An econometric decomposition of dairy output growth

Ahmad, Munir and Boris E., Bravo-Ureta

Pakistan Institute of Development Economics, Islamabad, University of Connecticut

1995

An Econometric Decomposition of Dairy Output Growth

Munir Ahmad and Boris E. Bravo-Ureta

Fixed effects production functions and stochastic production frontiers are estimated and used to decompose dairy farm output growth into technological progress, technical efficiency, and increased input use or the size effect. Unbalanced panel data for ninety-six Vermont dairy farmers for the 1971–84 period are utilized. The results show a 2.5% average annual increase in milk output. About 56% of this growth is attributed to the size effect and the remaining 44% to productivity growth. Technological progress contributed about 94% to total productivity growth, while improvements in technical efficiency accounted for only 6%.

Key words: dairy output growth, fixed effects, productivity, stochastic frontiers.

The U.S. dairy sector has been affected over time by various government regulations and technological improvements. Structural changes, including a reduction in the number of dairy farms and in the size of the national herd, and an increase in average herd size and a sharp rise in milk production per cow, have been accompanied by significant and persistent excess production of dairy products (Fallert, Blayney, and Miller). This surplus production has been absorbed over the years by government purchases of dairy products. However, the chronic deficit in the federal budget might force the U.S. government to curtail or even discontinue this type of intervention in the dairy industry. In this context, an understanding of the forces that drive milk production growth is important for farm managers and policy makers alike.

Productivity growth and the use of additional inputs are two major forces behind increased agricultural production. Productivity has two major components: (*a*) technological change, and (*b*) technical efficiency (Good et al.). The empirical literature dealing with the impact of technical efficiency and technological change on dairy production has followed separate tracks. Several studies have focused on the analysis of farm-level technical efficiency (e.g., Bravo-Ureta and Rieger, Tauer and Belbase), while a few have measured the impact of technological change on dairy production growth relying on "average" profit functions (e.g., Blayney and Mittelhammer, Quiroga).

Our objective in this paper is to decompose production growth, for an unbalanced panel data set including ninety-six Vermont dairy farms, into technological change, input-growth, and technical efficiency. This paper is the first attempt to carry out this type of decomposition for U.S. agriculture. The only studies to report such a decomposition for agriculture are by Fan, who examined farm production growth at the provincial level in China, and by Kumbhakar and Hjalmarsson, who analyzed output growth for a sample of Swedish dairy farms.

This study contributes to the productivity literature by comparing several features of the fixed effects model *vis-à-vis* the stochastic production frontier. We first present the methodological framework employed, followed by a description of the data used, and a discussion of the results and analysis.

Methodological Framework and Estimation Procedures

This section presents the stochastic frontier and fixed effects production models used to decom-

---

Munir Ahmad is assistant professor of agricultural economics at the Agricultural University of Faisalabad, Pakistan, and Boris E. Bravo-Ureta is professor of agricultural and resource economics at the University of Connecticut, and adjunct professor of economics at the University of Talca, Chile. Ahmad was a graduate student at the University of Connecticut when this research was completed.

The authors gratefully acknowledge the secretarial support of Dorine Nagy, the comments received by Farhed Shah and two anonymous reviewers, and, above all, the assistance of Horacio Cocchi. Storrs Agricultural Experiment Station Scientific Contribution No. 1536, University of Connecticut.

Amer. J. Agr. Econ. 77 (November 1995): 914–921

pose dairy output growth.[1] All models are based on the Cobb-Douglas specification.[2] First consider the stochastic frontier model (Aigner, Lovell, and Schmidt; Meeusen and van den Broeck; Battese and Coelli)

$$(1) \quad \ln Y_{it} = \alpha + \sum_k \beta_k \ln X_{kit} + \delta T + v_{it} - u_{it}$$

where $u_{it} = \eta_{it} u_i = e^{[-\eta(t-T)]} u_i$ and $t \in \tau(i)$ for $i = 1, 2, \ldots, N$. The subscripts k, i, and t stand for inputs, firms, and time, while α, β_k, and δ are parameters, and T is a smooth time-trend representing technological change.[3] The term v_{it} is assumed to be independent and identically normally distributed with mean zero and constant variance, while u_i is a nonnegative truncation of a normal distribution with mean μ and constant variance, or half normal with mean zero and constant variance.

