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Total Factor Productivity Growth and Technical Change in a Profit Function Framework

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Abstract

This paper develops a framework for measuring and decomposing TFP changes, within the parametric approach, by using directly the estimated parameters of a profit function. Two alternative relationships are derived for measuring and decomposing TFP changes via a profit function based on two alternative definitions of the rate of technical change, i.e., input- and output-based. Initially a long-run equilibrium framework is assumed and then the analysis is extended to the case of temporary equilibrium. The latter framework is applied to US agriculture by estimating a translog profit function and analyzing TFP changes during the period 1948–1994.

Keywords: TFP measurement and decomposition, profit function, technical change

1. Introduction

Accurate measures of Total Factor Productivity (TFP) and reliable decomposition of its sources can be obtained within the parametric approach only if the appropriate structural and behavioral assumptions are correctly specified (Callan, 1991). Structural assumptions refer to returns to scale, technical change, productive efficiency, and capacity utilization, whereas behavioral assumptions refer to the objective function of the firm(s), market structure, and the importance of various regulations. Most efforts to improve the theoretical framework of TFP measurement and attribution, using the parametric approach, have been based on duality and particularly, on cost function.[1] Denny *et al*. (1981) considered the role of technical change and returns to scale in TFP changes for competitive, monopolistic and regulated firms. Morrison (1986), Berndt and Fuss (1986), and Nadiri and Prucha (1990) incorporated in addition the impact of capacity utilization in the case of competitive firms and Morrison (1992) extended it to monopolistic firms. Bauer (1990) considered the impact of productive efficiency on TFP changes for competitive and monopolistic firms, while Granderson (1997) extended it to case of regulated firms.

Instead of a cost function, a profit function may also be used for parametrically measuring and decomposing TFP changes, on the basis of a different behavioral assumption. If firms are profit maximizing, then it may be more appropriate to use the dual profit function rather than the cost function to represent the firm's or industry's production decisions (Ray and Segerson, 1991). This is more likely in the case of highly competitive industries, such as services and small manufacturing, in which firms are price takers in input and output markets and there are no production regulations.[2] Use of the profit function allows both output and input levels to be determined endogenously and to adjust accordingly to changes in prices and technology. This feature overcomes a serious limitation of the cost function which assumes that output levels are not affected by factor price changes and thus, the indirect effect of these changes (via output levels) on factor demand is ignored (Lopez, 1982).[3] All the above are obtained at the cost of a stronger behavioral assumption, however profit maximization always implies cost minimization while the opposite is not necessarily true.

There have been several previous attempts in developing a framework for measuring and decomposing TFP growth by using a profit function, but with limited success. Levy (1981), Ray and Segerson (1991) and Fox (1996) focused only on the measurement of the rate of technical change via a profit function (i.e., the rate of profit augmentation). Other studies relied on information obtained from an estimated profit function but then used either index numbers (i.e., Jayne *et al*., 1994; Coelli, 1996), or a primal approach (i.e., Luh and Stefanou, 1991, 1993; Lynde and Richmond, 1993; Fousekis and Papakonstantinou, 1997) for measuring and decomposing TFP changes. Specifically, in their approach the estimated profit function is used only to compute shadow values of quasi-fixed inputs, which are then utilized in Divisia index and in a production function based decomposition of TFP growth, respectively. Bernstein (1994) did the first attempt to develop a framework for measuring and decomposing TFP growth within a profit function using dual concepts, but presented only one side of the problem. In particular, he relied only on the input-based measure of the rate of technical change, while as explained in the next section an output-based measure of technical change may also be defined within a profit function framework.

The main objective of this paper is to develop a framework for measuring and decomposing TFP changes, within the parametric approach, by using directly the estimated parameters of a profit function. Due to the endogeneity of both inputs and outputs in a profit function framework, two measures of the rate of technical change (i.e., input- and output-based) can be defined and consequently, two alternative relationships are developed for decomposing TFP changes. For the latter, we provide a slightly different, but easier to interpret, relationship than that developed by Bernstein (1994). It is also shown that the two alternative decomposition relationships provide similar information about the sources of TFP changes, but different quantitative results in the presence of non-constant returns to scale.

The rest of this paper proceeds as follows. Dual measures of the degree of returns to scale and of the rate of technical change within a profit function framework are developed in the next section. In the third section, we briefly examine (for purposes of completeness only) the case of TFP decomposition within a long-run profit function framework and next we provide a rigorous treatment of the case of temporary equilibrium by using a restricted profit function, which is more relevant to empirical applications. An empirical application of this framework is presented in the fourth section by estimating a translog profit function for US agriculture using data of the period 1948–1994. Concluding remarks follow in the last section.

2. Dual Measures of Returns to Scale and of the Rate of Technical Change

The accuracy of the measurement and decomposition of TFP growth in a profit function depends on the definition of the rate of technical change used; that is, whether outputs or inputs are held constant. These alternative measures of the rate of technical change are related to each other according to the degree of returns to scale. In order to develop a decomposition of TFP growth using a profit function, a clear presentation of the measures of returns to scale and of the rate of technical change is necessary from the outset.

In the case of multi-output technologies, returns to scale are defined in the context of a transformation function, $F(q, x; t) = 0$, as:

$$\rho = -\sum_{i=1}^{n} F_{x_i} x_i \Big/ \sum_{j=1}^{m} F_{q_j} q_j,$$

where $F_{x_i} = \partial F/\partial x_i$, $F_{q_j} = \partial F/\partial q_j$, and x and q refer to input and output quantities, respectively (Caves *et al.*, 1981). This definition requires all inputs to be variable and first-order conditions to be satisfied, in order output increases to take place long the expansion path. Using the first-order conditions and Hotelling's lemma, a dual measure of the degree of returns to scale is given as:

$$\rho = \left(\frac{-\sum_{i=1}^{n} S_i}{\sum_{j=1}^{m} R_j} \right) = \left(\frac{\sum_{i=1}^{n} w_i x_i \big/ \pi}{\sum_{j=1}^{m} p_j q_j \big/ \pi} \right) = \frac{TC}{TR} = 1 - \left(\sum_{j=1}^{m} \frac{\partial \ln \pi}{\partial \ln p_j} \right)^{-1}, \tag{1}$$

where $S_i = w_i x_i/\pi$, $R_j = p_j q_j/\pi$, $\pi = \pi(p, w; t)$ is a well-defined long-run profit function, w and p refer to input and output prices respectively, *TC* is total cost, and *TR* is total revenue. This measure, proposed by Caves *et al.* (1982), is valid when producers maximize profits, are in long-run equilibrium and operate in perfectly competitive input and output markets.

