# Measuring the Components of Aggregate Productivity Growth in U.S. Agriculture

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A method of decomposing the growth in total factor productivity into effects due to nonconstant returns to scale and technical change was applied to the U.S. agricultural sector. The scale effects and technical changes were measured using an economically estimated two-output, three-input translog cost model. Total factor productivity as conventionally measured grew at an average annual rate of 1.56% from 1950–82. This growth rate, however, misrepresented the rate of technical change in U.S. agriculture primarily due to the nonconstant scale effects.

*Key words:* productivity, returns to scale, technical change, translog cost model.

Productivity growth is often cited as one of the major factors contributing to the continued economic growth of the postwar agricultural sector. Approaches to the measurement of productivity growth and technical change may be grouped into two broad categories: (*a*) analyses for which a change in total factor productivity is interpreted as the rate of change of an index of aggregate output divided by an index of aggregate input or (*b*) analyses which involve estimating the rate of shift of production relations. To compare the empirical measures resulting from the two approaches and to decompose productivity growth into components associated with scale and technical change, one needs to understand the assumptions and methodology underlying each approach. For example, in constructing a measure of total factor productivity (TFP) growth based on the divisia indexing procedure, the rate of growth of inputs and outputs are weighted by their average cost shares and revenue shares, respectively. This index of TFP growth is equivalent to a measure of the rate of technical change if we assume that there are competitive markets and constant-returns-to-scale technology.

Recently, researchers have attempted to relax some of these assumptions. Berndt and Khaled estimated aggregate cost function models for the U.S. manufacturing sector that simultaneously identified substitution elasticities, scale economies, and the rate and bias of technical change. Denny, Fuss, and Waverman have relaxed the competitive equilibrium assumptions for the output market and decomposed the rate of productivity growth for a regulated sector into scale effects, nonmarginal cost pricing effects, and technological change. Chan and Mountain showed how the divisia or Tornqvist-Theil index of total factor productivity can be modified to account for nonconstant returns to scale. Callan applied the Denny, Fuss, and Waverman decomposition framework to the electric utility industry.

The purpose of this paper is to implement a framework for comparing alternative approaches to measuring TFP growth in one sector of the U.S. economy, the agricultural sector. In doing so, we provide some evidence on the components of aggregate productivity growth which reflect a decomposition of the TFP growth into factors associated with nonconstant returns to scale and technical change.

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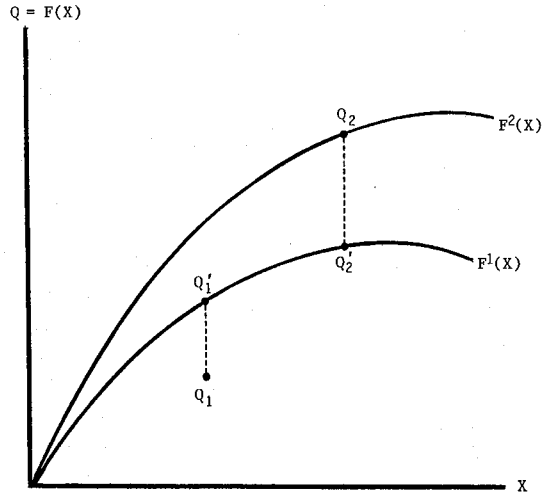


**Figure 1. Explaining productivity differences**

Section two reviews the relationship between a divisia productivity index and the technology. The index-based measure of TFP and results of decomposing the TFP growth rate based on an econometrically estimated cost function for U.S. agriculture are provided in the third section. Section four offers a comparison of these results with other research; concluding comments are provided in the last section.

## Productivity Indexes and Technology

Production theory provides a basis for analyzing the factors that explain output level changes. Generally, the rate of output depends on three factors: the state of technology or kind of production process utilized, the quantities and types of resources put into the production process, and the efficiency with which those resources are utilized. A simple example illustrates how each of these factors influences measured productivity. Figure 1 shows single-output neoclassical production functions $F^1(X)$ and $F^2(X)$, which represent the technically efficient combinations of input $X$ and output $Q$ for two different production processes. Let $Q_1$ and $Q_2$ be the outputs observed in periods 1 and 2, and assume production process $F^1$ was used in period 1 and $F^2$ was used in period 2. Because these two observations lie on different rays from the origin, TFP, measured as the average product of factor $X$, is greater in period 2 than in period 1. This measured productivity change can be attributed to three distinct phenomena. First, $Q_1$ is below $F^1(X)$, indicating technical inefficiency; efficient production would have resulted in output $Q_1'$. Second, output $Q_2$ was produced with a greater input than was $Q_1$, so there is a difference in scale of production, which explains the difference between, say, $Q_1'$ and $Q_2'$. Third, production function $F^2$ exhibits a higher total productivity than $F^1$, which explains the gap between $Q_2'$ and $Q_2$. Thus, differences in productive efficiency, the scale of production, and the state of technology all may explain part of the observed differences in TFP.