The model given in equation (1) is estimated using the computer program FRONTIER (Coelli). This program first provides maximum likelihood estimates of the production frontier model which serve as a basis for calculating technical efficiency (*TE*) measures at each data point as $TE_{it} = \exp(u_{it})$ (Battese and Coelli).

The following four alternative stochastic frontier models are estimated below: (*a*) stochastic frontier assuming that *TE* is time invariant and follows a half-normal distribution (SFIN); (*b*) stochastic frontier assuming that *TE* is time invariant and follows a truncated-normal distribution (SFIT); (*c*) stochastic frontier assuming that *TE* is time variant and follows a half-normal distribution (SFVN); and (*d*) stochastic frontier assuming that *TE* is time variant and follows a truncated-normal distribution (SFVT).

The stochastic frontier methodology has been criticized because it assumes that *TE* is uncorrelated with other variables included in the model. However, if management affects the productivity of other inputs, it should be incorporated explicitly in the production function; otherwise one faces the omitted variables problem (Griliches). This misspecification can be avoided by applying the fixed-effects methodology where a dummy variable for each firm is introduced as a proxy for management (Hoch 1958, 1962; Mundlak 1961, 1978; Schmidt and Sickles). Hoch (1976) has argued that the firm dummies can be interpreted as a measure of *TE*, thus establishing a clear link between the production frontier methodology and the fixed effects model.

A general fixed-effects Cobb-Douglas production function can be written as

$$(2) \quad \ln Y_{it} = \alpha + \sum_k \beta_k \ln X_{kit} + \delta T + u_i + v_{it}$$

where u_i represents farm-specific effects (Greene). Following Mundlak (1961) and assuming that TE is time invariant (i.e., u_i is constant over time), the production model is written as

$$(3) \quad \ln Y_{it} = \alpha + \sum_k \beta_k \ln X_{kit} + \delta T + \sum_i \gamma_i D_i + v_{it}$$

where D_i is a farm-specific dummy variable having a value of 1 for the *i*th farm and 0 otherwise. This model, which is estimated using the least squares with dummy variables (LSDV) procedure (Greene), is the basis for calculating farm-specific technical efficiency as $TE_i = \exp\gamma_i / \max(\exp\gamma_i)$.

The assumption that *TE* is constant over time can be relaxed by replacing $u_i = \sum_i \gamma_i D_i$ in equation (2) for $\gamma_i + \rho_i T$ as suggested by Mundlak (1978). Thus, equation (2) is rewritten as

$$(4) \quad \ln Y_{it} = \alpha + \sum_k \beta_k \ln X_{kit} + \delta T + [\gamma_i + \rho_i T] + v_{it}$$

where ρ_i is a farm-specific slope parameter with respect to time.

Following Cornwell, Schmidt, and Sickles, and Fecher and Pestieau, time-varying efficiency can be estimated in two steps. The first step is the same procedure applied in the time-invariant case. In the second step, γ_i and ρ_i are estimated using the residuals ($\hat{\varepsilon}_{it}$) from the first step, which include farm effects as well as the usual error term. To calculate time-variant *TE* measures, these residuals are regressed using ordinary least squares, thus obtaining

$$(5) \quad \hat{\varepsilon}_{it} = \sum_i \gamma_i D_i + \sum_i \rho_i D_i T + v_{it}$$

---

[1] For recent reviews of different aspects of the frontier function literature see Bauer (1990b), and Bravo-Ureta and Pinheiro.

[2] Several experiments were conducted comparing the Cobb-Douglas with different translog specifications and the results show that *TE* measures were unaffected by alternative functional forms. However, as is often the case, the translog models presented several violations of regularity conditions, hence, the choice of the Cobb-Douglas specification for the analysis presented in this paper. (For details see Ahmad.)

[3] The term η "…is an unknown scalar parameter and $\tau(i)$ represents the set of (T_i) time periods among the T periods involved for which observations for the *i*th [farm] are obtained" (Battese and Coelli, p. 154). Technical efficiency increases, remains constant, or decreases overtime when the value of $\eta > 0$, $\eta = 0$ or $\eta < 0$, respectively.

where v_{it} is i.i.d. $N(0, \sigma_v^2)$. The predicted values from equation (5), written as $\hat{u}_{it}$, are the basis for calculating *TE*, at each data point, where $TE_{it} = \exp \hat{u}_{it} / \max(\exp \hat{u}_{it})$ (Fecher and Pestieau).