In short-run equilibrium, the degree of (short-run) returns to scale, ρ_z, is defined with respect to both variable and quasi-fixed inputs, without assuming that quasi-fixed inputs are at their long-run equilibrium levels. That is, the degree of short-run returns to scale is evaluated at the subequilibrium point represented by the existing (observed) quantities of outputs, quasi-fixed and variable inputs. Then, the degree of short-run returns to scale is related to capacity utilization (Morrison Paul, 1999).[4] Following Nadiri and Prucha (1990) and Bernstein (1994), the primal measure of the degree of short-run returns to scale is given us:

$$\rho_z = -\left(\sum_{i=1}^{n} F_{x_i} x_i^s + \sum_{k=1}^{h} F_{z_k} z_k \right) \Big/ \sum_{j=1}^{m} F_{q_j} q_j^s, \tag{2}$$

where the transformation function is defined as $F(q^s, x^s; z, t) = 0$, $F_{z_k} = \partial F/\partial z_k$, and z refers to quasi-fixed inputs. By using the first-order conditions, Hotelling lemma and the derivative property, $M_k = \partial \ln \pi^s / \partial \ln z_k$, a dual measure of returns to scale may be defined as:

$$\rho_z = \left(\frac{-\sum_{i=1}^n S_i^s + \sum_{k=1}^h M_k}{\sum_{j=1}^m R_j^s} \right) = \frac{C^*}{TR^s} = 1 - \left(\sum_{j=1}^m \frac{\partial \ln \pi^s}{\partial \ln p_j} \right)^{-1} + \frac{\sum_{k=1}^h \frac{\partial \ln \pi^s}{\partial \ln z_k}}{\sum_{j=1}^m \frac{\partial \ln \pi^s}{\partial \ln p_j}}, \qquad (3)$$

where $S_i^s = w_i x_i^s / \pi^s$, $R_j^s = p_j q_j^s / \pi^s$, $\pi^s = \pi^s(p, w; z, t)$ is a well-defined short-run profit function, TR^s is a short-run revenue, $C^* = \sum_{i=1}^n w_i x_i^s + \sum_{k=1}^h (\partial \pi^s / \partial z_k) z_k$ is total shadow cost and $\partial \pi^s / \partial z_k = v_k(p, w; z, t)$ is the shadow value of the k^{th} quasi-fixed input.[5] Bernstein (1994) used the first equality in (3), whereas the second equality may be viewed as a generalization of the Caves *et al*. (1982) definition of returns to scale under short-run equilibrium.

In the context of a profit function, the rate of technical change can be computed as an output-based or as an input-based measure (Caves *et al*., 1981, 1982). The *output-based measure of the rate of technical change* presents the rate of output expansion that may be achieved with technical progress without changing input use and it is defined as:

$$\pi_t^p = (\partial F / \partial t) / \sum_{j=1}^m F_{q_j} q_j ,$$

where $\partial F / \partial t$ represents the shift of the transformation function over time. This measure was proposed by Hulten (1978) and used by Caves *et al*. (1981), Antle and Capalbo (1988), Nadiri and Prucha (1990) and Luh and Stefanou (1991, 1993), among others. In the single-product case, $\partial F / \partial q = 1$ and thus, $\pi_t^p = (\partial F / \partial t)/q = \partial \ln F / \partial t$, which is the well-known (primal) measure of technical change proposed by Solow (1957).

The *input-based measure of the rate of technical change*, on the other hand, is defined as the potential saving in input use that becomes feasible with technical progress and still produces the same amount of output as before:[6]

$$\pi_t^{p'} = (\partial F / \partial t) / \sum_{i=1}^n F_{x_i} x_i .$$

In the case of temporary equilibrium and the existence of quasi-fixed inputs, this measure is given as follows:

$$\pi_t^{sp'} = (\partial F / \partial t) / \left(\sum_{i=1}^n F_{x_i} x_i^s + \sum_{k=1}^h F_{z_k} z_k \right),$$

and represents a short-run measure of the rate of technical change. Nadiri and Prucha (1990) and Bernstein (1994) used this measure.

The relationship between the primal measures of the rate of technical change defined above and the rate of profit augmentation, π_t, is derived by using the first-order conditions, Hotelling's lemma, and either (1) or (3). First consider the output-based measure of the rate of technical change, π_t^p, in the case of long-run equilibrium:

$$\pi_i^p = \left(\frac{\partial \pi}{\partial t}\right)\left(\frac{1}{TR}\right) = \left(\frac{\partial \ln \pi}{\partial t}\right)\left(\frac{\pi}{TR}\right) = \pi_t\left(\frac{TR - TC}{TR}\right)$$
$$= \pi_t\left(\sum_{j=1}^{m} R_j\right)^{-1} = \pi_t(1-\rho), \qquad (4)$$

where π_t measures the changes in profits that are due to technical change by holding all input and output prices constant. Notice that Ray and Segerson (1991) also derived the first equality in (4). In this case, π_t reflects the profit gains that would result from technological progress if firms respond optimally (i.e., adjust their output and input levels appropriately) and a larger amount of output is produced by the same amount of inputs. In the presence of decreasing returns to scale, π_t overstates the primal rate of technical change.

In the case of temporary equilibrium, (4) should be replaced by

$$\pi_t^{sp} = \left(\frac{\partial \ln \pi^s}{\partial t}\right)\left(\frac{\pi^s}{TR^s}\right) = \pi_t^s\left(\frac{TR^s - C^*}{TR^s}\right) = \pi_t^s\left(\sum_{j=1}^{m} R_j^s\right)^{-1}$$
$$= \pi_t^s\left(1 - \rho_z + \left(\frac{\sum_{k=1}^{h} M_k}{\sum_{j=1}^{m} R_j^s}\right)\right) \qquad (5)$$

which has a similar interpretation. Ray and Segerson (1991) also derived the first equality in (5). It should be noted than in the presence of short-run constant returns to scale, the primal rate of technical change is equal to the rate of profit augmentation weighted by the ratio of shadow to revenue (short-run profit) share.