Growth accounting was a natural extension of the early research by Kuznets and others to develop consistent national accounts data. In the absence of technological advance the growth in total output can be explained in terms of the growth in total factor input. This view was supported by the neoclassical theory of production and distribution: competitive equilibrium and constant returns to scale imply that payments to factors exhaust total product. However, if there was technological advance, payments to factors would not exhaust total product, and there would remain a residual output not explained by total factor input. This famous "residual," as Domar termed it, was associated with productivity growth in the early growth accounting literature and remains a fundamental concept in the measurement and explanation of productivity growth. Research by numerous economists has been devoted to measuring and explaining the residual. (For example, see Kendrick 1961, 1973; Denison 1967, 1979; Jorgenson and Griliches. For literature surveys see Nadiri and Dogramaci.)

The growth accounting approach is implemented by compiling detailed accounts of inputs and outputs, aggregating them into input and output indexes, and using these indexes to calculate a TFP index. In determining aggregate output and aggregate input measures, the method by which the raw data is combined into a manageable number of subaggregates and, in turn, reaggregated is important. The theory of index numbers addresses this issue. Recent advances have made it possible to identify the economic assumptions about the underlying aggregation functions that are implicit in the choice of an indexing procedure (Diewert 1976, 1981a).[1]

[1] The methodological linkages between index numbers and production technology were delineated in the late 1970s by Diewert and others. This research showed that nonparametric methods

The divisia index of TFP growth is the residual growth in outputs not accounted for by the growth inputs. This index is defined in terms of the proportional rate of growth of productivity:

$$\dot{TFP} = \dot{Q} - \dot{F}, \tag{1}$$

where

$$\dot{Q} = \sum_j \frac{p_j Q_j}{R} \dot{Q}_j \quad \text{and} \tag{2}$$

$$\dot{F} = \sum_i \frac{w_i x_i}{C} \dot{x}_i. \tag{3}$$

Here $p_j$ and $Q_j$ denote the price and quantity of output $j$, $\dot{Q}_j$ denotes the proportionate rate of growth of output $j$, $R$ denotes total revenue, $w_i$ and $x_i$ denote price and quantity of input $i$, $\dot{x}_i$ denotes proportionate rate of growth of input $i$, and $C$ denotes total cost.

The discrete approximations to equations (1), (2), and (3) are given by the Tornqvist-Theil approximations:

$$\Delta TFP = \Delta \log Q - \Delta \log F \tag{4}$$

$$\Delta \log Q = \log \frac{(Q_t)}{Q_{t-1}} = \frac{1}{2} \sum_j (r_{jt} + r_{j,t-1}) \cdot \log\left(\frac{Q_{jt}}{Q_{j,t-1}}\right) \tag{4a}$$

$$\Delta \log F = \log \frac{(F_t)}{F_{t-1}} = \frac{1}{2} \sum (s_{it} + s_{i,t-1}) \cdot \log\left(\frac{x_{it}}{x_{i,t-1}}\right), \tag{4b}$$

where $r_{jt}$ is the revenue share of output $Q_j$ in period $t$, and $s_{it}$ is the cost share of input $i$ in period $t$. These approximations provide the basis for calculating the index of TFP reported in table 1.

$\dot{TFP}$ can be used to approximate the rate of technological progress if the production technology exhibits extended Hicks-neutral technical change and is linearly homogenous, and producers are characterized by competitive behavior.[2] Capalbo and Denny provide a theoretical development and an empirical test of the approximation for the U.S. and Canadian agricultural sectors.

An alternative approach to measuring changes in total factor productivity is based on a direct application of the Tornqvist-Theil index number theory, rather than indirectly as an approximation to continuous-time derivatives. This alternative approach leads to an exact formula for TFP that is suitable for discrete data, but the formula is contingent on the cost function being of the translog form. As a result, the exact index number approach to TFP measurement also involves an approximation, since it is unlikely that the technology can be precisely represented by a translog cost function over the entire range of prices and quantities. Furthermore, since the Tornqvist-Theil indexes are based on cost and revenue shares and utilize Shephard's lemma in their

**Table 1. Total Factor Productivity for U.S. Agriculture, 1950-82 (1977 = 100)**

| | | | |
|---|---|---|---|
| 1950 | 67.00 | 1970 | 84.36 |
| 1951 | 68.87 | 1971 | 88.70 |
| 1952 | 71.89 | 1972 | 89.69 |
| 1953 | 74.33 | 1973 | 91.15 |
| 1954 | 74.21 | 1974 | 94.40 |
| 1955 | 73.51 | 1975 | 96.32 |
| 1956 | 79.11 | 1976 | 96.31 |
| 1957 | 77.19 | 1977 | 100.00 |
| 1958 | 78.62 | 1978 | 97.29 |
| 1959 | 75.84 | 1979 | 102.50 |
| 1960 | 77.99 | 1980 | 102.31 |
| 1961 | 78.64 | 1981 | 109.63 |
| 1962 | 80.17 | 1982 | 110.71 |
| 1963 | 81.54 | | |
| 1964 | 83.41 | | |
| 1965 | 82.62 | | |
| 1966 | 83.45 | | |
| 1967 | 85.44 | | |
| 1968 | 85.63 | | |
| 1969 | 86.55 | | |

impose an implicit structure on the technology. For example, the Laspeyres indexing procedure, used in much of the early productivity studies by the USDA, was shown to be exact for, or imply, either a linear production function in which all inputs are perfect substitutes or a Leontief function for which there is no input substitution. The geometric index is exact for a Cobb-Douglas production function; while the Tornqvist-Theil index, which is also an approximation to the divisia index, is exact for a homogenous translog production function.