The stochastic frontier and fixed-effects models discussed above are used to decompose dairy output growth into technological change, *TE*, and the size effect. To show this decomposition, assume that the estimated Cobb-Douglas production function is

$$\text{(6)} \quad \ln \hat{Y}_{it} = \ln \hat{A}_t + \ln \hat{TE}_{it} + \textstyle\sum_k \hat{\beta}_k \ln X_{kit}$$

where the first term on the right-hand side of equation (6) represents technological change, the second term is the *TE* component, and the third term is the size effect. The total derivative of equation (6) with respect to time can be expressed as

$$\text{(7)} \quad \dot{Y}/Y = \dot{A}/A + \dot{TE}/TE + \textstyle\sum_k \hat{\beta}_k (\dot{X}/X)$$

where the dots represent time derivatives. The left-hand side of equation (7) is the rate of output growth which is equal to technological change ($\dot{A}/A$) plus changes in *TE* ($\dot{TE}/TE$) and changes in the level of inputs or the size effect $[\sum_k \hat{\beta}_k (\dot{X}/X)]$. These components of output growth, for the fixed-effects and the stochastic frontier models, are approximated by

$$\text{(8)} \quad \dot{A}/A = \hat{\delta}$$

$$\text{(9)} \quad \dot{TE}/TE = \ln \hat{TE}_{it} - \ln \hat{TE}_{it-1}$$

and

$$\text{(10)} \quad \textstyle\sum_k \hat{\beta}_k (\dot{X}/X) = \sum_k \hat{\beta}_k (\ln X_{kit} - \ln X_{kit-1}).$$

If *TE* is time invariant, then equation (10) is zero and output growth is composed only of technological progress and the size effect.

Data and Variable Definitions

The data for this study come from ninety-six Vermont dairy farms participating in the Electronic Farm Record Keeping System (ELFAC) from 1971 to 1984. The number of observations available per farm varies from a low of six to a high of fourteen. Pooling the data from all ninety-six farms yields a total of 1,072 observations.

A single equation production function model is used, in which the dependent variable is annual milk output measured in hundred weight.[4] The following six inputs are included as explanatory variables: (*a*) number of dairy *Cows*; (*b*) total *Labor*, including hired and family labor, measured in worker equivalents; (*c*) purchased dairy *Concentrate Feed*, measured in tons; (*d*) *Animal Expense*, consisting of veterinary medicine, breeding, and animal supplies; (*e*) *Crop Expense*, comprising fertilizer, seed, spray, lime, repairs and maintenance on machinery and equipment, and gas and oil; and (*f*) *Other Expense*, including electricity, hauling, miscellaneous expenses, and depreciation on buildings and equipment set at 3% and 15% of the stock value, respectively.

Price indexes were used to obtain implicit quantities of each component included in the three aggregate inputs (i.e., *Animal Expense*, *Crop Expense*, and *Other Expense*). The index of prices paid by farmers was obtained from U.S. Department of Agriculture (USDA) (*Agricultural Statistics*, various issues). Price indexes for fertilizer, seed, chemicals, machinery, equipment and buildings, and prices for gasoline and electricity were also obtained from USDA (*Agricultural Prices*, various issues). Descriptive statistics for the inputs included in the model are given in table 1.

Results and Analysis

The parameter estimates for the four stochastic frontier models and the fixed effects model are presented in table 1. All the estimates are significant at the 1% level, except for those corresponding to *Crop Expense*, which is significant at the 5% level in the model SFVT; *Labor*, which is not significant in any of the models; and *Time*, which is not significant in the SFVN and SFVT models.

To compare the performance of the five models shown in table 1, various statistical hypotheses are also tested. The results of these tests, summarized in table 2, lead to the following conclusions: (*a*) the OLS model, excluding farm effects, is rejected in favor of either the FIXED, SFIN, or SFIT formulations; (*b*) all models show increasing returns to size; (*c*)

---

[4] The econometric estimation of this model is justified if profits are assumed to be maximized with respect to anticipated output instead of realized output (Hoch 1958, 1962). Moreover, in a Monte Carlo study, Gong and Sickles found that a single equation production function performed better than a system estimator.