Similarly, in the case of the input-based measure of the rate of technical change, $\pi_t^{p'}$, and long-run equilibrium:

$$\pi_t^{p'} = \left(\frac{\partial \pi}{\partial t}\right)\left(\frac{1}{TC}\right) = \left(\frac{\partial \ln \pi}{\partial t}\right)\left(\frac{\pi}{TC}\right) = \pi\left(\frac{TR - TC}{TC}\right)$$
$$= \pi_t\left(-\sum_{i=1}^{n} S_i\right)^{-1} = \pi_t(\rho^{-1} - 1) \quad (6)$$

where π_t reflects the profit gains that result from a reduction in the quantity of inputs required for producing an equal amount of output as before. Thus,, it reflects the reduction in input requirements indirectly through cost reduction captured by the effect of input prices (Levy, 1981). From (6) it is clear that π_t overstates (understates) the primal rate of technical change when returns to scale are greater (less) than 0.5. Moreover, $\pi_t = \pi_t^{p'}$ when $\rho = 0.5$. Thus, $\pi_t^{p'}$ is inconsistent, when compared to π_t^p, in reflecting changes in the rate of profit augmentation, depending on the degree of (long-run) decreasing returns to scale. In the case of short-run equilibrium, (6) analogue is:

$$\pi_t^{sp'} = \left(\frac{\partial \ln \pi^s}{\partial t}\right)\left(\frac{\pi^s}{TC^s}\right) = \pi_t^s \left(-\sum_{i=1}^{n} S_i^s + \sum_{k=1}^{h} M_k\right)^{-1}$$
$$= \pi_t^s \left(\rho_z^{-1} - 1 + \left(\frac{\sum_{k=1}^{h} M_k}{\sum_{i=1}^{n} S_i^s + \sum_{k=1}^{h} M_k}\right)\right) \qquad (7)$$

Bernstein (1994) also derived the second equality in (7).

Equations (4) and (6) may be viewed as extensions of the work of Ohta (1974) and Caves *et al*. (1981), in relating primal and dual measures of the rate of technical change, in the case of long-run profit function. Moreover, by combining (5) and (7) it can be shown that $\pi_t^{sp} = \rho_z \pi_t^{sp'}$ (Nadiri and Prucha, 1990), which relates the primal input- and output-based measures of technical change under short-run equilibrium. This is analogous to the relationship $\pi_t^{p} = \rho \pi_t^{p'}$, derived by Caves *et al*. (1981) for the case of long-run equilibrium.

3. Decomposition of TFP Growth Using a Profit Function

The decomposition of TFP growth in a profit function framework can be accomplished following two alternative approaches relying on the definitions of the rate of technical change presented in the previous section. In either case, a corresponding adjustment should be made with respect to the terms measuring the effect of returns to scale on TFP growth. For completeness purposes only, we briefly examine first the case of a long-run profit function and then we proceed in much more detail with the case of temporary equilibrium.

Unrestricted (long-run) profit function

Totally differentiating the long-run profit function, $\pi = \pi(p, w; t)$, with respect to t, dividing both sides by π, and using Hotelling's lemma, results in:

$$\frac{d \ln \pi}{dt} = \sum_{j=1}^{m}\left(\frac{p_j q_j}{\pi}\right)\dot{p}_j - \sum_{i=1}^{n}\left(\frac{w_i x_i}{\pi}\right)\dot{w}_i + \frac{\partial \ln \pi}{\partial t}, \qquad (8)$$

where $\dot{p}_j = d \ln p_j/dt$ and $\dot{w}_i = d\ln w_i/dt$. Similarly, by taking the total differential of the profit definition, $\pi = \sum_{j=1}^{m} p_j q_j - \sum_{i=1}^{n} w_i x_i$, with respect to t, dividing through by π and rearranging terms, yields:

$$\frac{d \ln \pi}{dt} = \sum_{j=1}^{m}\left(\frac{p_j q_j}{\pi}\right)\dot{p}_j + \sum_{j=1}^{m}\left(\frac{p_j q_j}{\pi}\right)\dot{q}_j - \sum_{i=1}^{n}\left(\frac{w_i x_i}{\pi}\right)\dot{w}_i - \sum_{i=1}^{n}\left(\frac{w_i x_i}{\pi}\right)\dot{x}_i, \qquad (9)$$

where $\dot{q}_j = d \ln q_j/dt$ and $\dot{x}_i = d\ln x_i/dt$. By equating (8) and (9), dividing through by

$-\sum_{i=1}^{n} S_i = TC/\pi$, and using (1) and (6), the conventional Divisia index of TFP changes under condition of long-run equilibrium,

$$T\dot{F}P = \dot{Q} - \dot{X} = \sum_{j=1}^{m} \left(\frac{p_j q_j}{TR}\right) \dot{q}_j - \sum_{i=1}^{n} \left(\frac{w_i x_i}{TC}\right) \dot{x}_i, \quad (10)$$

may be written as:

$$T\dot{F}P = \pi_t(\rho^{-1} - 1) + (1 - \rho^{-1})\dot{Q} = \pi_t^{p'} + (1 - \rho^{-1})\dot{Q}. \quad (11)$$

Equation (11) provides a measure and a decomposition frame for TFP growth that is obtained from an input-based definition of technical change. Alternatively, by equating (8) and (9), dividing through by $\sum_{j=1}^{m} R_j = TR/\pi$, and using (1) and (6), equation (10) may be written as:

$$T\dot{F}P = \pi_t(1 - \rho) + (\rho - 1)\dot{X} = \pi_t^{p} + (\rho - 1)\dot{X}. \quad (12)$$

Equation (12) is a measure and decomposition frame of TFP growth with an output-based definition of technical change.

The first term in both (11) and (12) presents the effect of technical change on TFP growth. For a well-defined profit function, this effect vanishes only when the rate of technical change, or equivalently the rate of profit augmentation, is equal to zero. Otherwise, it is expected to be positive for progressive technical change. The second term in (11) and (12) gives the effect of returns to scale, which is negative under decreasing returns to scale. Moreover, from (11) and (12) it follows that the rate of profit augmentation, π_t, is a biased and incorrect measure of the TFP growth. Nevertheless, this measure, although biased and incorrect, has been used (Levy, 1981; Fox, 1996) in the past to capture TFP change.

Restricted (short-run) profit function

To incorporate in addition the impact of quasi-fixed inputs' capacity utilization on TFP growth, temporary (short-run) equilibrium should be assumed and consequently, a restricted profit function is used.[7] As emphasized by Berndt and Fuss (1986), Morrison (1986) and Hulten (1986), in order to derive accurate measures of TFP in a temporary equilibrium framework, quasi-fixed inputs should be evaluated at their shadow rather than their rental prices. Following Nadiri and Prucha (1990), marginal productivity of the quasi-fixed inputs, instead of their unit cost, are evaluated at shadow prices. Although we do so by using a dual function, i.e., the short-run profit function, rather than the production function, as Nadiri and Prucha (1990) did.

