Efficiency Analysis of Developing Country Agriculture: A Review of the Frontier Function Literature

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This article reviews and critiques the frontier literature dealing with farm level efficiency in developing countries. A total of 30 studies from 14 different countries are examined. The country that has received most attention is India, while rice has been the most studied agricultural product. The average technical efficiency (TE) index from all the studies reviewed is 72%. The few studies reporting allocative and economic efficiency show an average of 68% and 43%, respectively. These results suggest that there is considerable room to increase agricultural output without additional inputs and given existing technology. Several of the studies reviewed have sought to explain farm level variation in TE. The variables most frequently used for this purpose have been farmer education and experience, contacts with extension, access to credit, and farm size. With the exception of farm size, the results reveal that these variables tend to have a positive and statistically significant impact on TE. This paper shows that considerable effort has been devoted to measuring efficiency in developing country agriculture using a wide range of frontier models. Despite all this work, the extent to which efficiency measures are sensitive to the choice of methodology remains uncertain.

The role that agriculture should play on economic development has been recognized for years.[1] The adoption of new technologies designed to enhance farm output and income has received particular attention as a means to accelerate economic development (Schultz; Kuznets; and Hayami and Ruttan). However, output growth is not only determined by technological innovations but also by the efficiency with which available technologies are used (Nishimizu and Page). The potential importance of efficiency as a means of fostering production has yielded a substantial number of studies focusing on agriculture.

In the 1960s the 'poor but efficient hypothesis', advanced by T.W. Schultz, generated a great deal of empirical work designed to test the allocative or price efficiency of peasant farmers (e.g., Hopper; Chennareddy; and Sahota). In the early 1970s, Lau and Yotopoulos published two important papers where they developed a dual profit function model to measure both allocative and technical efficiency.[2] Meanwhile, a separate body of efficiency literature evolved based on a seminal paper written by Farrell in 1957. Farrell's original work has given rise to a host of related models known collectively as frontier methodology.

A major improvement of the frontier models over the Lau and Yotopoulos formulation is the ability of the former to provide firm specific efficiency measures while the latter yields efficiency measures only for groups of firms. In addition, the fact that the frontier is consistent with the textbook definition of a production, profit and cost function (i.e., with the notion of maximality or minimality), has made this tool very popular in applied production analysis (Forsund, Lovell and Schmidt). This popularity is evidenced by the proliferation of methodological and empirical frontier studies over the last two decades.

The purpose of this article is to take stock of what we have learned from some of these frontier studies by reviewing the literature dealing with farm level efficiency in developing countries. The

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[1] For an earlier analysis of the role of agriculture in economic development see Johnston and Mellor, and Nicholls. For a more recent discussion see Hayami and Ruttan (pp. 11–40).

[2] This profit function model has been applied by several researchers including Sidhu, Junankar, Khan and Maki, and Trosper. An extension of this model has been developed by Toda (1976 and 1977).

plan of the paper is to first present a summary of the frontier function methodology to provide a frame of reference for readers not familiar with this topic. Next we review efficiency measures reported in the literature for a wide range of developing countries along with analyses that have sought to explain efficiency variation across farms. We then discuss some key methodological issues that arise in the empirical analysis of efficiency using frontiers. Finally, a summary is presented along with some policy implications stemming from the studies reviewed and suggestions for further research.

Frontier Function Methodology

The original frontier function model introduced by Farrell uses the efficient unit isoquant to measure economic efficiency, and to decompose this measure into technical and allocative efficiency. In this model, technical efficiency (TE) is defined as the firm's ability to produce maximum output given a set of inputs and technology. Stated differently, technical inefficiency reflects the failure of attaining the highest possible level of output given inputs and technology. It is important to distinguish TE from technological change, where the latter reflects an upward shift of the production function or a downward shift of the unit isoquant. Allocative (or price) efficiency (AE) measures the firm's success in choosing the optimal input proportions, i.e., where the ratio of marginal products for each pair of inputs is equal to the ratio of their market prices. In Farrell's framework, economic efficiency is a measure of overall performance and is equal to TE times AE (i.e., EE = TE × AE).

The large number of frontier models that have been developed based on Farrell's work can be classified into two basic types: parametric and non-parametric. Parametric frontiers rely on a specific functional form while non-parametric frontiers do not.[3] Another important distinction is between deterministic and stochastic frontiers. The deterministic model assumes that any deviation from the frontier is due to inefficiency, while the stochastic approach allows for statistical noise.

The deterministic parametric approach was initiated by Aigner and Chu, who estimated a Cobb-Douglas production frontier through linear and quadratic programming techniques. This procedure was further developed by Timmer, who introduced the probabilistic frontier production model. Timmer estimated a series of frontier production functions dropping at each stage the extreme observations. This process continues until the rate of change of the parameter estimates stabilizes. All these deterministic programming approaches yield estimators with undefined statistical properties.

Another class of deterministic parametric models is the statistical production frontier proposed by Afriat, in which technical efficiency is measured by a one-sided disturbance term. When explicit assumptions for the distribution of the disturbance term are introduced, the frontier is estimated by the maximum likelihood method. If no assumptions are made concerning the distribution of the error term, the frontier can be estimated by the corrected ordinary least squares method (COLS) which consists of neutrally (i.e., the intercept only) shifting the frontier upwards until no positive error term remains.

The stochastic frontier production model incorporates a composed error structure with a two-sided symmetric and a one-sided component (Aigner, Lovell, and Schmidt; and Meeusen and van den Broeck). The one sided component reflects inefficiency, while the two-sided error captures the random effects outside the control of the production unit including measurement errors and other statistical noise typical of empirical relationships.

The estimation of a stochastic frontier function can be accomplished in two ways. First, if no explicit distribution for the efficiency component is made, then the production frontier can be estimated by a stochastic version of COLS. On the other hand, if an explicit distribution is assumed, such as exponential, half-normal or gamma, then the frontier is estimated by maximum likelihood methods. According to Greene (1980), the maximum likelihood estimates (MLE) make use of the specific distributions of the disturbance term and, thus, are more efficient than COLS. The initial inability of calculating individual firm efficiency measures from the stochastic frontier model was overcome by the work of Jondrow, Lovell, Materov and Schmidt.

More recent developments in frontier methodology include multi-equation models based on production, cost or profit function specifications (Bauer; Schmidt and Lovell; and Kumbhakar). Other recent extensions of the stochastic frontier approach are models that take advantage of panel data structures (Pitt and Lee; Battese, Coelli and Colby; and Cornwell, Schmidt and Sickles). A ma-

[3] Readers interested on detailed reviews of frontier function methods are referred to Forsund, Lovell, and Schmidt; Schmidt; Battese; Bauer; and Seiford and Thrall.

jor advantage of panel data models is that there is no longer need to assume that inefficiency is independent of the regressors. In addition, these models do not restrict the efficiency term to follow a specific distribution for the inefficiency term while making these restrictions testable propositions (Bauer).