Table 1. Parameter Estimates of C-D Functions: Time Invariant Technical Efficiency

Variable/Parameter	Mean	FIXED	SFIN	SFIT	SFVN	SFVT
Intercept		4.289[a]	4.811[a]	4.784[a]	4.812[a]	4.785[a]
		(0.112)	(0.073)	(0.097)	(0.075)	(0.167)
Cows	64.7	0.774[a]	0.679[a]	0.705[a]	0.678[a]	0.705[a]
	(32.4)	(0.035)	(0.030)	(0.031)	(0.030)	(0.038)
Labor	4.2	0.011	0.014	0.015	0.014	0.015
	(1.2)	(0.019)	(0.018)	(0.018)	(0.018)	(0.018)
Feed	159.9	0.175[a]	0.198[a]	0.198[a]	0.199[a]	0.198[a]
	(111.9)	(0.014)	(0.014)	(0.014)	(0.014)	(0.015)
Animal Expense	20.6	0.071[a]	0.059[a]	0.071[a]	0.060[a]	0.071[a]
	(13.7)	(0.012)	(0.011)	(0.011)	(0.012)	(0.013)
Crop Expense	31.4	0.031[a]	0.036[a]	0.034[a]	0.037[a]	0.034[b]
	(23.7)	(0.012)	(0.011)	(0.011)	(0.012)	(0.017)
Other Expense	37.6	0.053[a]	0.057[a]	0.063[a]	0.058[a]	0.063[a]
	(25.9)	(0.015)	(0.014)	(0.014)	(0.014)	(0.018)
Time		0.010[a]	0.011[a]	0.010[a]	0.010	0.010
		(0.001)	(0.001)	(0.001)	(0.024)	(0.021)
$\overline{R}^2$	—	0.96	—	—	—	—
LLF	—	—	805.62	817.21	828.05	840.01
F. Coefficient	—	1.11	1.04	1.08	1.06	1.11
$\sigma_s^2 = \sigma_v^2 + \sigma^2$	—	—	0.043[a]	0.020[a]	0.042[a]	0.020[a]
			(0.006)	(0.002)	(0.003)	(0.008)
$\gamma = \sigma^2/\sigma_s^2$	—	—	0.756[a]	0.476[a]	0.750[a]	0.476[a]
			(0.036)	(0.046)	(0.026)	(0.218)
μ	—	—	0	0.273[a]	0	0.273[a]
				(0.069)		(0.160)

Note: Model and variable definitions are given in the text. Standard errors are in parentheses.
[a] Significant at 1%.
[b] Significant at 5%.

model SFIN is rejected against SFIT, implying that the truncated normal distribution is preferable to the half-normal distribution for the one-sided error term in the stochastic frontier; (*d*) both the SFIN and SFIT models reveal that *TE* is time invariant; and (*e*) the FIXED model indicates that *TE* does vary over time. In addition, a Hausman test is performed to compare the SFIT with the FIXED model. This test rejects the former in favor of the latter, suggesting that *TE* is correlated with the inputs used in the model. In sum, these tests reveal that the FIXED model, when *TE* is time variant, is the most suitable one for the data under analysis; hence, this model is the basis for the decomposition analysis that follows.[5]

The decomposition analysis indicates that from 1971 to 1984 output increased at a 2.46% annual rate (table 3). This growth rate stems from a 1.38% increase in the use of inputs, 1.01% technological progress, and 0.07% improvement in *TE*. This implies that the rate of annual productivity growth is 1.08%, which is about 27% less than the size effect. To put these results in perspective, it is useful to compare them with the few related papers found in the literature. Only two studies for agriculture decompose productivity growth into *TE* and technological change. The first of these is by Fan, who, using a stochastic production frontier and regional level data for Chinese agriculture, found an annual rate of productivity growth of about 2.1%. He estimated that 62% of this growth was due to increases in *TE*, while the remaining 38% was attributed to technological progress. The second study by Kumbhakar and Hjalmarsson, based on a fixed-effects production function and data for Swedish dairy farms, obtained a rate of technological progress ranging from 3.5% per year in the beginning of the sample period to 1.0% at the end. These authors also found that *TE* was time invariant.

Five nonagriculture studies report annual rates of technological change varying from 0% to 2.4%, and *TE* ranging from –1.0% to 2.0%. The results of three of these studies show that technological change was the dominant factor

---

[5] For a detailed explanation of the tests performed see Ahmad (chaps. 3 and 5).