To proceed totally differentiate the short-run profit function, $\pi^s = \pi^s(p, w; z, t)$, with respect to t yields:

$$\frac{d\pi^s}{dt} = \sum_{j=1}^{m} \left(\frac{\partial \pi^s}{\partial p_j}\right)\left(\frac{dp_j}{dt}\right) + \sum_{i=1}^{n} \left(\frac{\partial \pi^s}{\partial w_i}\right)\left(\frac{dw_i}{dt}\right) + \sum_{k=1}^{h} \left(\frac{\partial \pi^s}{\partial z_k}\right)\left(\frac{dz_k}{dt}\right) + \frac{\partial \pi^s}{\partial t}. \quad (13)$$

Dividing both sides of (13) by π^s, using Hotelling's lemma and $M_k = \partial \ln \pi^s / \partial \ln z_k$, and after rearranging terms results in:

$$\frac{d \ln \pi^s}{dt} = \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{\pi^s} \right) \dot{p}_j - \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{\pi^s} \right) \dot{w}_i + \sum_{k=1}^{h} M_k \dot{z}_k + \frac{\partial \ln \pi^s}{\partial t}. \tag{14}$$

Since $\pi^s = \sum_{j=1}^{m} p_j q_j^s - \sum_{i=1}^{n} w_i x_i^s$ (Diewert, 1973), its total differential with respect to t yields:

$$\frac{d \ln \pi^s}{dt} = \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{\pi^s} \right) \dot{p}_j + \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{\pi^s} \right) \dot{q}_j^s - \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{\pi^s} \right) \dot{w}_i - \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{\pi^s} \right) \dot{x}_i^s. \tag{15}$$

By equating (14) and (15), the following relationship may be obtained:

$$\frac{\partial \ln \pi^s}{\partial t} = \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{\pi^s} \right) \dot{q}_j^s - \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{\pi^s} \right) \dot{x}_i^s - \sum_{k=1}^{h} M_k \dot{z}_k. \tag{16}$$

Then, divide (16) by $-\sum_{i=1}^{n} S_i^s + \sum_{k=1}^{h} M_k = C^* / \pi^s$ to obtain:

$$\left(\frac{\partial \ln \pi^s}{\partial t} \right) \left(\frac{\pi^s}{C^*} \right) = \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{C^*} \right) \dot{q}_j^s - \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{C^*} \right) \dot{x}_i^s - \sum_{k=1}^{h} \left(\frac{v_k z_k}{C^*} \right) \dot{z}_k. \tag{17}$$

Using (3) and (7), and rearranging terms, (17) may also be written as:

$$\dot{Q} = \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{TR^s} \right) \dot{q}_j^s = \pi_t^{sp'} + (\rho_z^{-1} - 1) \dot{Q} + \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{C^*} \right) \dot{x}_i^s + \sum_{k=1}^{h} \left(\frac{v_k z_k}{C^*} \right) \dot{z}_k \tag{18}$$

Equation (18) shows that the growth of aggregate output is attributed to technical change (first term), to short-run scale economies (second term), and to input growth (the last two terms) consisting of the growth of both variable and quasi-fixed inputs, with the latter evaluated at shadow prices. Substituting (18) into the conventional Divisia index of TFP growth,

$$T\dot{F}P' = \dot{Q} - \dot{X}' = \sum_{j=1}^{m} \left(\frac{p_j q_j^s}{TR^s} \right) \dot{q}_j^s - \sum_{i=1}^{n} \left(\frac{w_i x_i^s}{TC'} \right) \dot{x}_i^s - \sum_{k=1}^{h} \left(\frac{r_k z_k}{TC'} \right) \dot{z}_k, \tag{19}$$

where $TC' = \sum_{i=1}^{n} w_i x_i^s + \sum_{k-1}^{h} r_k z_k$, r refers to the rental price of quasi-fixed inputs and $\dot{z}_k = d \ln z_k / dt$, and noticing that $TC' - C^* = \sum_{k=1}^{h} (r_k - v_k) z_k$, yields:

$$T\dot{F}P = \pi_t^{sp'} + (1 - \rho_z^{-1}) \dot{Q} + \sum_{i=1}^{h} \left[\frac{(r_k - v_k) z_k}{TC^s} \right] \left(\dot{X}' - \dot{z}_k \right) \tag{20}$$

The first term in (20 refers to the technical change effect and it is expected to be positive under progressive technological change. The second term refers to the scale effect and it is positive (negative) under short-run increasing (decreasing) returns to scale as long as output increases and *vice versa*. This term vanishes under short-run constant returns to scale. The last term refers to the temporary equilibrium effect and it is positive (negative) when rental prices are greater (less) than shadow prices, quasi-fixed inputs are over- (under-) utilized and variable inputs use increase. The last term vanishes when shadow and rental prices are equal; in such a case, (20) reduces to (12).

Equation (20) presents a measure and decomposition of TFP that corresponds to the input-based measure of technical change and is similar but apparently not the same as that developed by Bernstein (1994). The main difference is with the measurement of the temporary equilibrium effect, which is evaluated in terms of shadow cost in (20) and in terms of profits in Bernstein (1994). The former has, however, a clearer and simpler interpretation in a temporary equilibrium framework.

Using an output-based definition of technical change, an alternative frame of TFP measurement and decomposition may be derived by dividing (16) by $\sum_{j=1}^{m} R_j^s = TR^s/\pi^s$:

$$\left(\frac{\partial \ln \pi^s}{\partial t}\right)\left(\frac{\pi^s}{TR^s}\right) = \sum_{j=1}^{m}\left(\frac{p_j q_j^s}{TR^s}\right)\dot{q}_j^s - \sum_{i=1}^{n}\left(\frac{w_i x_i^s}{TR^s}\right)\dot{x}_i^s - \sum_{k=1}^{h}\left(\frac{v_k z_k}{TR^s}\right)\dot{z}_k. \tag{21}$$

Using (3) and (5), and rearranging terms, (21) may also be written as:

$$\begin{aligned}\dot{Q} \;=\; & \pi_t^{sp} + (\rho_z - 1)\left(\sum_{i=1}^{n}\left(\frac{w_i x_i^s}{C^*}\right)\dot{x}_i^s + \sum_{k=1}^{h}\left(\frac{v_k z_k}{C^*}\right)\dot{z}_k\right)\\ & + \sum_{i=1}^{n}\left(\frac{w_i x_i^s}{C^*}\right)\dot{x}_i^s + \sum_{k=1}^{h}\left(\frac{v_k z_k}{C^*}\right)\dot{z}_k. \end{aligned} \tag{22}$$

Equation (22) shows that the growth of aggregate output is attributed to technical change (first term), to scale economies (second term), and to input growth (the sum of the last two terms). Then, by substituting (22) into (19) and noticing that $TC' - C^* = \sum_{k=1}^{h}(r_k - v_k)z_k$, yields:

$$\begin{aligned}T\dot{F}P' \;=\; & \pi_t^{sp} + (\rho_z - 1)\left(\sum_{i=1}^{n}\left(\frac{w_i x_i^s}{C^*}\right)\dot{x}_i^s + \sum_{k=1}^{h}\left(\frac{v_k z_k}{C^*}\right)\dot{z}_k\right)\\ & + \rho_z \sum_{k=1}^{h}\left[\frac{(r_k - v_k)z_k}{TC^s}\right]\left(\dot{X}' - \dot{z}_k\right). \end{aligned} \tag{23}$$

Equation (23) provides an alternative framework for decomposing TFP growth within a profit function framework using an output-based definition of technical change. The first term in (23) refers to the effect of technical change into TFP growth, which is expected to be positive under progressive technological change. This corresponds to the output-based measure of the rate of technical change. The second term presents the scale effect since the input-side measure of short-run economies of scale is defined upon both variable and quasi-fixed inputs. In the case of optimal adjustment of quasi-fixed inputs, these terms may add up to a factor similar to the second term in (12). Under short-run decreasing (increasing) returns to scale, the second term is negative (positive) as long as input use increases, and *vice versa*. This term vanishes under short-run constant returns to scale. The third term refers to the temporary equilibrium effect associated with the variable and quasi-fixed inputs, respectively. It is positive (negative) when rental prices are greater (less) than shadow prices, quasi-fixed inputs are over- (under-) utilized and variable inputs use increase. The last term vanishes when shadow and rental prices are equal; in this case, (23) reduces to (12).

