine for the existence of outliers in our sample using the maximum normal residual test (Snedecor and Cochran, 1989). The computed test statistic rejects the existence of outliers at the 5% level of significance.

[22] These tests have been conducted by using the generalized likelihood-ratio statistic, $\lambda = -2\{ln\,L(H_0) - ln\,L(H_1)\}$, where $L(H_0)$ and $L(H_1)$ denote the values of the likelihood function under the null (H_0) and the alternative (H_1) hypothesis, respectively.

[23] The test-statistic computed as $\sqrt{b_1} = m_3 / m_2^{3/2}$ (with m_3 and m_2 being the third and second moments of the residuals and b_1 the coefficient of skewness) is 1.547, well above the corresponding critical value at the 5% level of significance (0.298).

[24] Here we refer to only those factors that found to be statistically significant (see Table 2). LFA and improvement plans are found to have no statistically significant impact on both the mean and the variance of the technical efficiency function.

[25] The hypothesis of a zero technical change has also been tested in the presence of a Cobb-Douglas production frontier. This hypothesis (i.e., $\beta_{\mathrm{jk}} = \beta_{\mathrm{T}} = \beta_{TT} = \beta_{Tj} = 0$ for all *j* and *k*) is also rejected at the 5% level of significance (see Table 3).

[26] The only exception is Fan (1991) who has calculated the effect of technical change residually. In this case, the contribution of technical change into TFP growth is overestimated (underestimated) in the presence of increasing (decreasing) returns to scale.

[27] On the other hand, the role of private extension services is limited in areas with low population density and poor infrastructure, such as the LFA where the majority of Greek sheep farms is located.