Frontier Function Studies of Developing Country Agriculture

For expository purposes, the studies reviewed in this section are divided, according to the type of methodology used, into two major groups: I) Deterministic Production Frontiers; and II) Stochastic Production Frontiers. In turn, the studies using deterministic models are subdivided into a) parametric and b) non-parametric frontiers, while those based on stochastic models are subdivided into a) cross-sectional, b) panel data, and c) dual frontiers. An important point to keep in mind is that all stochastic frontiers are of the parametric type. Some key characteristics of the studies reviewed are presented in Table 1.

In addition to focusing on some methodological aspects and on the reported efficiency levels, we also summarize the findings concerning the relationship between efficiency and various socioeconomic variables. Two approaches are commonly used to examine these relationships. One approach is to compute correlation coefficients or to conduct simple non-parametric analyses. The other route, usually referred to as a second step analysis, is to first measure farm level efficiency and then to estimate a regression model where efficiency is expressed as a function of socioeconomic attributes. Table 2 presents the most salient features of the studies that have examined efficiency variation across farms.

I. Deterministic Production Frontiers

a) *Parametric Frontiers:* Shapiro and Müller measured technical efficiency through a deterministic Cobb-Douglas production frontier obtained by linear programming. A major objective of this study was to analyze the roles of information and modernization in the production process of 40 cotton farms in Tanzania. Using correlation analysis, Shapiro and Müller found that technical efficiency had a high positive association with both general modernization and information.

Shapiro investigated technical efficiency for a sample of 37 Tanzanian cotton farmers. A Cobb-Douglas production frontier, derived by linear programming, yielded a 66% average level of technical efficiency. These results led the author to conclude that, in contrast with the 'poor but efficient' hypothesis advanced by T.W. Schultz, production in traditional agriculture suffered significant inefficiencies.

Belbase and Grabowski used the COLS procedure to estimate a deterministic Cobb-Douglas production frontier model to investigate efficiency in Nepalese agriculture. A model where the dependent variable was the total value of rice, maize, millet and wheat production yielded an average technical efficiency level of 80%. Separate frontiers were estimated for rice and maize which revealed average efficiency levels of 84% and 67%, respectively. Based on the efficiency measures obtained from the equation for all crops, correlation analysis showed that nutritional levels, income, and education were significantly related to TE, while no relationship was found for farming experience. The study suggested that technical efficiency gains could be attained through extension and education, and that the introduction of new technologies has been a key element in raising productivity in Nepalese agriculture.

Ali and Chaudry examined the technical, allocative and economic efficiency for a sample of 220 farmers located in four irrigated cropping districts of the Pakistani Punjab. Separate Cobb-Douglas probabilistic production frontiers were estimated for each district. The average TE, EE and AE measures reported were 84%, 51% and 61%, respectively. Based on these measures the authors concluded that technical inefficiency caused from 40 to 50% loss in farm profits, while the loss in profits due to allocative inefficiency was only around 2%.

Taylor, Drummond and Gomes formulated a Cobb-Douglas deterministic frontier production function to analyze the impact of a World Bank sponsored credit program (PRODEMATA) on allocative and technical efficiencies for a sample of Brazilian farmers. The production frontier was estimated using both COLS and maximum likelihood (statistical frontier) assuming that, in the latter case, the non-negative farm effects had a gamma distribution. Estimates of technical efficiency for farms participating in the credit program versus non-participants revealed no major differences between the two groups. Moreover, participants exhibited allocative efficiencies slightly lower than the rest. Hence, these results imply that this credit program was not successful in improving farm level efficiency.

b) *Non-Parametric Frontiers:* The only application we found of a non-parametric frontier methodology to farm data from a developing country is

Table 1. Empirical Estimates of Technical Efficiency

Author(s)	Country	Product	Sample Size	TE %	AE %	EE %
I. Deterministic Production Frontiers						
a) Parametric Frontiers						
Shapiro and Muller	Tanzania	Cotton	40	—[a]	—	—
Shapiro	Tanzania	Cotton	37	66	—	—
Belbase & Grabowski	Nepal	Whole Farm	537	80	—	—
		Rice	—	84	—	—
		Maize	—	67	—	—
Ali & Chaudry	Pakistan	Crops	220	84	61	51
Taylor, Drummond & Gomes	Brazil	Whole Farm	433	17	74	13
Ekanayake & Jayasuriya	Sri Lanka					
	Head	Rice	63	53	—	—
	Tail	Rice	61	50	—	—
Average				***63***	***68***	***32***
b) Non-Parametric Frontiers						
Ray	India	Whole Farm	63	—	—	—
Average				—	—	—
II. Stochastic Production Frontiers						
a) Cross-Sectional Frontiers						
Kalirajan (1981)	India	Rice	70	67	—	—
Huang & Bagi	India	Whole Farm	151	89	—	—
Kalirajan & Shand (1985)	India	Rice	91	—	—	—
Bagi	India	Five Crops	58	91	—	—
Kalirajan (1984)	Philippines	Rice	81	63	—	—
Kalirajan & Flinn	Philippines	Rice	79	50	—	—
Ekanayake	Sri Lanka					
	Head	Rice	63	100	—	—
	Tail	Rice	61	50	—	—
Ekanayake & Jayasuriya	Sri Lanka					
	Head	Rice	63	100	—	—
	Tail	Rice	61	50	—	—
Taylor & Shonkwiler	Brazil	Whole Farm	433	71	—	—
Rawlins	Jamaica	Crops	152	73	—	—
Phillips & Marble	Guatemala	Maize	1384	75	—	—
Kalirajan (1990)	Philippines	Rice	103	79	—	—
Squires & Tabor	Indonesia	Java Rice	429	69	—	—
	Indonesia	off-Java Rice	323	70	—	—
	Indonesia	Cassava	161	57	—	—
	Indonesia	Peanuts	177	68	—	—
	Indonesia	Mung Beans	69	55	—	—
Bravo-Ureta & Evenson	Paraguay	Cotton	87	58	70	41
		Cassava	101	59	89	52
Pinheiro	Dominican Republic	Crops	60	70	44	31
Average				***70***	***68***	***41***
b) Panel Data Frontier						
Kalirajan & Shand (1986)	India	Rice	34	70	—	—
Battese, Coelli & Colby	India	Whole Farm	38	84	—	—
Battese & Coelli (1992)	India	Whole Farm	15	85	—	—
Dawson, Lingard & Woodford	Philippines	Rice	22	89	—	—
Kalirajan (1991)	India	Rice	30	69	—	—
Battese & Tessema	Aurepalle*	Whole Farm		100	—	—
*(Indian villages)	Shirapur	Whole Farm	35	84	—	—
	Kanzara	Whole Farm	38	76	—	—
Fan	China	Aggregate	29	77	—	—
Average				***82***	—	—
c) Dual Frontiers						
Ali & Flinn	Pakistan	Rice	120	—	—	69
Bailey, Biswas, Kumbhakar & Schulthies	Ecuador	Milk	68	88	—	—
Average				***88***	—	***69***

[a]Figure not reported in the study.