Equation (23) provides similar qualitative information with (20), as TFP growth is attributed to technical change, short-run returns to scale, and adjustment of quasi-fixed inputs to long-run equilibrium levels. Nevertheless, quantitative measures of TFP change and composition obtained through (20) and (23) will in general be different. It can be shown however that the two alternative forms of TFP decomposition, as derived from (20) and (23), coincide when the technology exhibits short-run constant returns to scale. Given $\pi_t^{sp} = \rho_z \pi_t^{sp'}$ it is clear that under short-run constant returns to scale the input- and the output-based measures of the rate of technical change are equal to each other. The scale effect vanishes both (31) and (35) when $\rho_z = 1$. Finally, $\rho_z = 1$ implies that the third term in (20) and (23) are equal to each other.

Under short-run non-constant returns to scale, (20) and (23) will provide different results of TFP measurement and decomposition. Given $\pi_t^{sp} = \rho_z \pi_t^{sp'}$ it is clear that the first term in (20) is less (greater) than the corresponding terms in (23) under short-run decreasing (increasing) returns to scale. The same is essentially true by comparing the third term in (20) and (23). Moreover, the second term in (20) is less (greater) than the second term in (23) as $\rho_z < (>) 1$ and $\dot{Q} - \rho_z \left(\sum_{i=1}^{n} \left(\frac{w_i x_i^s}{C^*} \right) \dot{x}_i^s + \sum_{k=1}^{h} \left(\frac{v_k z_k}{c^*} \right) \dot{z}_k \right) < 0$. However, the opposite is true if output growth is faster than the weighted growth of variable and quasi-fixed inputs, with the degree of short-run returns to scale used as a weight. In the former case, TFP growth measured through (20) is less (greater) than that measured through (23) when short-run returns to scale are decreasing (increasing). In the latter case, however, an unambiguous comparison for TFP growth cannot *a priori* be obtained.

Even though both alternatives provide accurate and theoretically consistent measures of TFP changes within a profit function framework, they may result in quite different policy implications regarding the sources of productivity growth.[8] In the absence of short-run constant returns to scale, it is clear from (20) and (23) that the relative magnitude of the factors explaining TFP would be different. These deviations tend to increase as we move further away from short-run constant returns to scale. Hence, under certain circumstances, it is possible that the two alternative measures may assign different relative importance to factors such as technical progress, scale economies and capacity utilization for enhancing TFP. However, as Chavas and Cox (1994, p. 371) have already noted the choice between input- and output-based productivity indices remains an unresolved issue.

Nevertheless, there is a direct correspondence between (23) and the decomposition developed in previous studies (e.g., Luh and Stefanou, 1991, 1993; Lynde and Richmond, 1993; Fousekis and Papakonstantinou, 1997) using a primal approach and assuming profit maximization. In both cases, the effects of technical change, scale economies, and temporary equilibrium are measured in a conceptually analogous way; i.e., are output-based oriented measures. This can be seen from (5) for the effect of technical change and from (2) and (3) for the effect of scale economies. These relationships establish the aforementioned primal-dual correspondence. In contrast, there is no such correspondence between (20) and the primal formulation of TFP decomposition as the effects of technical change, scale economies and temporary equilibrium are measured in an input-contracting rather than an output-expanding manner.

4. Empirical Model and Results

The empirical implementation of this theoretical framework for the measurement and decomposition of TFP growth within a profit function is provided for US agriculture during the period 1948–1994. The empirical model is based on a translog restricted profit function, with two outputs (crops and livestock), two variable inputs (total labor and intermediate inputs), and a quasi-fixed input (an aggregate of land, structures, durable equipment, and animal capital). Data and a detailed description of variables used are given in Ball *et al.* (1997).

Empirical model

It is assumed that the production technology of US agriculture can be represented by a translog restricted profit function, which consists a second-order Taylor series approximation of the true underlying technology around a point coinciding with the base year (i.e., 1987) of the sample. The translog restricted profit function is given as:

$$
\begin{aligned}
\ln \pi^s \;=\;& \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln w_i + \frac{1}{2}\sum_{i=1}^{n}\sum_{f=1}^{l} \alpha_{if} \ln w_i \ln w_f + \sum_{j=1}^{m} \beta_j \ln p_j \\
& + \frac{1}{2}\sum_{j=1}^{m}\sum_{g=1}^{s} \beta_{jg} \ln p_j \ln p_g + \sum_{i=1}^{n}\sum_{j=1}^{m} \gamma_{ij} \ln w_i \ln p_j + \beta_3 \ln z + \frac{1}{2}\beta_4 (\ln z)^2 \\
& + \sum_{i=1}^{n} \gamma_i \ln w_i \ln z + \sum_{j=1}^{m} \delta_j \ln p_j \ln z + \beta_5 t + \frac{1}{2}\beta_6 t^2 + \sum_{i=1}^{n} \varepsilon_i \ln w_i t \\
& + \sum_{j=1}^{m} \vartheta_j \ln p_j t + \beta_7 \ln z t
\end{aligned} \tag{24}
$$

It is well known that translog is a flexible functional form which does not impose any *a priori* restrictions on the structure of production. Using Hotelling's lemma, the following relationships for output, input and shadow profit shares may be obtained:

$$
R_j^s \;=\; \beta_j + \sum_{g=1}^{s} \beta_{jg} \ln p_g + \sum_{i=1}^{n} \gamma_{ij} \ln w_i + \delta_j \ln z + \vartheta_j t \tag{25}
$$

$$S_i^s = \alpha_i + \sum_{f=1}^{l} \alpha_{if} \ln w_f + \sum_{j=1}^{m} \gamma_{ij} \ln p_j + \gamma_i \ln z + \varepsilon_i t \tag{26}$$

$$M_k = \beta_5 + \beta_6 \ln z + \sum_{i=1}^{n} \gamma_i \ln w_i + \sum_{j=1}^{m} \delta_j \ln p_j + \beta_7 t \tag{27}$$