[2] Blackorby, Lovell, and Thursby define Hicks-neutral technical change as the invariance of the expansion path to technical change; this concept of neutrality does depend on assumptions about homotheticity of the technology. If the technology is homothetic, then Hicks neutrality (the marginal rates of technical substitution and optimal factor proportions are invariant to technological change) implies extended Hicks neutrality, where the latter is defined as the case in which the production function can be written in the strongly separable form.

derivation, the exact index number approach implicitly assumes competitive behavior.[3]

The econometric or parametric approach to productivity measurement is based on econometric estimation of the production technology. The methodology used by most studies employing flexible functional forms was introduced in Berndt and Christensen's seminal paper on the translog production function. This methodology involves specifying a function representing the technology (such as a production or cost function) and econometrically estimating it or its derivatives or both. Technological progress is one of the more difficult factors affecting observed differences in TFP to characterize quantitatively in econometric time-series models. With few exceptions (notably Denny, Fuss, and Waverman; Denny et al.), disembodied technical change has been modeled using a time-trend variable. In the context of a cost function, the technical change trend variable represents total cost diminution. Researchers recognize that such a representation serves only to represent the passage of time.

The econometric approach allows the researcher to relax some of the assumptions implicit in the index numbers approach. A production function, such as the translog, can be estimated without making assumptions about neutrality of technological change, returns to scale, or industry equilibrium. Moreover, because the estimated model has known statistical properties, confidence intervals can be constructed around the estimates. However, to be able to estimate an aggregate production function model, outputs must be aggregated into a single index, so input-output separability must be assumed. For sufficient degrees of freedom and to mitigate multicollinearity problems, it is also necessary to aggregate input data into a small number of categories which can be done only under input separability assumptions.

The link between the conventional TFP measure and the theory of production based on either the aggregate production or cost function has been addressed in the literature.[4] Defining $\dot{A} = (\partial f/\partial t)(1/f)$ as the proportionate intertemporal shift in the production function, $Q = f(x_1, \ldots, x_n, t)$, the derivative of the production function with respect to time can be expressed as

$$\dot{Q} = \sum \frac{\partial f}{\partial x_i}\frac{x_i}{Q}\dot{x}_i + \dot{A}.$$

Assuming cost minimization, $\partial f/\partial x_i = w_i/(\partial C/\partial Q)$,

$$\dot{Q} = \sum_i \epsilon_{CQ}^{-1}\frac{w_i x_i}{C}\dot{x}_i + \dot{A},$$

where $\epsilon_{CQ}$ is the elasticity of cost with respect to output. Using (3),

$$\dot{A} = \dot{Q} - \epsilon_{CQ}^{-1}\dot{F} \quad \text{or} \quad \dot{Q} = \dot{A} + \epsilon_{CQ}^{-1}\dot{F}. \tag{5}$$

Equation (5) is used to link the narrower definition of productivity denoted by $\dot{A}$, which is a measure of technical change, to the conventional measure of TFP given in (1):

$$T\dot{F}P = \dot{A} + (\epsilon_{CQ}^{-1} - 1)\dot{F}. \tag{6}$$

Under constant returns to scale $\epsilon_{CQ} = 1$, so the conventionally measured rate of growth of TFP is identical to the rate of technical change, the latter measured as a marginal shift in the single-output production function. If the sector is characterized by increasing or decreasing returns to scale, the measure of total factor productivity growth reflects not only the effects of technical change but also a scale effect.

A parallel analysis has been developed utilizing an aggregate cost function, $C = g(w_1, \ldots, w_n, Q, t)$. Differentiating this with respect to time, employing Shephard's lemma ($\partial g/\partial w_i = x_i$), and dividing through by $C$, yields

$$\frac{1}{C}\frac{dC}{dt} = \sum_i \frac{w_i x_i}{C}\dot{w}_i + \frac{\partial g}{\partial Q}\frac{Q}{C}\dot{Q} + \frac{1}{C}\frac{\partial g}{\partial t}. \tag{7}$$

Equation (7) can be rewritten as

$$\dot{B} = \dot{C} - \sum \frac{w_i x_i}{C}\dot{w}_i - \epsilon_{CQ}\dot{Q}, \tag{8}$$

where $\dot{B} = (1/C)\,\partial C/\partial t$ denotes the proportionate shift in the cost function. In (8), $\dot{B}$ is decomposed into the change in costs minus the

[3] Caves, Christensen, and Diewert have shown that the translog input and output indexes are exact for the geometric mean of the Malmquist input and output indexes, respectively, for periods $t = 0$ and $t = 1$, "when the underlying aggregator functions are both translog (not necessarily homogeneous), but with different parameters." This result implies that the Tornqvist-Theil productivity index is superlative in a considerably more general sense than shown by Diewert (1976).