Table 2. Socio-Economic Factors Related to Technical Efficiency in Third World Agriculture

Author	Country	Product	Average Technical Efficiency %	Socio* Economic Factors
I. Deterministic Production Frontiers				
a) Parametric Frontiers				
Shapiro & Muller	Tanzania	Cotton	—	Information (+)
				Modernization (+)
Belbase & Grabowski	Nepal	Whole Farm	80	Income (+)
		Rice	84	Education (+)
		Maize	67	Nutrition (+)
				[Experience]
Ali & Chaudry	Pakistan	Mixed Crops	84	Irrigation (+)
Taylor, Drummond & Gomes	Brazil	Whole Farm	17	[Credit]
b) Non-Parametric Frontiers				
Ray	India	Mixed Crops	—	Information (+)
				[Farm Size]
II. Stochastic Production Frontiers				
a) Cross-Sectional Frontiers				
Kalirajan (1981)	India	Rice	67	Management Policies (+)
				Experience (+)
				Ext. Visits (+)
				[Education, Tenure]
Huang & Bagi	India	Whole Farm	89	[Farm Size]
Kalirajan & Shand (1985)	India	Rice	—	Non-formal Educ (+)
				[Schooling]
Bagi	India	Mixed Crops	91	Irrigation (+)
				Larger Farms (+)
				Education (+)
				Fertilizer (+)
Kalirajan (1984)	Philippines	Rice	63	Extension (+)
				Experience (+)
				[Tenure, Age, Edu]
Kalirajan & Flinn	Philippines	Rice	50	Transplanting (+)
				Experience (+)
				Extension (+)
				Fertilizer (+)
Ekanayake	Sri-Lanka	Rice		Literacy (+)
		Head	100	Experience (+)
		Tail	50	Credit (+)
Taylor & Shonkwiler	Brazil	Whole Farm	71	[Credit]
Rawlins	Jamaica	Mixed Crops	73	Rural Development (+)
Phillips & Marble	Guatemala	Maize	75	School Yrs ≥4 (+)
				[School Yrs <4]
Kalirajan (1990)	Philippines	Rice	79	Crop Establish. (+)
				Non-Farm Income (+)
				[Years of Educ., Time of Establish., Tenure]
Squires & Tabor	Indonesia	Java Rice	69	[Farm Size, Farm Region]
		off-Java Rice	70	[Farm Size, Farm Region]
		Cassava	57	[Farm Size, Farm Region]
		Peanuts	68	[Farm Size, Farm Region]
		Mung Beans	55	[Farm Size, Farm Region]
Bravo-Ureta & Evenson	Paraguay	Cotton	58	Credit (+)
		Cassava	59	Extension Hrs. (+)
				[Size, Age, Educ.]
Pinheiro	Dominican Republic	Mixed Crops	70	Education (+)
				Age <25 (+)
				Experience (+)
				[Contract, Credit, Agr. Ref, Farm Size, People per Houshld.]

Table 2. Socio-Economic Factors Related to Technical Efficiency in Third World Agriculture (continued)

Author	Country	Product	Average Technical Efficiency %	Socio* Economic Factors
b) Panel Data Frontiers				
Kalirajan & Shand (1986)	India	Rice	70	Experience (+) Education (+) Credit (+) Extension (+)
Kalirajan (1991)	India	Rice	69	Access to Ext. (+) Confidence in Tech. (+) [School Years, Farm size]
c) Dual Frontiers				
Ali & Flinn	Pakistan	Rice	69*	Education (+) Off-Farm Employment (−) Credit (+)

*The signs inside the parenthesis reflect the direction of statistically significant associations between technical efficiency and the various socioeconomic variables. The variables shown inside brackets had no statistically significant association with technical efficiency.
*This is a measure of profit efficiency rather than technical efficiency.

the study by Ray, who used linear programming to measure efficiency for a sample of 63 West Bengal farms. The efficiency measures were decomposed into output or technical efficiency, and into informational efficiency. The latter was defined as the ratio between optimal output given the existing technology and optimal output when additional technology information is available. Univariate and multivariate statistical tests were conducted to compare the performance of three farm groups classified according to size. The results revealed that, although there was no significant difference in output efficiency across farm size groups, informational efficiency was very low for the small farms. The author suggested that marked improvements could be attained by the diffusion of information about the standard crop production technology.

To summarize, a total of seven deterministic studies were reviewed in this section, six parametric and one non-parametric. The parametric studies, five of which relied on the Cobb-Douglas functional form, reported efficiency measures ranging from 17% to 84% with an average of 63%. The average allocative and economic efficiency for the two studies in this group reporting these measures are 68% and 32%, respectively. The only non-parametric study included did not report average efficiency.

II. Stochastic Production Frontiers

a) *Cross-Sectional Frontiers:* Several of the efficiency studies performed using stochastic methodology have focused on Indian agriculture, a subject that has captured the attention of economists for a long time (Bhagwati and Chakravarty). The earliest stochastic frontier function study using Indian data appears to be the one by Kalirajan (1981). This author explored TE in paddy production for a random sample of farms located in the State of Tamil Nadu by estimating, using maximum likelihood, a Cobb-Douglas production frontier. A second step analysis showed that management practices and contacts with local extension agents had a significant positive impact on technical efficiency.

Huang and Bagi examined the TE of a sample of 151 farms in the Punjab and Haryana states of India, based on a translog production frontier estimated via maximum likelihood. The study showed an average TE level close to 90%, while the performance of small vis-à-vis large farms was almost equal.

Kalirajan and Shand estimated a Cobb-Douglas production frontier by maximum likelihood for a random sample of 91 paddy farmers from the Coimbatore district in the Indian state of Tamil Nadu. In a second step analysis, where farm level TE was the dependent variable, these authors found that the level of schooling was not statistically significant in explaining differences between maximum and actual yields. However, the farmers' non-formal education, defined as their understanding of current technology, had a significant positive role on productivity.

Bagi examined farm-level technical efficiencies for individual crops based on data from a sample of

58 multi-crop farms in the Indian State of Uttar Pradesh. The analysis proceeded with the estimation, by maximum likelihood, of separate Cobb-Douglas stochastic production frontiers for five crops (wheat, gram, gram/barley, paddy, and jwar/arhar). The results suggested that the partial elasticities of production varied from crop to crop, that TE levels were different for each crop as well as across farms, and that average TE was higher for irrigated crops (paddy and wheat). Bagi's analysis indicated that consolidation of individual plots into farm units could increase output as well as technical efficiency for all crops. Significant positive effects in output and technical efficiency were also reported for education, fertilizer use, and input quality.