The monotonicity condition on the profit function requires that it is non-decreasing (non-increasing) in prices for all outputs (inputs) and non-decreasing in the stock of the quasi-fixed input. At the point of approximation, these imply that the output and shadow (input) profit shares are positive (negative). A sufficient conditions for this is that $\beta_j \geq 0$ for all j, $\beta_5 \geq 0$, and $\alpha_i \leq 0$ for all i, respectively. Symmetry with respect to output and input prices implies that $\beta_{jg} = \beta_{gj}$, $\alpha_{if} = \alpha_{fi}$ and $\gamma_{ij} = \gamma_{ji}$. In addition, linear homogeneity of (24) with respect to output and input prices requires that $\sum_{i=1}^{n} \alpha_i + \sum_{j=1}^{m} \beta_j = 1$, $\sum_{i=1}^{n} \gamma_i + \sum_{j=1}^{m} \delta_j = 0$, $\sum_{i=1}^{n} \varepsilon_i + \sum_{j=1}^{m} \vartheta_j = 0$, and $\sum_{j=1}^{m} \beta_{jg} + \sum_{j=1}^{m} \gamma_{ij} = \sum_{i=1}^{n} \alpha_{if} + \sum_{i=1}^{n} \gamma_{ij} = 0$. Similar to symmetry and linear homogeneity parameter restrictions are obtained through the adding-up property of (25) and (26). Finally, for convexity of (24) with respect to prices, the Hessian matrix of second order derivatives needs to be positive semi-definite. That is, all principal minors have non-negative determinants. On the other hand, concavity with respect to the quasi-fixed input requires the associated Hessian to be negative semi-definite.

The system of (24), (25) and (26) is estimated with iterative SUR to account for contemporaneous correlation of error terms, with the exclusion of the intermediate inputs' profit share equation to avoid singularity of the estimated variance-covariance matrix, due to adding-up property. Moreover, to ensure the underlying optimization process (i.e., profit maximization), across equation restrictions are imposed in the parameters appearing in more than one of the estimated equations. Due to the presence of autocorrelation, the procedure described in Judge *et al*. (1981) is used to correct for autocorrelation in each equation separately.[9] Then, the transformed system is estimated using iterative SUR.

Empirical results

The estimated parameters of the translog restricted profit function for US agriculture are presented in Table 1. The restrictions for linear homogeneity and symmetry of profit function in prices (at given fixed factor levels) were imposed *a priori*. The fitted restricted profit function satisfied all theoretical properties. It satisfied the monotonicity property at all data points as the fitted output profit shares are found to be positive and the variable input profit shares negative, while the shadow profit share of capital is found to be positive. Moreover, at the point of approximation, the estimated translog profit function is found to be convex function of prices as the diagonal elements of the corresponding Hessian matrix are of the correct sign and all determinants of its principal minors are positive.[10] Finally, the estimated profit function is found to be concave with respect to the quasi-fixed factor.[11]

Measures of the rate of profit augmentation, short-run returns to scale, and capacity utilization are reported in Table 2. For the translog profit function, the rate of profit augmentation

Table 1. Estimated parameters of translog restricted profit function, US agriculture, 1948–1994.

Parameter	Estimated Value	Standard Error	Parameter	Estimated Value	Standard Error
α_0	−0.050	0.004	α_{22}	−0.547	0.046
β_1	1.343	0.026	β_3	0.094	0.058
β_2	1.664	0.032	β_4	−1.479	0.284
α_1	−1.451	0.040	γ_1	−0.738	0.222
α_2	−0.557	0.017	γ_2	−0.104	0.305
β_{11}	0.732	0.045	δ_1	−0.428	0.333
β_{12}	−1.401	0.064	δ_2	1.270	0.184
γ_{11}	0.239	0.063	β_5	0.062	0.010
γ_{12}	0.430	0.047	β_6	−0.001	0.001
β_{22}	0.833	0.061	ϑ_1	−0.037	0.002
γ_{21}	0.251	0.050	ϑ_2	−0.019	0.003
γ_{22}	0.316	0.052	ε_1	−0.008	0.005
α_{11}	−0.291	0.088	ε_2	0.065	0.005
α_{12}	−0.199	0.026	β_7	−0.048	0.011

is given as

$$\pi_t^s = \beta_5 + \beta_6 t + \sum_{i=1}^{n} \varepsilon_i \ln w_i + \sum_{j=1}^{m} \vartheta_j \ln p_j + \beta_7 \ln z. \tag{28}$$

The rate of profit augmentation in US agriculture increased with an annual average rate of 7.81% during the period 1948–1994.[12] However, it decreased over time from 9.01% in the 1950s to 8.83% in the 1960s and to 7.22% in the period 1970–1982, and further to 6.34% in the period 1983–1994.

With regard to scale, it is found that US agriculture exhibited decreasing short-run returns to scale, averaging 0.87 during the period 1948–1994 (see Table 2). The degree of short-run returns to scale also diminished over time. Short-run returns to scale were found to be almost constant during the 1950s and the 1960s, but decreased thereafter. The range of short-run returns to scale is estimated to be 0.81 during the period 1970–1982, falling to 0.69 during 1983–1994. On the other hand, US agriculture was characterized by capacity

Table 2. Measures of π_t, short-run returns to scale, and capacity utilization US agriculture, 1948–1994.

	π_t	ρ_z	$\frac{(r_k - v_k)z_k}{TC^s}$
1950–1959	9.01	1.03	−0.13
1960–1969	8.83	0.98	0.08
1970–1982	7.22	0.81	0.35
1983–1994	6.34	0.69	0.53
1950–1982	8.32	0.92	0.13
1948–1994	7.81	0.87	0.22

Table 3. Decomposition of TFP growth, US agriculture, 1948–1994.

	Effect of Technical Change	Scale Effect	Temporary Equilibrium Effect	TFP Growth
Input-based Measure				
1950–1959	1.98	0.08	0.44	2.49
1960–1969	2.20	−0.03	−0.30	1.86
1970–1982	2.57	−0.56	−1.62	0.37
1983–1994	3.08	−0.77	0.95	3.23
1950–1982	2.29	−0.21	−0.63	1.43
1948–1994	2.46	−0.35	−0.20	1.91
Output-based Measure				
1950–1959	2.04	−0.10	0.46	2.40
1960–1969	2.17	0.07	−0.29	1.94
1970–1982	2.07	0.66	−1.17	1.56
1983–1994	2.13	−0.60	0.66	2.18
1950–1982	2.10	0.26	−0.44	1.92
1948–1994	2.11	0.03	−0.14	1.99

over-utilization during the 1950s, with capital under-utilized thereafter. More importantly, the degree of capacity under-utilization increased over time (see Table 2).