Table 2. Specification Tests for Alternative Models

Model	F. Value	F. Critical	χ^2 Value	χ^2 Critical	Result*
		Fixed effects models			
No farm-specific effects					
OLS versus FIXED	8.7	1.3	—	—	R OLS
Constant returns to size (CRS)					
FIXED	488.2	3.8	—	—	R CRS
Time invariant TE					
FIXED second step	3.2	1.3	—	—	R TI
		Stochastic frontiers models			
OLS versus stochastic frontier					
OLS versus SFIN	—	—	358.4	6.3	R OLS
OLS versus SFIT	—	—	381.6	9.2	R OLS
Constant returns to size (CRTS)					
SFIN	—	—	5.2	3.8	R CRS
SFIT	—	—	16.3	6.6	R CRS
Half normal (HN) versus truncated normal (TN)					
SFIN versus SFIT	—	—	23.2	6.6	R HN
Time-invariant TE					
SFIN versus SFVN	—	—	0.4	6.6	A TI
SFIT versus SFV	—	—	0.4	6.6	A TI
		Fixed effect versus stochastic frontier models			
SFIT versus FIXED	—	—	84.3	12.6	R SFIT

Note: R = reject, A = accept.

Table 3. Output Growth Decomposition Based on the FIXED Model

Year	Total Growth	Change in Inputs	Technological Change	Change in Tech. Eff.
1971–72	3.26	1.91	1.01	0.34
1972–73	1.19	−0.02	1.01	0.34
1973–74	5.42	4.06	1.01	0.34
1974–75	3.64	2.86	1.01	−0.20
1975–76	3.80	3.32	1.01	−0.50
1976–77	2.89	0.24	1.01	−0.50
1977–78	1.07	0.57	1.01	−0.50
1978–79	3.07	−0.30	1.01	2.31
1979–80	3.15	1.35	1.01	0.78
1980–81	−3.70	−0.10	1.01	−4.60
1981–82	1.94	1.41	1.01	−0.50
1982–83	8.79	3.75	1.01	4.03
1983–84	−2.50	−3.10	1.01	−0.50
1971 to 1984 (%)	33.63 (100)	19.94 (59.32)	13.13 (39.04)	0.55 (1.64)
Annual average (%)	2.46 (100)	1.38 (56.10)	1.01 (41.06)	0.07 (2.85)

Table 4. Decomposition of the Total Input or Size Effect Based on the FIXED Model

Input	Annual Growth (%)	Standard Deviations	Minimum	Maximum
All Inputs	1.382	9.320 (100)	–65.167	44.177
1. *Cows*	0.965	5.336 (69.85)	–33.589	28.826
2. *Labor*	0.051	0.168 (3.68)	–0.732	0.857
3. *Concentrate Feed*	0.199	5.276 (14.43)	–52.366	28.967
4. *Animal Expense*	0.042	2.067 (3.02)	–8.152	11.272
5. *Crop Expense*	0.056	1.018 (4.07)	–3.227	4.779
6. *Other Expense*	0.064	0.998 (4.94)	–3.523	3.687

in productivity growth (i.e., Good et al., Ray and Kim, Bauer 1990a), while in the other two studies changes in *TE* were the key component (i.e., Nishimizu and Page, Fecher and Pestieau).

A decomposition of the size effect into each of the six inputs included in the production model indicates that 70% of the size effect is contributed by *Cows* and 14% by *Concentrate Feed* (table 4).[6] The contribution of the other inputs to the size effect is as follows: *Labor* (4%), *Animal Expense* (3%), *Crop Expense* (4%), and *Other Expense* (5%). The comparison of total milk produced between 1971 and 1984 reveals an overall increase of about 34%. Of this overall increase, about 59% came from the size effect, 39% from technological change, and 2% from improvements in *TE*.

Spearman rank correlation coefficients are calculated to explore further the relationship between the annual rate of growth in milk production and herd size (i.e., *Cows*), input use per cow, and *TE* (table 5). These correlations show a significant positive relationship between the rate of growth in milk output and herd size, *Concentrate Feed* per cow and *Crop Expense* per cow. *Animal Expense* per cow also has a positive effect on the rate of growth in milk output. The association is weak between the rate of growth in production and *Other Expense* per cow and *TE*. On the other hand, the rate of growth in milk production is found to have a negative but nonsignificant association with the use of *Labor* per cow. *Concentrate Feed* and *Other Expense* per cow have a strong positive correlation with *TE*. The relationship between *TE* and *Animal Expense* and *Crop Expense* per cow is positive but nonsignificant. By contrast, *TE* shows a weak but negative relationship with *Labor* per cow.