Kalirajan (1984) examined how the efficient use of new technology affected production levels in 81 Philippine rice farmers, using a translog stochastic production frontier. The results revealed a wide variation in technical efficiencies across farms ranging from 42% to 91%, with only 30% of the farmers operating close to the frontier. The results of a second step model, showed that the number of farm visits by extension agents was significant in explaining the wide variation in the observed levels of technical efficiency. Kalirajan concluded that the new technology was not fully understood by the farmers in the sample.

Kalirajan and Flinn estimated a translog stochastic production frontier by maximum likelihood to measure TE for a sample of 79 farmers in the Philippines. These authors regressed TE on several farm specific biological and socio-economic variables. The results indicated that crop establishment by transplanting rice seedlings, fertilizer application, years of farming, and extension contacts had a significant influence in the level of technical efficiency among sample farmers.

Ekanayake examined efficiency for a sample of 123 Sri-Lankan rice farmers. The sample was divided into head and tail, according to whether the farm had good (head) or poor (tail) water access. Separate stochastic Cobb-Douglas production frontiers were estimated for each group via maximum likelihood. The results suggested that there was no significant technical inefficiency for farmers with better water access (head). However, for the poorly situated group (tail) there was significant technical inefficiency (50%). In a second step analysis, Ekanayake found that literacy, experience, and credit availability had a significant positive impact on the technical efficiency level of the tail farmers. This was also true when analyzing the tail farmers' ''apparent'' allocative efficiency (AAE), defined as the ratio of profit at predicted output to maximum profit. In addition, technical efficiency was found to be significantly related to AAE.

Ekanayake and Jayasuriya, using the same data set as Ekanayake, compared the effects of estimating TE using a stochastic frontier versus a deterministic COLS model. The authors found that, for the 'head' farmers, COLS yielded an average TE of 53% while the stochastic method gave an average of 100%. By contrast, both procedures reveal a 50% mean TE level for the 'tail' farmers.

In another comparative study, Taylor and Shonkwiler used the same data set as Taylor, Drummond and Gomes to evaluate the performance of a deterministic frontier with that of a stochastic frontier assuming a Cobb-Douglas production model. The frontier parameters were estimated by maximum likelihood methods, assuming a gamma distribution for the former and a half-normal for the latter. The results showed that for both groups, participants and non-participants, average technical efficiency estimates for the stochastic frontier (71% and 70%) were much higher than those obtained from the deterministic frontier specification (17% and 5.9%). Given the large difference between the two models and the extremely low technical efficiency estimates obtained by the deterministic specification, the authors concluded that the latter produced misleading results. An important similarity, however, was that the credit program was found to have no impact on improving technical efficiency under both models.

Rawlins evaluated the effects of the Jamaican Second Integrated Rural Development Project (IRDPII) on the level of technical efficiency for a sample of peasant farmers. This evaluation was based on data for 80 farmers participating in the IRDPII and for 72 non-participants. A Cobb-Douglas stochastic production frontier was estimated for each of the two groups. The results revealed that there was relatively less variation of the frontier across IRDPII farms. However, technical efficiency for the non-participants (75%) was higher than that of the participants (71%). Despite these results, the author concluded that the program succeeded in shifting outward the production frontier of the participant farmers.

Phillips and Marble examined the influence of education on technical efficiency for a sample of 1348 Guatemalan maize producers. In their analysis, a Cobb-Douglas stochastic production frontier was fitted via COLS. The analysis revealed that education, measured either in terms of literacy or years of schooling, had a positive but statistically insignificant effect on productivity. The authors went on to conclude that four or more years of formal education were required before increases in productivity could be observed.

Kalirajan (1990) set out to obtain consistent and efficient estimates of economic efficiency—firm specific TE and input specific AE—for a sample of 103 Philippine rice farmers. Using a translog stochastic production frontier, the mean technical efficiency was estimated to be 79%, with a low of 64% and a high of 92%. Input specific AE indicated that farmers were inefficient with respect to all inputs. The results of a second step analysis, also based on maximum likelihood methods, showed that non-farm income and method of crop establishment were the major factors affecting technical efficiency.

Squires and Tabor used a translog stochastic production frontier, estimated by maximum likelihood procedures, to measure crop-specific technical efficiency in Indonesian agriculture. The results suggest that technical efficiency estimates are higher for the production of irrigated rice compared to the other three crops. The mean TE estimates for Java rice, off-Java rice, cassava, peanuts, and mung beans were 69%, 70%, 57%, 68% and 55%, respectively. A second step analysis showed that TE is not significantly related to farm size.

Bravo-Ureta and Evenson, using the decomposition methodology developed by Kopp and Diewert, as modified by Bravo-Ureta and Rieger (1991), examined the technical, allocative and economic efficiency for a sample of peasant farmers from Eastern Paraguay. Separate Cobb-Douglas production frontiers were estimated for 87 cotton and 101 cassava producers. The average EE, TE and AE levels for the cotton farmers were 41%, 58% and 70%, respectively. The corresponding figures for the cassava producers were 52%, 59% and 89%. F-tests were used to examine the association between TE, AE and EE, and farm size, operator age, education, extension contacts and credit. Surprisingly, the results revealed a very weak connection between efficiency and socioeconomic characteristics.

Using the same methodology as Bravo-Ureta and Evenson, Pinheiro recently estimated a Cobb-Douglas total value product frontier to analyze EE, TE and AE for a sample of 60 peasant farmers located in the Dajabon region of the Dominican Republic. He found that the average EE, TE and AE for the sample were 31%, 70% and 44%, respectively. In a second step analysis, Pinheiro found that education and farmer experience had a positive impact on TE. He also found that contract farming, being an agrarian reform beneficiary, and farm size were positively associated with EE and AE, while household size exhibited a negative impact on both of these measures of performance.

b) *Panel Data Frontiers:* An emerging and promising area in efficiency analysis concerns the use of panel data. The first detailed discussion of frontier function methodology for panel data is the paper by Schmidt and Sickles. More recent contributions to this methodology have been made by Battese and Coelli (1988 and 1992), Kalirajan (1991), Cornwell, Schmidt and Sickles, and Kumbhakar. In this section we review seven studies that have relied on agricultural panel data to estimate stochastic frontier functions for developing countries.