The results of measurement and decomposition of TFP growth in US agriculture are reported on Table 3, for input- and output-based measures of technical change, using (20) and (23), respectively. In addition, the TFP indices based on two alternative measures are presented on Table 4. On average, the estimated annual rate of TFP growth was 1.91% with the input-based measure of technical change and 1.99% with the output-based measure of technical change (see last column of Table 3). This difference is mainly due to the magnitude of the scale effect, which is measured differently in the two forms of TFP decomposition. Interestingly enough, it is not true that TFP growth rate measured through (20) is always greater than that measured through (23), as one would expect.[13] In fact, the opposite is found to be true for the period 1960 to 1982.

The two alternative measures provide rather similar estimates of TFP growth in the 1950s and the 1960s, but quite different ones for the period 1970–1994. For example, the estimated average annual growth rate of TFP based on (20) is almost four times smaller than that based on (23) for the period 1970–1982, while it is one and a half times greater for the period 1983–1994 (see Table 3). These differences are due to the scale effect in the former case and to the effect of technical change in the latter. Compared with previous estimates (see Table 5), the output-based estimates seem more reasonable and closer to other results.

The effect of technical change, given in the first column, is on average greater when it is computed with an input-based rather than an output-based measure of the rate of technical change, because of decreasing returns to scale in the short-run. This is true for all sub-periods under consideration except the 1950s when US agriculture exhibited slightly increasing short-run returns to scale. However, the differences tend to increase over time because the degree of short-run returns to scale decreased. For both forms of decomposing TFP, the technical change effect is positive, indicating that US agri-

Table 4. TFP indices for US agriculture using a parametric profit function approach.

Year	Input-based Measure	Output-based Measure
1948	0.631	0.623
1949	0.636	0.631
1950	0.652	0.647
1951	0.673	0.664
1952	0.690	0.681
1953	0.710	0.699
1954	0.725	0.714
1955	0.734	0.724
1956	0.750	0.739
1957	0.766	0.754
1958	0.781	0.768
1959	0.794	0.781
1960	0.807	0.794
1961	0.820	1.807
1962	0.833	0.820
1963	0.846	0.833
1964	0.859	0.846
1965	0.873	0.860
1966	0.885	0.872
1967	0.895	0.884
1968	0.902	0.892
1969	0.911	0.902
1970	0.917	0.910
1971	0.931	0.924
1972	0.947	0.938
1973	0.964	0.952
1974	0.989	0.964
1975	0.999	0.976
1976	1.007	0.989
1977	1.000	1.000
1978	1.029	1.015
1979	1.031	1.028
1980	1.034	1.036
1981	0.973	1.033
1982	0.942	1.029
1983	1.009	1.047
1984	0.956	1.047
1985	0.989	1.068
1986	1.024	1.083
1987	1.031	1.095
1988	1.106	1.112
1989	1.115	1.125
1990	1.134	1.137
1991	1.157	1.150
1992	1.149	1.165
1993	1.205	1.176
1994	1.186	1.192

Table 5. Comparison of TFP growth rate (%) measures for US agriculture, (average annual).

Study		1950–59	1960–69	1970–82	1983–94	1950–82	1948–94
				Accounting Approach			
Theil-Tornqvist Index							
USDA	(I)[1]	2.02	1.42				
	(II)[2]					1.47	
Ball (1985)		2.59	1.65				
Capalbo (1988a)		1.37	1.16	2.26		1.56	
Jorgenson & Gollop (1992)						1.58[3]	
Lambert (1998)						1.12	
Fisher Index							
Ball et al (1997)		1.87	2.22	1.97	2.57	2.02	1.94
Lambert (1998)						1.17	
				Non-parametric Approach[4]			
Cox & Chavas (1990)		2.48	1.84	2.49		1.79[5]	
Chavas & Cox (1992)	(I)[6]	2.71	1.55	2.82		2.39	
	(II)[7]	1.86	1.79	2.38		2.05	
Chavas & Cox (1994)	(I)[8]	1.82	1.47	1.74		1.69	
	(II)[9]	2.13	1.69	1.96		1.94	
Lambert (1998)	(I)[8]					1.22[10]	
	(II)[9]					1.67[10]	
				Parametric Approach			
Production Function							
Capalbo (1988b)						1.50[11]	
Luh & Stefanou (1991)		1.26	1.22	1.90		1.50	
Luh & Stefanou (1993)		1.18	0.93	1.71		1.31	
Cost Function							
Capalbo (1988a)						1.27	
Profit Function							
Present Study	(I)[8]	2.49	1.86	0.37	3.23	1.43	1.91
	(II)[9]	2.40	1.94	1.56	2.18	1.92	1.99

Notes: [1] Reported in Ball (1985)
[2] Reported in Trueblood and Ruttan (1995)
[3] Refers to the period 1948–1985 and it is reported in Trueblood and Ruttan (1995)
[4] Calculated by the authors from published TFP indices in Cox and Chavas (1990) and Chavas and Cox (1992, 1994)
[5] Refers to the period 1950–1983
[6] Based on 30-year lag specification of R&D
[7] Based on 15-year lag specification of R&D
[8] Input-based measure
[9] Output-based measure
[10] These are the outer bound estimates
[11] Refers to the period 1948–1982

culture exhibited progressive technical change. Also, in both cases, the largest portion of TFP growth is attributed to technical change. Nevertheless, the input-based measure indicates a continuous increase in the rate of technical change, while the output-based measure shows a slowdown in the rate of technical change during the period 1970–1982.

Significant differences arise with respect to the scale effect, which is given in the second column of Table 3. Using the input-based measure of the rate of technical change, based on (20), the scale effect is, on average, negative while with the output-based measure of the rate of technical change, using (23), it is on average positive, albeit very small. These differences are due to different definitions of the scale effect in the two forms of decomposition. Nevertheless, in both (20) and (23), the magnitude of the scale effect is smaller and relatively less significant compared to the technical change effect.

The magnitude and the sign of the temporary equilibrium effect is rather similar in the two measures (see Table 3). The capacity utilization of the quasi-fixed input (capital) had a generally negative contribution to TFP growth in US agriculture. Given that the weighted sum of variable and quasi-fixed inputs decreased over time, the sign of the temporary equilibrium effect indicates that, on average, the rental price of capital was greater than its shadow price, implying that capital was under-utilized during the period 1948–1994.

A comparison of the results reported in Table 3 with those of previous studies concerning measurement of TFP growth in US agriculture is given in Table 5.[14] The results of the present study show interesting differences from he results of earlier studies using other measurement and decomposition methods. The result of the present study conform broadly with those of Ball *et al*. (1997), who used a Fisher TFP index and found strong TFP growth rates in the 1950s and 1960s and a decline in TFP growth in the 1970s. Our results, however, are sharply different than those of Capalbo (1988), who utilized a Theil-Tornqvist TFP index, and Luh and Stefanou (1991, 1993), who used a primal approach. Luh and Stefanou (1991, 1993) found much lower TFP growth rates in the 1950s and 1960s and an acceleration of TFP growth in the 1970s.