Surprisingly, the correlation between herd size and *TE* is negative and significant at the 1% level. Byrnes et al. reached a similar conclusion based on a nonparametric production frontier analysis of Illinois grain farms. However, the rate of change in *TE* is positively related to herd size as demonstrated by a Spearman rank correlation equal to 0.10 (significant at the 5% level). Thus, the data suggests that efficiency and size are inversely related, but that the rate of increase in *TE* is positively related to farm size.[7]

Concluding Comments

The results of this paper indicate that the size effect played a greater role than productivity growth in increasing milk production during the period of study. It was also found that productivity growth was primarily fueled by technological progress, while changes in technical efficiency played a minor role. The findings showed that average technical efficiency was around 77% and exhibited slight variation for the sample as a whole during the 1971–84 pe-

---

[6] The contribution of each input to the total size effect is calculated as the log change of the *k*th input weighted by the respective input elasticity divided by the total size effect.

[7] Other researchers, including Kumbhakar, Biswas, and Bailey, and Bravo-Ureta and Rieger, have reported a positive association between *TE* and farm size, while Bravo-Ureta found no relationship between these two variables.

Table 5. Correlation Coefficients Between Output Growth, Technical Efficiency, Herd Size and per Cow Inputs Based on the FIXED Model

	Output Growth	Technical Efficiency
Cows (herd size)	0.18[a]	–0.23[a]
Concentrate Feed per cow	0.18[a]	0.45[a]
Labor per cow	–0.07	–0.02
Animal Expense per cow	0.08[b]	0.03
Crop Expense per cow	0.20[a]	0.03
Other Expense per cow	0.08[b]	0.19[a]
Technical efficiency	0.02	1.00

[a] Significant at 1%.
[b] Significant at 10%.

riod. It is important to note that this period, particularly the late 1970s and early 1980s, was highly profitable in dairy production.

A comprehensive analysis of the impact of government intervention in the dairy sector is beyond the scope of this paper. Nevertheless, based on studies dealing with other sectors, one could speculate that a major cause for the slow rate of growth in technical efficiency has been the protection afforded to the dairy industry by government programs (e.g., Nishimizu and Page, Fecher and Pestieau). According to Lall, a protective environment is not conducive to achieving high efficiency levels. Moreover, Lall contends that even maintaining static efficiency levels under a protective environment, while rapid changes in technology are taking place, involves education and training, constant interaction among producers, and an effective flow of information. Consequently, with the emergence and likely rapid adoption of biotechnologies, farmers will have to improve their skills so that they can use such technologies effectively. Under these conditions, the role of the extension system would become increasingly important in assisting farmers in the improvement of their managerial skills.

[Received April 1994;
final revision received June 1995.]

References

Ahmad, M. "An Econometric Analysis of Output Growth Using Panel Data: The Case of Vermont Dairy Farms." PhD thesis, Department of Agricultural and Resource Economics, University of Connecticut, 1994.

Aigner, D.J., C.A.K. Lovell, and P.J. Schmidt. "Formulation and Estimation of Stochastic Frontier Production Function Models." *J. Econometrics* 6(July 1977):21–37.

Battese, G.E., and T.J. Coelli. "Frontier Production Functions, Technical Efficiency and Panel Data: With Application to Paddy Farmers in India." *J. Productivity Anal.* 3(June 1992):153–69.

Bauer, P.W. "Decomposing TFP Growth in the Presence of Cost Inefficiency, Nonconstant Returns to Scale, and Technological Progress." *J. Productivity Anal.* 1(June 1990a):287–99.

——. "Recent Developments in the Econometric Estimation of Frontiers." *J. Econometrics* 46(October/November 1990b):39–56.

Blayney, D.P., and R.C. Mittelhammer. "Decomposition of Milk Supply Response into Technology and Price Induced Effects." *Amer. J. Agr. Econ.* 72(November 1990):862–72.

Bravo-Ureta, B.E. "Technical Efficiency Measures for Dairy Farms Based on a Probabilistic Frontier Function Model." *Can. J. Agr. Econ.* 34(November 1986):399–415.