Kalirajan and Shand estimated a translog production frontier for paddy using a balanced panel data for 34 farm households from the Tinnevely district in South India.[4] The period covered goes from the second crop in 1981 to the second crop in 1983 which yields five observations per farm given that each year had two crops. Assuming that efficiency is time invariant, the results gave an average level of TE of 70.2% with a low of 64% and a high of 91%. In order to test the notion that TE is time invariant, separate stochastic frontiers were estimated for each cross section. A chi-square statistic was then used to test the null hypothesis that the parameters for each pair of frontiers, one pair at a time, were the same. These pairwise comparisons supported the notion that TE was time invariant for this sample. In a second step analysis, Kalijaran and Shand formulated a linear model to examine the relationship between TE and four socioeconomic variables. These results showed a positive relationship between TE and farming experience, education, access to credit, and extension services.

Battese, Coelli and Colby, based on earlier work by Battese and Coelli (1988), introduced a model allowing for unbalanced panel data while maintaining the assumption that efficiency for a given firm remained constant over time. Using the Cobb-Douglas functional form, Battese, Coelli and Colby estimated a production frontier for a sample of farmers from Aurepalle, a village located in the state of Andhra Pradesh in India. The sample consisted of 289 observations encompassing 38 farm households that provided data for at least one year over the period 1975–76 to 1984–85. The analysis reveals TE measures ranging from 66.2% to 91.4% with a mean of 83.7%.

In a more recent paper, Battese and Coelli

[4] A balanced panel data set is one in which each firm in the sample is observed in every time period covered by the data.

(1992) introduced a stochastic production frontier model which permits individual firm level efficiency levels to vary over time while allowing the data set to be unbalanced. The authors employed a subset of the data used by Battese, Coelli and Colby consisting of 15 paddy farmers for the period of 1975–76 through 1984–85. For nine farms, data were available for all ten years while in some cases data were available for only four years. Five alternative Cobb-Douglas models were estimated and various tests supported the notion that individual firm technical efficiency levels were time variant. The results showed that farm level TE ranged from 67.6% to 88.6% in 1975–76, and from 88.8% to 96.2% in 1984–85.

Dawson, Lingard and Woodford estimated a Cobb-Douglas stochastic production frontier by maximum likelihood procedures, using panel data for a sample of 22 rice farmers for the years 1970, 1974, 1979, 1982 and 1984 from Central Luzon in the Philippines. These authors assumed technical efficiency to be invariant over time. The results revealed a fairly narrow range of technical efficiency going from 84% to 95% with a mean of 89.3%. The authors compared the frontier results with those obtained from covariance analysis. Although the latter methodology yielded a mean efficiency level of only 58.6%, the Spearman correlation coefficient between the two sets of efficiency vectors was 0.95. Given the relatively high efficiency levels obtained with the frontier approach the authors concluded that, in their study area, there was little room for increasing output by better use of existing resources and that future gains in rice output would have to come from additional technological progress.

Kalirajan (1991) used panel data for the period 1983–86 for a sample of 30 Indian rice farmers from the Coimbatore district to estimate, via maximum likelihood, a translog stochastic production frontier. His analysis revealed that technical efficiency across the sample farms ranged from 53% to 95% with a mean of 69.3%. Additional analyses showed that TE measures for a given firm did not change significantly over time. The results of a second step analysis, indicated that access to extension services and confidence in the technology (technical advice) were the major determinants of technical efficiency at the farm level.

Battese and Tessema estimated, by maximum likelihood, Cobb-Douglas stochastic production frontiers based on unbalanced panel data from a random sample of three Indian villages for the years 1975–76 to 1984–85. In this study, statistical tests were performed to discriminate between models in which both input elasticities and technical inefficiency were allowed to vary over time from time-invariant models. The hypothesis that the input elasticities were time-invariant was rejected for two of the three villages. The results also indicate that inefficiency was significant in two of the villages, and that in one case, inefficiency was significantly different over time while in the other it was time-invariant.

The last study to be reviewed in this section was recently published by Fan who, based on earlier work by Nishimizu and Page, decomposed output growth in Chinese agriculture into increases in inputs, technological change, and institutional reform. Fan assumes that improvements in technical efficiency over time are a reflection of the institutional reforms enacted in Chinese agriculture over the period analyzed. He estimated a simplified translog production frontier using aggregate data from 29 provinces, municipalities, and autonomous regions for the years 1965, 1970, 1975, and 1976 through 1986. The results showed that, for the whole country, the total growth in agricultural production from 1965 to 1985 was 5.04% per year. Of this total growth, 57.7% was attributed to total input growth and the remaining 42.3% to growth in total factor productivity. In turn, about 63% of the growth in total factor productivity was found to stem from improvements in technical efficiency with the remaining 37% from technological change.

c) *Dual Frontiers:* As is the case with panel data frontiers, dual based frontier methodologies are relatively recent. We have found only two applications of dual frontiers to developing country situations. In one of these applications, Ali and Flinn used a single equation dual profit frontier model to examine farm-specific profit efficiency ". . . defined as the ability of a firm to achieve the highest possible profit, given the prices and levels of fixed factors of that firm" (p. 304). A translog stochastic profit frontier was estimated via maximum likelihood for a random sample of 120 rice producers from the Pakistani Punjab. The computed range in profit inefficiency went from a low of 5% to a high of 87% with a mean of 31%. In other words, the average farmer realized 31% less in profits than what would be possible given efficient resource use. In a second step model, where loss of profit was regressed on several household characteristics, the authors found that education had a significant role in reducing profit inefficiency. In addition, farmers reporting off-farm employment and difficulties in securing credit to purchase fertilizer exhibited higher levels of profit inefficiency.

The second dual based study is by Bailey, Biswas, Kumbhakar and Schulthies who analyzed the technical, allocative and size inefficiency for a sample of 68 Ecuadorian dairy farms. Size inefficiency occurs when a firm fails to produce at the point where marginal cost equals output price. The analysis was accomplished by estimating a system of equations consisting of the production frontier and the first order conditions for profit maximization assuming a Cobb-Douglas technology. The results indicate that the average loss in profits due to technical inefficiency ranged from 24.4% for small farms to 22.7% for the large operations. The average increase in cost due to allocative inefficiency ranged from 8.4% for small farms to 5.6% for large farms. Size inefficiency measures revealed that in most cases milk price exceeded marginal cost, implying that the production level was less than optimal. The average loss in profits due to size inefficiency goes from 12.8% for small farms to 11.8% for large farms. Based on the results reported in the paper we calculated an average technical efficiency level of around 88%.

To sum up, in this section we reviewed 24 stochastic frontier studies, 17 of which used the Cobb-Douglas functional form while the remaining seven employed translog models. The average TE for the 15 studies using cross-sectional data was 70%, with a low of 50% and a high of 100%. The average AE and EE estimates reported were 68% and 41%, respectively. Panel data frontiers were estimated in seven studies which yielded an average TE of 82%, and a range going from 69% to 100%. Finally, only one of the two dual frontier studies reviewed reported a TE measure (88%).