A more direct comparison can be carried with Chavas and Cox (1994), who reported primal input- and output-based measures of TFP growth in US agriculture during the period 1950–1982, using non-parametric techniques and assuming long-run equilibrium. Our estimate of the average annual TFP during the same period is slightly lower (see Table 5). This is explained by the fact that the contribution of the temporary equilibrium effect is negative. In both cases, however, the output-based measure is greater than the input-based measure, indicating decreasing returns to scale.

5. Concluding Remarks

This paper develops a theoretical framework for measurement and decomposition of TFP growth using a profit function framework. Within the proposed framework, estimates of TFP growth and identification of its sources are obtained by using directly the estimated parameters of a profit function. The proposed framework offers two alternative estimates of TFP growth based on the output- and the input-based measures of the rate of technical change. It encompasses previous developments proposed by Bernstein (1994), who used a measure of TFP growth that is similar, but apparently not the same, with the one developed in the presence of the input-based measure of the rate of technical change. The paper also shows clearly the relation of the two alternative measures of the rate of technical change and makes them directly comparable, deriving both forms of TFP measurement and decomposition using he same methodology.

A quantitative illustration of the results is presented by estimating a translog restricted profit function for US agriculture using published data for the period 1948–1994. The results of TFP measurement and decomposition based on two alternative measures of the rate of technical change are very interesting. Although the average TFP growth rates for the entire period are very similar (1.91% and 1.99% in the cases of the input- and the output-based measures of the rate of technical changes), the rates for various sub-periods are quite different. For example, for the period 1970–1982 not only is the average TFP growth rate different (0.37% and 1.56% in the cases of the input- and the output-based measures of the rate of technical changes), but there are also other differences, such as in the sign of the scale effect. It seems that the difference is mainly due to the scale effect, while the effect of technical change differs less and the temporary equilibrium effect is similar in both cases.

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Notes

1. However, there have been some studies following a primal approach for decomposing TFP changes, such as Berndt and Fuss (1986), Bauer (1990), and Lovell (1996).
2. Agriculture is also a highly competitive industry and farmers' objective is best described by profit maximization as long as there are no production quotas. For the U.S. agriculture in particular, profit maximization is a commonly employed behavioral assumption; see Weaver (1983), Shumway (1983), Antle (1984), Ball (1988), Huffman and Evenson (1989), Luh and Stefanou (1991, 1993), among others.
3. There are advantages of using a profit function in estimating multiproduct technologies for price-taking firms because inconsistencies in the econometric estimation due to simultaneous equation problems are avoided, as no endogenous variables (output or input levels) are used as explanatory variables (Lopez, 1982).
4. In particular, if observed output falls to the left of the minimum point of the long-run average cost curve, increasing short-run returns to scale may be associated with either under- or over-utilization, while decreasing short-run returns to scale imply over-utilization. In contrast, if observed output falls to the right of the minimum point of the long-run average cost curve, increasing short-run returns to scale imply under-utilization, while decreasing short-run returns to scale may be associated with either under- or over-utilization.

5. In the case of profit function, it is not as straightforward as in the case of cost function (see Morrison, 1986) to derive a relationship between short- and long-run returns to scale. The long-run profit maximization problem with all inputs variable need not result in the same optimal output bundle as the one derived from the short-run problem, where some of the inputs are restricted to be quasi-fixed. Nevertheless, one can find the optimal long-run stock of quasi-fixed inputs through the derivative property $M_k = \partial \ln \pi^s / \partial \ln z_k$ and then substitute it into short-run output supply and factor demand functions to derive their long-run counterparts. Sometimes this becomes quite complicated as for example in the case of translog profit function, where a numerical solution is required to derive the optimal (long-run) level of quasi-fixed inputs. By using (1) and (3), $\rho = \rho_z + (\sum \partial \ln \pi / \partial \ln p_j)^{-1} - (\sum \partial \ln \pi^s(p, w, z(p, w)) / \partial \ln p_j)^{-1} + \sum M_k(p, w, z(p, w)) / \sum R_j(p, w, z(p, w)) = \rho_z + \sum M_k(p, w, z(p, w)) / \sum R_j(p, w, z(p, w))$. We would like to thank C. Morrison and one reviewer for raising this point.
6. Graphically and in terms of a production function, the output-based measure of the rate of technical change is measured vertically. Thus, it shows the rate of output increase, due to a shift in production surface, by using the same amount of inputs as before. In contrast, the input-based measure of the rate of technical change is measured horizontally and indicates the amount of potential input saving for producing the same amount of output as before, but operating at the new production function.
7. The following analysis is developed in the absence of adjustment cost, but it can be extended into a fully dynamic framework.
8. The distinction between input- and output-based decomposition of TFP growth in a profit framework is also important in the presence of productive inefficiency. For a theoretically consistent decomposition of TFP change in such a case, the former should be associated with an input-based measure of technical inefficiency and the latter with an output-based measure. For a derivation of input- and output-based measure of productive (technical and allocative) inefficiency within a primal and a profit function see Kumbhakar (1996).
9. The profit function (36) and the profit share equation of livestock were corrected for third-order autocorrelation by using a Cochrani-Orcutt procedure, while the profit share equation of labor was corrected for first-order autocorrelation.
10. This is equivalent to positive semi-definiteness of the modified Hessian (Antle and Capalbo, 1988). The determinants of the principal minors of the modified Hessian are $H_1 = 1.193$, $H_2 = 1.617$, $H_3 = 1.237$ and $H_4 = 0.332$ and its eigenvalues 0.0005, 0.1918, 0.7222, and 5.8014.
11. At the point of approximation, the determinants of the principal minors of the Hessian matrix corresponding to quasi-fixed factor are found to be 0.094 and -1.479.
12. Diewert's (1976) quadratic approximation lemma is used to convert the continuous time model developed in the second and third section to discrete variables calculations used in the fourth section.
13. In absolute terms however the input-based TFP index is greater than the output-based index during the period 1948–1980, while the opposite is true for the rest of the period under consideration (see Table 4).
14. A comparison of the explanatory power of different approaches used to measure TFP in US agriculture is not always possible because in the studies using the primal approach to decompose the growth in TFP (e.g., Luh and Stefanou, 1991, 1993) the rate of technical change is calculated as a residual. A comparison may however be possible with Capalbo (1988a) parametric cost function approach regarding the period 1950–1982. In the case of cost function, the unexplained residual is 18.6%, while in the case of profit function is 8.3% and 23.1% for the output- and the input-based measures of TFP growth, during the same period.

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