Bravo-Ureta, B.E., and A.E. Pinheiro. "Efficiency Analysis of Developing Country Agriculture: A Review of the Frontier Function Literature." *Agr. and Res. Econ. Rev.* 22(April 1993):88–101.

Bravo-Ureta, B.E., and L. Rieger. "Dairy Farm Efficiency Measurement Using Stochastic Frontiers and Neoclassical Duality." *Amer. J. Agr. Econ.* 73(May 1991):421–28.

Byrnes, P., R. Fair, S. Grosskopf, and S. Kraft. "Technical Efficiency and Size: The Case of Illinois Grain Farms." *Eur. Rev. Agr. Econ.* 14(1987):367–81.

Coelli, T.J. "A Computer Program for Frontier Production Function Estimation." *Econ. Letters* 39(May 1992):29-32.

Cornwell, C., P. Schmidt, and R.C. Sickles. "Production Frontiers with Cross-Sectional and Time-Series Variation in Efficiency Levels." *J. Econometrics* 46(October/November 1990):185-200.

Fallert, R.F., D. Blayney, and J. Miller. *Background for the 1990 Farm Legislation*. U.S. Department of Agriculture, Staff Report AGES 9020, March 1990.

Fan, S. "Effects of Technological Change and Institutional Reform on Production Growth in Chinese Agriculture." *Amer. J. Agr. Econ.* 73(May 1991):216–75.

Fecher, F., and P. Pestieau. "Efficiency and Competition in O.E.C.D. Financial Services." *The Measurement of Productive Efficiency Techniques and Applications*. H.O. Fried, C.A.K. Lovell, and P. Schmidt, eds., pp. 374–85. New York: Oxford University Press, 1993.

Good, D.H., M.I. Nadiri, L.H. Roller, and R.C. Sickles. "Efficiency and Productivity Growth Comparisons of European and U.S. Air Carriers: A First Look at the Data." *J. Productivity Anal.* 4(June 1993):115–25

Greene, W.H. *Econometric Analysis.* New York: Macmillan Publishing Company, 1990.

Griliches, Z. "Specification Bias in Estimation of Production Functions." *J. Farm Econ.* 39(1957):8–20.

Hoch, I. "Estimation of Production Function Parameters Combining Time Series and Cross-Section Data." *Econometrica* 30(1962):34–45.

___. "Returns to Scale in Farming: Further Evidence." *Amer. J. Agr. Econ.* 58(1976):745–49.

___. "Simultaneous Equation Bias in the Context of the Cobb-Douglas Production Function." *Econometrica* 26(1958):566–758.

Kumbhakar, S.C., B. Biswas, and D.V. Bailey. "A Study of Economic Efficiency of Utah Dairy Farmers: A System Approach." *Rev. Econ. and Statist.* 71(November 1989):595–604.

Kumbhakar, S.C., and L. Hjalmarsson. "Technical Efficiency and Technological Progress in Swedish Dairy Farms." *The Measurement of Productive Efficiency Techniques and Applications.* H.O. Fried, C.A.K. Lovell, and P. Schmidt, eds., pp. 257–70. New York: Oxford University Press, 1993.

Lall, S. "Understanding Technology Development." *Develop. and Change* 24(October 1993):719–53.

Meeusen, W., and J. van den Broeck. "Efficiency Estimation from Cobb-Douglas Production Functions with Composed Error." *Int. Econ. Rev.* 18(June 1977):435–44.

Mundlak, Y. "Empirical Production Function Free of Management Bias." *J. Farm Econ.* 43(February 1961):44–56.

___. "On the Pooling of Time Series and Cross Section Data." *Econometrica* 46(January 1978):69–85.

Nishimizu, M., and J.M. Page, Jr. "Total Factor Productivity Growth, Technological Progress and Efficiency Change: Dimensions of Productivity Change in Yugoslavia, 1975–78." *Econ. J.* 92(December 1982):920–36.

Quiroga, R. "The Structure of Dairy Production Technology: A Profit Function Approach." PhD thesis, Department of Agricultural and Resource Economics, University of Connecticut, 1991.

Tauer, L.W., and K.P. Belbase. "Technical Efficiency of New York Dairy Farms." *Northeastern J. Agr. and Res. Econ.* 16(April 1987):10–16.

U.S. Department of Agriculture (USDA). *Agricultural Statistics,* Washington DC, various issues.

___. *Agricultural Prices.* Washington DC, various issues.