Some Methodological Considerations

As is the case with all empirical work in economics, the frontier studies summarized in the preceding section are subject to criticism on a number of fronts. The purpose of this section is to discuss some methodological considerations that should be kept in mind when interpreting the studies reviewed. We make no attempt to determine how each of the studies reviewed measures up to each potential criticism. Such a task would unduly lengthen an already long paper.

The first factors to be included here are the sensitivity of efficiency measures to variations in input quality across farms that are explicitly accounted for, and to the choice of variables included in the model. Despite the potential distortions that these two factors might have on efficiency, it is not possible to determine their actual significance given that this type of information is not typically discussed in the literature. We should indicate, however, that Schmidt has argued that the decision of which variables to include in the model may have a more important effect on efficiency than on other features of the technology, such as economies of size.

The second important issue has to do with the choice between a non-parametric and a parametric specification, keeping in mind that the latter can be deterministic or stochastic. Gong and Sickles concluded recently that, due to lack of empirical analysis, little can be said about how non-parametric frontiers perform in relation to parametric models. However, several papers have compared the performance of different parametric frontier models, using the same data set, for developing as well as developed countries (e.g., Bravo-Ureta and Rieger, 1990; Ekanayake and Jayasuriya; Kopp and Smith; and Taylor and Shonkwiler). The studies reviewed here, as can be gleaned from the data presented in Table 1, show that stochastic models yield a somewhat higher average TE than their deterministic counterparts. In our opinion, it can be argued with justification that stochastic models are more reliable than deterministic models because the former account for statistical noise.

A third matter that arises, which is not unique to frontier studies, concerns the choice of functional form in parametric models. Despite its well known limitations, the Cobb-Douglas functional form has been widely used in farm efficiency analysis for both developing and developed countries. The pertinent question when interpreting parametric studies is the possible sensitivity of the efficiency measures to the choice of functional form. In one of the few studies examining the impact of functional form on efficiency, Kopp and Smith concluded ". . . that functional specification has a discernible but rather small impact on estimated efficiency" (p. 1058). The extent to which the results of Kopp and Smith can be generalized is not known. One can argue, however, that an integral part of applied production analysis should be the evaluation of the impact of functional form on the key results of the study. The methodological foundation for this type of evaluation stems from recent developments in the econometric literature dealing with specification tests (Greene, 1990a).

Another important issue that concerns the stochastic frontier models is the distributional assumptions made for the one-sided error. Much of the literature to date has followed the half normal distribution, as originally proposed by Aigner, Lovell and Schmidt, despite the fact that more flexible distributions are available. One of the few papers that have examined the sensitivity of the efficiency results to distributional assumptions was published recently by Greene (1990b), where he introduced a stochastic frontier specification that incorporates the gamma distribution. After comparing several specifications, Greene concluded that, for his data, efficiency levels were essentially the same for the half normal, truncated normal and exponential distributions while the gamma model yielded higher efficiency. As Bauer concluded in a recent review of new developments in frontier function methodology, additional empirical as well as theoretical work is needed to arrive at a better understanding of the effects that alternative distributional assumptions might have on efficiency.

A fifth methodological concern has to do with the use of the two step procedure to examine the determinants of efficiency. Critics of this approach contend that the socioeconomic variables should be incorporated directly in the production frontier model because such variables may have a direct impact on efficiency (Battese, Coelli and Colby). Kalirajan (1991) has recently defended the two step procedure by stating that socioeconomic attributes have a round about effect on production and, hence, should be incorporated into the analysis indirectly. Ray has argued that this procedure is justifiable if one assumes that the production function is multiplicatively separable in what he calls discretionary and nondiscretionary inputs. The latter inputs are those commonly used to explain variations in efficiency. One way out of this problem is to be found in a recent paper by Kumbhakar, Ghosh and McGuckin, who presented a model where the determinants of technical efficiency can be estimated together with the rest of the parameters of the frontier model.

A sixth consideration relates to the validity of efficiency results that rely on cross-sectional data. According to Dawson, efficiency measures derived from data for a single production period might be distorted by period specific abnormalities. If these distortions are significant, then the resulting efficiency measures might not be accurate. It is because of this potential problem that the recent developments in stochastic frontier models for panel data have been received with much enthusiasm in the profession.

The studies reviewed above relying on panel data yield, in general, higher average technical efficiency levels than those estimated using a single cross-section. In addition, some of the panel studies support the notion that efficiency varies over time. Despite these findings, the analysis to date is not sufficient to make a judgement concerning the impact on efficiency measures of using one cross-section versus a richer panel data set. One clear advantage of having panel data, as stated earlier, is that efficiency measures can be derived without imposing an arbitrary assumption on the distribution of the efficiency term, and without the need to assume that technical efficiency is uncorrelated with the inputs (Bauer).

The final methodological question we address here is the choice between estimating a single equation model as opposed to a system of equations. An a priori advantage of a system of equations is a potential gain in asymptotic efficiency in the estimates of the technology and efficiency. However, an important drawback lies on the difficulty in estimating systems that incorporate flexible functional forms (Bauer). Using a simulation approach, Gong and Sickles concluded that a single equation model performed much better than a system estimator in measuring firm level inefficiency. Although there is no basis for extrapolating these results to other settings, the simulation results do suggest that more complex frontier models do not necessarily yield a more desirable outcome.

Summary and Concluding Comments

A total of 30 frontier studies using farm level data from 14 different developing countries were reviewed. By far, the country that has received most attention from frontier researchers is India, accounting for 10 of the 30 studies. In addition, 13 of the studies reviewed focused specifically on rice, making this the most studied agricultural product by frontier researchers. These studies were divided into two groups and five subgroups based on the type of frontier methodology used.

The farm level technical efficiency indexes from all the studies reviewed range from 17% to 100% with an average of 72%. The reported allocative efficiency indexes range from a low of 43% to a high of 89% with an average of 68%. By contrast, the economic efficiency indexes go from 13% to 69%, with an average of 43%. A major conclusion stemming from these efficiency measures is that there is considerable room to increase agricultural output in developing countries without increasing input levels and without requiring the introduction of new technology.

It is interesting to note that most frontier studies have focused only on technical efficiency, even though it is by improving overall economic efficiency that major gains in output could be achieved. The relative importance of each of these two components has been the subject of a lively exchange in the literature (Leibenstein, 1966 and 1978; Comanor and Leibenstein; and Stigler). This suggests that additional efforts should be devoted to examining the impact of both allocative and technical efficiency on performance.

The question that logically emerges is what can be done to increase efficiency. The evidence summarized in this paper reveals that several variables have been introduced in models seeking to explain farm level variation in efficiency. The variables that have been used most frequently in these models are farmer education and experience, contacts with extension, access to credit, and farm size. With the exception of farm size, the results reveal that these variables tend to have a positive and statistically significant impact on technical efficiency. Specifically, this pattern was found in nine out of 14 studies for education, six out of seven for experience, six out of six for extension, and five out of eight for credit. In general, these results are consistent with the findings reported in the non-frontier literature (e.g., Lockheed, Jamison and Lau; and Birkhaeuser, Evenson and Feder).