[4] For example, see Solow; Griliches (1963, 1964); Jorgenson and Griliches; Ohta; Diewert (1976); Denny, Fuss, and Waverman.

change in aggregate inputs minus the scale effect.

Ohta showed that $\dot{B}$ is related to $\dot{A}$. Differentiating the cost equation, $C = \Sigma w_i x_i$, with respect to time yields

$$\dot{C} = \sum_i \frac{w_i x_i}{C} \dot{x}_i + \sum_i \frac{w_i x_i}{C} w_i, \quad \text{or}$$

$$\dot{C} - \sum \frac{w_i x_i}{C} w_i = \sum \frac{w_i x_i}{C} \dot{x}_i.$$

Substituting into (8) yields

$$(9) \qquad -\dot{B} = \epsilon_{CQ}\dot{Q} - \sum_i \frac{w_i x_i}{C} \dot{x}_i$$

$$= \epsilon_{CQ}\dot{Q} - \dot{F}.$$

A comparison of (5) and (9) indicates that $-\dot{B} = \epsilon_{CQ}\dot{A}$.

For the multiple-output case, where firms are minimizing the cost of producing $m$ outputs using $n$ inputs, the cost function is

$$C = g(w_1, \ldots, w_n, Q_1, \ldots, Q_m, t).$$

Denny, Fuss, and Waverman derive the following multiple output counterpart to (9):

$$(10) \qquad -\dot{B} = \sum_j \epsilon_{CQ_j}\dot{Q}_j - \sum_i \frac{w_i x_i}{C} \dot{x}_i,$$

where $\epsilon_{CQ_j}$ is the cost elasticity for the $j$th output. Equation (10) may be rewritten as

$$(11) \qquad -\dot{B} = \sum_j \epsilon_{CQ_j}\dot{Q}_j - \dot{F}$$

since the last term in (10) is the index of aggregate inputs.

Utilizing (11), the relationship between proportionate shifts in the cost function and the growth in the conventional measure of TFP given by (1) can be derived. Note that the output-weighting scheme utilized in (11) is related to the revenue share weights utilized in constructing the aggregate output index in (2). If output price is equal to marginal cost, then

$$\epsilon_{CQ_j} = (Q_j/C)(\partial C/\partial Q_j) = (p_j Q_j)/C,$$

and one can define aggregate output growth using either cost elasticities or revenue shares as weights:

$$(12) \qquad \sum_j \left[\frac{\epsilon_{CQ_j}}{\sum_j \epsilon_{CQ_j}}\right] \dot{Q}_j = \sum_j [p_j Q_j / \Sigma\, p_j Q_j] \dot{Q}_j$$

$$\equiv \dot{Q}.$$

**Table 2. Productivity Growth in U.S. Agriculture**

| Period | $T\dot{F}P$ | $\dot{Q}$ | $\dot{F}$ |
|---|---|---|---|
| 1950–59 | 1.37 | 1.56 | 0.19 |
| 1960–69 | 1.16 | 1.09 | −0.06 |
| 1970–82 | 2.26 | 2.60 | 0.34 |
| 1950–82 | 1.56 | 1.75 | 0.18 |

Utilizing (12), the relationship between the shift in the cost function and TFP growth is

$$(13) \qquad T\dot{F}P = -\dot{B} + (1 - \sum \epsilon_{CQ_j})\dot{Q}.$$

When producers sell at prices equal to the marginal costs and there are no scale economies or diseconomies, $T\dot{F}P$ reflects the effect of technical change as measured by shifts in the cost function. If the cost elasticities are known a priori or obtainable from the estimated parameters of a cost function, the scale effects can be separated from the intertemporal shifts of the aggregate cost function.

## Empirical Results

In this section an estimate of aggregate productivity growth for U.S. agriculture using the Tornqvist-Theil approximation to the divisia index of TFP [equation(4)] is compared to the parametrically obtained estimate of a shift in the aggregate cost function using the linkages reviewed in the previous section. Both measures are calculated using the same data set.[5]

The productivity index reported in table 1 is constructed using the Tornqvist-Theil approximations to the divisia indexing procedure. The average annual rates of growth of aggregate output, aggregate input, and TFP are given in table 2. TFP grew at an average annual rate of 1.56% over the period 1950–82; however, there have been substantial variations in this growth rate for selected subperiods. The 1960s were characterized by a nearly zero rate of growth of aggregate inputs and a slower increase in output growth relative to other years, resulting in the smaller rate of growth of TFP. In contrast, productivity growth escalated in the 1970s–early 1980s period, primarily led by

[5] The data are explained in Capalbo, Vo, and Wade.

the accelerated rate of growth of aggregate output.[6]

To implement the methodology for decomposing the index of TFP growth, one needs to quantify the cost-output elasticities and the shift of the aggregate cost function over time. These are obtained by econometrically estimating an aggregate cost model for U.S. agriculture. A two-output, three-input translog cost function was specified. All quantities and prices were normalized so that the point of approximation for the translog model occurred in 1966, the midpoint of the sample. Linear homogeneity in the factor prices and symmetry restrictions were imposed a priori. The set of equations consisting of the cost function, two of the three cost share equations, and the two revenue share equations were estimated as an iterative SUR system.[7] By construction, the factor cost shares sum to unity.

The model and the full set of parameter estimates are provided in table 3.[8] The time trend, $T$, is included as a variable to capture the effect of disembodied technological progress. The estimated aggregate cost function is increasing in output quantitites and factor prices and decreasing in the technology index. At the point of approximation, the supply function for crops is positively sloped; the demand functions for labor, capital, and material are negatively sloped. The supply function for livestock products violates the curvature restrictions; however, it is not statistically significant.[9]

Caves, Christensen, and Swanson derive the following formula for computing returns to scale from a total cost function:

$$(14) \qquad RTS = \left(\sum_i (\partial \ln C/\partial \ln Q_i)\right)^{-1} = \sum_i \epsilon_{CQ_i}^{-1}.$$

For the translog model, the cost-output elasticities are determined using the following expression:

$$\epsilon_{CQ_i} = \partial \ln C/\partial \ln Q_i = \alpha_i + \delta_{ii}\ln Q_i + \sum_{j \neq i} \delta_{ij}\ln Q_j + \sum_r \rho_{ir}\ln W_r + \delta_{it}T$$

for $i = 1, 2$.

The estimated elasticities are presented in table 4. The results indicate that on average the aggregate U.S. agricultural sector has been characterized by decreasing returns to scale in the postwar period: at the point of approximation of the model (1966), the returns-to-scale measure is .788 with standard error of .012.

The shift of the cost function, $\beta_t$, is determined using the following expression:

$$\frac{1}{C}\frac{\partial g}{\partial t} = \frac{\partial \ln C}{\partial t} = \left(\sum_{r=1}^{3} \gamma_{rt}\ln W_r + \sum_{i=1}^{2} \delta_{it}\ln Q_i + \phi_t + \phi_{tt}T\right).$$

This measure is equal to approximately 1.74 at the point of approximation. Furthermore, one should note that scale and technical change are related: $\partial \epsilon_{CQ_i}/\partial t$ is negative for both outputs at the point of approximation, which implies that technical change has been of a scale-augmenting nature.

The results of the decomposition of TFP, summarized in table 5, are based on the equation

$$\dot{TFP} = \left[\left(1 - \sum_j \epsilon_{CQ_j}\right)\dot{Q}\right] + (-\beta_t) + \epsilon_t,$$

[6] The growth rates of aggregate output and aggregate input mask significant variations that may have occurred in the composition of the indexes. For example, during the 1960s, which was characterized by a nearly zero aggregate input growth rate, there was a substantial decline in the labor share of total cost and a large increase in the materials share.

[7] The statistical estimation package utilized was SHAZAM. Potentially, there is an endogeneity problem involving output because, in deriving the revenue share equations, one makes use of the profit maximization conditions (Fuss and Waverman). Given the relatively limited sample size and in the absence of any obvious instruments, however, not much can be gained from a 2SLQ or a 3SLQ procedure.

[8] The translog cost function is a (local) second-order approximation to an arbitrary twice-continuously differentiable cost function. Like many flexible functional forms, it may not be globally consistent with the concavity in price property that cost functions must possess; furthermore, the approximation need not be close for all price and quantity (see Diewert 1976, 1981b). For these reasons the translog function is usually not used to predict outside the sample period.

[9] A constant-returns-to-scale specification of the translog model was also estimated but, based on the likelihood ratio test, decisively rejected in favor of the specification shown in table 3.

**Table 3. Translog Total Cost Function—Two Outputs, Three Inputs**

Model:

$$\ln TC = \alpha_0 + \sum_{i}^{2} \alpha_i \ln Q_i + \frac{1}{2}\sum_{i}^{2}\sum_{j}^{2} \delta_{ij} \ln Q_j + \sum_{r}^{3} \beta_r \ln W_r + \frac{1}{2}\sum_{r}^{3}\sum_{s}^{3} \gamma_{rs} \ln W_r \ln W_s + \sum_{i}^{2}\sum_{r}^{3} \rho_{ir} \ln Q_i \ln W_r + \phi_t T + \phi_{tt} \cdot T^2 + \sum_{i}^{2} \delta_{it} T \cdot \ln Q_i + \sum_{r}^{3} \gamma_{rt} T \ln W_r$$

$$S_r = \beta_r + \sum_{s}^{3} \gamma_{rs} \ln W_s + \sum_{i}^{2} \rho_{ir} \ln Q_i + \gamma_{rt} T \qquad r = 1, \ldots, 3$$

$$R_i = \alpha_i + \sum_{j}^{2} \delta_{ij} \ln Q_j + \sum_{r}^{3} \rho_{ir} \ln W_r + \delta_{it} T \qquad i = 1, 2$$