The results of the efficiency literature based on frontier methodology are generally consistent with the notion that human capital plays an important role in farm productivity in developing countries. Consequently, public investments designed to enhance human capital can be expected to generate additional output even in the absence of new technologies. The fact that significant increases in output could be obtained by making better use of available inputs and technology does not mean that research designed to generate new technology should be overlooked. Rather, those in the business of increasing the supply of agricultural products should keep in mind that there is much that can be done while the scientists are hard at work in developing the new know-how.

A surprising fact that emerges from this review of the literature is the limited number of studies reporting an analysis between farm size and efficiency. This is surprising given the importance that has been given to this subject in the development literature (e.g., Berry and Cline; Bardhan; and Carter). This subject is likely to continue to play an important role in the public policy arena in many developing countries and, hence, it seems to us that the frontier literature might be able to make a more substantial contribution to better inform this debate.

It is clear from this review that considerable effort has been devoted to measuring efficiency in developing country agriculture using a wide range of frontier models. Despite all this work, the extent to which efficiency measures are sensitive to the choice of methodology remains uncertain. The implication that can be derived from this point is that, given the importance and complexity of efficiency measurement, a more systematic effort is needed to evaluate the performance of various efficiency estimators for a given data set.

Finally, more work is also needed to get a better understanding of the major determinants of output and productivity growth. Recent advances in panel data methodologies, along with models that enable the joint estimation of efficiency and its determinants, open an exciting area for further research. Moreover, these methodologies make it possible to decompose total output growth into input growth, technical efficiency, and technological change. However, to make these methodologies truly useful, we will need to find the way to assemble the necessary data. In our judgement, this will prove to be a challenging undertaking.

REFERENCES

Afriat, S.N. "Efficiency Estimates of Production Functions." *International Economic Review* 13(1972):568–98.

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

Aigner, D.J., and S.F. Chu. "On Estimating The Industry Production Function." *American Economic Review* 58(1968):826–39.

Ali, M., and M.A. Chaudry. "Inter-Regional Farm Efficiency in Pakistan's Punjab: A Frontier Production Function Study." *Journal of Agricultural Economics* 41(1990):62–74.

Ali, M., and J.C. Flinn. "Profit Efficiency Among Basmati Rice Producers in Pakistan Punjab." *American Journal of Agricultural Economics* 71(1987):303–10.

Bagi, F.S. "Farm-Level Technical Efficiencies of Individual Crops." Unpublished paper, 1987.

Bailey, D., B. Biswas, S.C. Kumbhakar, and B.K. Schulthies. "An Analysis of Technical, Allocative and Scale Efficiency: The Case of Ecuadorian Dairy Farms." *Western Journal of Agricultural Economics* 14(1989):30–37.

Bardham, P.K. "Size, Productivity and Returns to Scale: An Analysis of Farm Level Data in Indian Agriculture." *Journal of Political Economy* 18(1973):1370–86.

Battese, G.E. "Frontier Production Functions and Technical Efficiency: A Survey of Empirical Applications in Agricultural Economics." *Agricultural Economics* 7(1992): 185–208.

Battese, G.E., and G.A. Tessema. *Estimation of Stochastic Frontier Production Functions with Time-Varying Parameters and Technical Efficiencies Using Panel Data from Indian Villages*. Revised version of paper presented at the 36th Annual Conference of the Australian Agricultural Economics Society at the Australian National University, Canberra, 10–12 February, 1992.

Battese, G.E., and T.J. Coelli. "Prediction of Firm-Level Technical Efficiencies with a Generalized Frontier Production Function and Panel Data." *Journal of Econometrics* 38(1988):387–89.

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

Battese, G.E., T.J. Coelli, and T.C. Colby. "Estimation of Frontier Production Functions and the Efficiencies of Indian Farms Using Panel Data from ICRISAT's Village Level Studies." *Journal of Quantitative Economics* 5(1989):327–48.

Bauer, P.W. "Recent Developments in the Econometric Estimation of Frontiers." *Journal of Econometrics* 46(1990): 39–56.

Belbase, K., and R. Grabowski. "Technical Efficiency in Nepalese Agriculture." *Journal of Developing Areas* 19(1985):515–25.

Berry, A.R., and W.R. Cline. *Agrarian Structure and Productivity in Developing Countries*. Baltimore: The Johns Hopkins University Press, 1979.

Bhagwati, J.N., and S. Chakravarty. "Contributions to Indian Economic Analysis: A Survey." *American Economic Review* 59(1969):2–67.

Birkhaeuser, D., R.E. Evenson, and G. Feder. "The Economic Impact of Agricultural Extension: A Review." *Economic Development and Cultural Change* 39(1991):607–50.

Bravo-Ureta, B.E., and R. Evenson. "Efficiency in Agricultural Production: The Case of Peasant Farmers in Eastern Paraguay." Manuscript Department of Agricultural and Resource Economics, University of Connecticut, Storrs, CT.

Bravo-Ureta, B., and L. Rieger. "Dairy Farm Efficiency Measurement Using Stochastic Frontiers and Neoclassical Duality." *American Journal of Agricultural Economics* 73(1991):421–28.

Bravo-Ureta, B., and L. Rieger. "Alternative Production Frontier Methodologies and Dairy Farm Efficiency." *Journal of Agricultural Economics* 41(1990):215–26.

Carter, M.R. "Identification of the Inverse Relationship Between Farm Size and Productivity: An Empirical Analysis of Peasant Agricultural Production." *Oxford Economic Papers* 36(1984):131–45.

Chennareddy, V. "Production Efficiency in South Indian Agriculture." *Journal of Farm Economics* 49(1967):816–20.

Comanor, W.S., and H. Leibenstein. "Allocative Efficiency, X-Efficiency and the Measurement of Welfare Losses." *Economica* 36(1969):304–9.

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

Dawson, P.J. "Measuring Technical Efficiency from Production Functions: Some Further Estimates." *Journal of Agricultural Economics* 36(1985):31–40.

Dawson, P.J., J. Lingard, and C.H. Woodford. "A Generalized Measure of Farm-Specific Technical Efficiency." *American Journal of Agricultural Economics* (1991): 1098–1104.

Ekayanake, S.A.B. "Location Specificity, Settler Type and Productive Efficiency: A Study of the Mahaweli Project in Sri Lanka." *Journal of Development Studies* 23(1987): 509–21.

Ekanayake, S.A.B., and S.K. Jayasuriya. "Measurement of Firm Specific Technical Efficiency: A Comparison of Models." *Journal of Agricultural Economics* 38(1987): 115–22.