Restrictions: Symmetry
Linear homogeneity in input prices

Variables:
$Q_1$: quantity index of crop products
$Q_2$: quantity index of livestock products
$W_1$: price index of family and hired labor
$W_2$: price index of land, structures, durable equipment, animal capital, and inventories
$W_3$: price index of materials (energy, feed and seed, chemicals, and miscellaneous inputs)
$TC$: total cost
$S_r$: $r$th input cost divided by total cost, $r = 1, 2, 3$
$R_i$: $i$th product revenue divided by total cost, $i = 1, 2$
$T$: time trend

Empirical results: U.S. agricultural sector, 1950–82; standard errors in parentheses

| | | | | | |
|---|---|---|---|---|---|
| $\alpha_0$ | 10.832 (0.008) | $\gamma_{11}$ | 0.071 (0.011) | $\rho_{21}$ | 0.008 (0.034) |
| $\alpha_1$ | 0.751 (0.017) | $\gamma_{22}$ | 0.236 (0.006) | $\rho_{23}$ | 0.139 (0.036) |
| $\alpha_2$ | 0.519 (0.009) | $\gamma_{33}$ | 0.160 (0.011) | $\phi_t$ | −0.017 (0.001) |
| $\delta_{11}$ | 0.621 (0.201) | $\gamma_{12}$ | −0.074 (0.006) | $\phi_{tt}$ | 0.001 (0.0001) |
| $\delta_{22}$ | 0.034 (0.185) | $\gamma_{13}$ | 0.002 (0.010) | $\delta_{1t}$ | −0.017 (0.004) |
| $\delta_{12}$ | 0.043 (0.123) | $\gamma_{23}$ | −0.162 (0.005) | $\delta_{2t}$ | −0.004 (0.003) |
| $\beta_1$ | 0.245 (0.003) | $\rho_{11}$ | −0.025 (0.037) | $\gamma_{1t}$ | −0.005 (0.001) |
| $\beta_2$ | 0.425 (0.003) | $\rho_{22}$ | −0.149 (0.023) | $\gamma_{2t}$ | 0.006 (0.001) |
| $\beta_3$ | 0.330 (0.005) | $\rho_{12}$ | −0.213 (0.021) | $\gamma_{3t}$ | −0.001 (0.008) |
| | | $\rho_{13}$ | 0.238 (0.033) | | |

where $\epsilon_t$ is the residual associated with the fact that the terms on the right-hand side are based on estimated parameters of the translog model. Parametrically measured technical change is approximately 12% greater than the measure of productivity growth. The results indicate that the conventional index of the rate of growth of TFP understates the rate of technological progress for the U.S. agricultural sector in the 1950–82 period primarily due to the decreasing returns-to-scale characterization.

## Comparison with Other Research Results

Griliches (1963, 1964) attributed the changes in aggregate output to changes in the quantity and quality of inputs and to economies of scale. His empirical results are based on an econometrically estimated Cobb-Douglas production function for U.S. agriculture utilizing 1949, 1954, and 1959 data for sixty-eight regions of the United States, and geometric indexes of

**Table 4. Cost-Output Elasticities**

| Year | Cost Output Elasticities ($\epsilon_{CQ}$) | |
|---|---|---|
| | Crops | Livestock |
| 1950 | 1.032 | 0.666 |
| 1951 | 1.024 | 0.651 |
| 1952 | 0.993 | 0.616 |
| 1953 | 1.012 | 0.629 |
| 1954 | 0.984 | 0.630 |
| 1955 | 0.960 | 0.620 |
| 1956 | 0.956 | 0.613 |
| 1957 | 0.890 | 0.582 |
| 1958 | 0.888 | 0.570 |
| 1959 | 0.829 | 0.549 |
| 1960 | 0.842 | 0.546 |
| 1961 | 0.832 | 0.552 |
| 1962 | 0.825 | 0.555 |
| 1963 | 0.814 | 0.549 |
| 1964 | 0.794 | 0.546 |
| 1965 | 0.788 | 0.535 |
| 1966 | 0.751 | 0.519 |
| 1967 | 0.722 | 0.498 |
| 1968 | 0.693 | 0.480 |
| 1969 | 0.668 | 0.465 |
| 1970 | 0.601 | 0.446 |
| 1971 | 0.641 | 0.446 |
| 1972 | 0.680 | 0.467 |
| 1973 | 0.718 | 0.479 |
| 1974 | 0.706 | 0.469 |
| 1975 | 0.718 | 0.457 |
| 1976 | 0.664 | 0.441 |
| 1977 | 0.654 | 0.424 |
| 1978 | 0.623 | 0.405 |
| 1979 | 0.634 | 0.387 |
| 1980 | 0.575 | 0.368 |
| 1981 | 0.582 | 0.337 |
| 1982 | 0.571 | 0.336 |

aggregate output and input growth between 1940 and 1960. In his 1963 study, he concluded:

> . . . the main sources of conventionally measured productivity increases in United States Agriculture during the 1940–60 period appear to have been:
>
> 1. Improvements in the quality of labor as a consequence of a rise in educational levels
> 2. Improvements in the quality of machinery services that had been disguised by biases in the standard price indexes used to deflate capital equipment expenditures
> 3. Underestimation of the contribution of capital and overestimation of the contribution of labor to output growth by the conventional factor-share based weights
> 4. Economies of scale[5] [5 The imputation of part of the observed growth in output to the last two sources arises out of the denial of the conventional assumption of equilibrium.] (page 332)

Griliches' 1964 study, which includes public research and development (R&D) expenditures as an explanatory variable in the aggregate production function, indicates that the R&D expenditures "affect the level of agricultural output 'significantly' and that their social rate of return is quite high" (p. 961). With respect to the analysis of the productivity residual, the results

**Table 5. Decomposition of Conventionally Measured TFP Growth in U.S. Agriculture, 1950-82**

| | Components of $\dot{TFP}$ | | |
|---|---|---|---|
| $\dot{TFP}$ | Nonconstant Returns to Scale $(1 - \Sigma_j \epsilon_{CQj})\dot{Q}$ | Shift of the Cost Function $(-\dot{\beta}_t)$ | Residual $(\epsilon_t)$ |
| 1.56 | −0.470 (0.032) | 1.740 (0.110) | 0.29 |

> . . . reduce somewhat the role of economies of scale, increase somewhat the role of education and other input quality change, and assign for the first time a substantial role to the previously unmeasured contribution of public investment in agricultural research and extension to the explanation of the growth in the aggregate output of agriculture. . . the total can be divided into three roughly equal parts: the contribution of input quality change (in labor and other inputs), of economies of scale, and of investments in research and extension. (pages 970–971)

The methods of decomposing the TFP residual and the empirical results presented in this paper differ from the methods and conclusions reached by Griliches. These differences may in part be because of the differences in the data and differences in the specification of the underlying production function. Griliches uses a homothetic production technology (Cobb-Douglas). Furthermore, R&D expenditures do not enter explicitly into the translog cost function, although their *ex post* impact may be considered as lumped into the time-trend variable.

Our econometric results, based on aggregate time-series data, do not support an increasing returns-to-scale characterization of U.S. agriculture over the period 1950–82, although technical change was of a scale-augmenting nature. Griliches (1963) tempers his findings of economies of scale by indicating that this result could be biased by incomplete adjustment for all input quality changes.

We can decompose the growth of aggregate output reported in table 2 into components

attributable to input quality changes and scale change in the following manner. First, the divisia aggregate input index reflects adjustments for changes in the composition and education of the labor forces, the use of service prices for capital and land, and adjustments to the pesticides and fertilizer inputs which reflect quantities of active ingredients applied. A lower bound on the effect of these adjustments on the rate of growth of the aggregate input index can be approximated by comparing the rate of growth of the divisia aggregate input index to the rate of growth of the USDA aggregate input index, which is for the most part not adjusted to the same degree for quality changes. The USDA index grew at an average annual rate of −0.06% from 1950–82 (USDA). Thus, the difference due to adjustment for input quality changes is approximately .24% [.18 − (−.06)].

Second, as noted earlier, the econometrically estimated measure of average returns to scale is .788. This implies that a .24% increase in average rate of growth of aggregate inputs over the 1950–82 period translates into a .19 change in the average rate of growth of aggregate output. Thus approximately 11% of the observed average annual rate of growth of aggregate output is due to the rate of growth of aggregate input. The remaining 89% is due to technical change, assuming of course that there has been productive efficiency. We conclude that, based on the analysis presented in this paper, the growth of aggregate agricultural output over the 1950–82 period is primarily due to technical change; a substantially smaller proportion of the growth of aggregate output is attributed to the combined effect of scale and the quality-adjusted growth of aggregate input.

## Conclusions

A method of decomposing the growth in TFP into effects due to nonconstant returns to scale and technical change was applied to the U.S. agricultural sector. The scale effects and the rate of technical change were measured using a two-output, three-input translog total cost model. Total factor productivity as conventionally measured grew at an average annual rate of 1.56% 1950–82. This growth rate, however, misrepresented the rate of technical change in U.S. agriculture primarily because of scale effects. The conventionally measured index of TFP tended to understate the rate of technical change in U.S. agriculture, reflecting the decreasing-returns-to-scale characterization of U.S. agriculture in the post-World War II era.

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## References

Berndt, E. R., and L. R. Christensen. "The Translog Function and the Substitution of Equipment, Structures, and Labor in U.S. Manufacturing, 1929–68." *J. Econ.* 1(1973):81–114.

Berndt, E. R., and M. S. Khaled. "Parametric Productivity Measurement and Choice Among Flexible Functional Forms." *J. Polit. Econ.* 87(1979):1220–44.

Blackorby, C., C. A. K. Lovell, and M. C. Thursby. "Extended Hicks-Neutral Technological Change." *Econ. J.* 86(1976):845–52.

Brown, R. S., and L. R. Christensen. "Estimating Elasticities of Substitution in a Model of Partial Static Equilibrium: An Application to U.S. Agriculture, 1947–74." *Modeling and Measuring Natural Resource Substitution,* eds., E. Berndt and B. Field, pp. 209–29. Cambridge MA: MIT Press, 1981.

Callan, S. J. "Productivity, Scale Economics, and Technical Change: Reconsidered." *S. Econ. J.* 54(1988): 715–24.

Capalbo, S. "A Comparison of the Results of Econometric Models of U.S. Agriculture." *Agricultural Productivity: Measurement and Explanation,* eds., S. Capalbo and J. Antle. Washington DC: Resources for the Future, 1988.

Capalbo, S., and M. Denny. "Testing Long-Run Productivity Models for the Canadian and U.S. Agricultural Sectors." *Amer. J. Agr. Econ.* 68(1986):615–25.

Capalbo, S., T. Vo, and J. Wade. "An Econometric Database for Measuring Agricultural Productivity and Characterizing the Structure of U.S. Agriculture." Disc. Pap. Ser. No. RR85-01, Washington DC: Resources for the Future, 1985.

Caves, R., L. R. Christensen, and W. E. Diewert. "The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity." *Econometrica* 50(1982):393–414.

Caves, R., L. R. Christensen, and J. A. Swanson. "Productivity Growth, Scale Economies, and Capacity Utilization in U.S. Railroads, 1955–74." *Amer. Econ. Rev.* 71(1981):994–1002.

Chan, M. W. L., and D. C. Mountain. "Economies of Scale and the Tornqvist Discrete Measure of Productivity Growth." *Rev. Econ and Statist.* 65(1983):663–67.

Denison, E. F. *Accounting for Slower Economic Growth.* Washington DC: The Brookings Institution, 1979.

———. *Why Growth Rates Differ.* Washington DC: The Brookings Institution, 1967.

Denny, M., M. Fuss, C. Everson, and L. Waverman. "Estimating the Effects of Diffusion of Technological Innovations in Telecommunications: The Production Structure of Bell Canada." *Can. J. Econ.* 14(1981): 26–43.

Denny, M., M. Fuss, and L. Waverman. "The Measurement and Interpretation of Total Factor Productivity in Regulated Industries, with an Application to Canadian Telecommunications." *Productivity Measurement in Regulated Industries,* eds., T. Cowing and R. E. Stevenson. New York: Academic Press, 1981.

Diewert, E. "Exact and Superlative Index Numbers." *J. Econometrics* 4(1976):115–45.

———. "The Economic Theory of Index Numbers: A Survey." *Essays in the Theory and Measurement of Consumer Behaviour in Honour of Sir Richard Stone,* ed., A. Deaton, pp. 163–208. London: Cambridge University Press, 1981a.

———. "The Theory of Total Factor Productivity Measurement in Regulated Industries." *Productivity Measurement in Regulated Industries,* eds., T. Cowing and R. Stevenson. New York: Academic Press, 1981b.

Dogramaci, A., ed. *Productivity Analysis, A Range of Perspectives.* Studies in Productivity Analysis, vol. 1. Boston: Martinus Nijhoff Publishing Co., 1981.

Domar, E. "On the Measurement of Technological Change." *Econ. J.* 71(1961):709–29.

Fuss, M., and L. Waverman. "Multi-Product Multi-Input Cost Functions for a Regulated Utility: The Case of Telecommunications in Canada." *Studies in Public Regulation,* ed., G. Fromm. Cambridge MA: MIT Press, 1981.

Griliches, Z. "Research Expenditures, Education, and the Aggregate Agricultural Production Function." *Amer. Econ. Rev.* 54(1964):961–74.

———. "The Sources of Measured Productivity Growth: U.S. Agriculture, 1940–1960." *J. Polit. Econ.* 71(1963): 331–46.

Jorgenson, D., and Z. Griliches. "The Explanation of Productivity Change." *Rev. Econ. Stud.* 34(1967):249–83.

Kendrick, J. W. *Postwar Productivity Trends in the United States, 1948–1969.* New York: National Bureau of Economic Research, 1973.

———. *Productivity Trends in the United States.* Princeton NJ: Princeton University Press for the National Bureau of Economic Research, 1961.

Kuznets, S. "Long-Term Changes in the National Income of the United States of America Since 1870." *Income and Wealth,* series II. Cambridge: Bowes and Bowes, 1952.

Nadiri, I. M. "Some Approaches to the Theory and Measurement of Total Factor Productivity: A Survey." *J. Econ. Lit.* 8(1970):1137–77.

Ohta, M. "A Note on the Duality Between Production and Cost Functions: Rate of Return to Scale and Rate of Technical Progress." *Econ. Stud. Quart.* 25(1974): 63–65.

Solow, R. "Technical Change and the Aggregate Production Function." *Rev. Econ. and Statist.* 39(1957):312–20.

U.S. Department of Agriculture, Econ. Res. Serv. *Economic Indicators of the Farm Sector, Production and Efficiency Statistics, 1983.* Washington DC, 1985.