Fan, S. "Effects of Technological Change and Institutional Reform on Production Growth in Chinese Agriculture." *American Journal of Agricultural Economics* 73(1991): 266–75.

Farrell, M. "The Measurement of Productivity Efficiency." *Journal of the Royal Statistical Society A* 120(1957):253–90.

Forsund, F.R., C.K. Lovell, and P. Schmidt. "A Survey of Frontier Production Functions and Their Relationships to Efficiency Measurement." *Journal of Econometrics* 13(1980):5–25.

Gong, B., and R. Sickles. "Finite Sample Evidence on Performance of Stochastic Frontier Models Using Panel Data." *Journal of Productivity Analysis* 1(1989):229–61.

Greene, W.H. "A Gamma Distributed Stochastic Frontier Model." *Journal of Econometrics* 46(1990a):141–63.

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

Greene, W.H. "Maximum Likelihood Estimation of Econometric Frontier Functions." *Journal of Econometrics* 13(1980):27–56.

Hayami, Y., and V. Ruttan. *Agricultural Development: An International Perspective*. Baltimore: The Johns Hopkins University Press, 1985.

Hopper W.D. "Allocation Efficiency in a Traditional Indian Agriculture." *Journal of Farm Economics* 47(1985):611–24.

Huang, C.J., and F.S. Bagi. "Technical Efficiency on Individual Farms in Northwest India." *Southern Economic Journal* 51(1984):108–15.

Johnston, B.F., and J.W. Mellor. "The Role of Agriculture in Economic Development." *American Economic Review* 51(1961):566–93.

Jondrow, J., C.A. Lovell, S. Materov, and P. Schmidt. "On Estimation of Technical Inefficiency in the Stochastic Frontier Production Function Model." *Journal of Econometrics* 19(1982):233–38.

Junankar, P.N. "Tests of the Profit Maximization Hypothesis: A Study of Indian Agriculture." *Journal of Development Studies* 6(1980):186–203.

Kalirajan, K. "An Econometric Analysis of Yield Variability in Paddy Production." *Canadian Journal of Agricultural Economics* 29(1981):283–94.

Kalirajan, K. "Farm-Specific Technical Efficiencies and Development Policies." *Journal of Economics Studies* 11(1984):3–13.

Kalirajan, K. "On Measuring Economic Efficiency." *Journal of Applied Econometrics* Vol. 5 (1990):75–85.

Kalirajan, K. "The importance of Efficient Use in the Adoption of Technology: A Micro Panel Data Analysis." *Journal of Productivity Analysis* 2(1991):113–26.

Kalirajan, K., and J.C. Flinn. "The Measurement of Farm-Specific Technical Efficiency." *Pakistan Journal of Applied Economics* II(1983):167–80.

Kalirajan, K., and R.T. Shand. "Types of Education and Agricultural Productivity: A Quantitative Analysis of Tamil Nadu Rice Farming." *The Journal of Development Studies* 21(1985):232–43.

Kalirajan, K., and R.T. Shand. "Estimating Location-Specific and Firm-Specific Technical Efficiency: An Analysis of Malaysian Agriculture." *Journal of Economic Development* 11(1986):147–60.

Khan, M.H., and D.R. Maki. "Effects of Farm Size on Economic Efficiency: The Case of Pakistan." *American Journal of Agricultural Economics* 61(1979):Feb.

Kopp, R.J., and W.E. Diewert. "The Decomposition of Frontier Cost Functions Deviations into Measures of Technical and Allocative Efficiency." *Journal of Econometrics* 19(1982):319–31.

Kopp, R.J., and V.K. Smith. "Frontier Production Function Estimates for Steam Electric Generation: A Comparative Analysis." *Southern Economic Journal* 47(1980):1049–59.

Kumbhakar, S.C., S. Ghosh, and J.T. McGuckin. "A Generalized Production Frontier Approach for Estimating Determinants of Inefficiency in U.S. Dairy Farms." *Journal of Business and Economic Statistics* 9(1991):279–86.

Kumbhakar, S.C. "The Specification of Technical and Allocative Inefficiency in Stochastic Production and Profit Frontiers." *Journal of Econometrics* 34(1987b):335–48.

Kuznets, S. *Modern Economic Growth: Rate, Structure, and Spread*. New Haven: Yale University Press, 1966.

Lau, L.J., and P.A. Yotopoulos. "A Test for Relative Efficiency and Applications to Indian Agriculture." *American Economic Review* 61(1971):94–109.

Leibenstein, H. "Allocative Efficiency vs. 'X-Efficiency'." *American Economic Review* 56(1966):392–415.

Leibenstein, H. "X-Inefficiency Xists—Reply to an Xorcist." *American Economic Review* 68(1978):203–11.

Lockheed, M.E., Jamison, D.T., and Lau, L.J. "Farmer Education and Farm Efficiency: A Survey." *Economic Development and Cultural Change* 29(1980):37–76.

Meeusen, W., and van den Broeck. "Efficiency Estimation from Cobb-Douglas Production Function with Composed Error." *International Economic Review* 18(1977):435–44.

Nicholls, W.H. "The Place of Agriculture in Economic Development." In *Agriculture in Economic Development*, edited by Carl K. Eicher and Lawrence W. Witt, 11–44, New York: McGraw-Hill, 1964.

Nishimizu, M., and J.M. Page, Jr. "Total Factor Productivity Growth, Technological Progress and Technical Efficiency Change: Dimensions of Productivity Change in Yugoslavia, 1965–78." *The Economic Journal* 92(1982):920–36.

Phillips, M.J., and R.P. Marble. "Farmer Education and Efficiency: A Frontier Production Function Approach." *Economics of Education Review* 5(1986):257–64.

Pinheiro, A. "An Econometric Analysis of Farm Level Efficiency of Small Farms in the Dominican Republic." M.S. Thesis, University of Connecticut, Storrs, 1992.

Pitt, M., and L.F. Lee. "The Measurements and Sources of Technical Inefficiency in the Indonesian Weaving Industry." *The Journal of Development Economics* 9(1981):43–64.

Rawlins, G. "Measuring the Impact of I.R.D.P.II upon the Technical Efficiency Level of Jamaican Peasant Farmers." *Social and Economic Studies* 34(1985):71–96.

Ray, S.C. "Measurement and Test of Efficiency of Farms in Linear Programming Models: A Study of West Bengal Farms." *Oxford Bulletin of Economics and Statistics* 47(1985):371–86.

Sahota, G.S. "Efficiency of Resource Allocation in Indian Agriculture." *American Journal of Agricultural Economics* 50(1968):584–605.

Schmidt, P. "Frontier Production Functions." *Econometric Review* 4(1985–86):289–328.

Schmidt, P., and C.A.K. Lovell. "Estimating Technical and Allocative Inefficiency Relative to Stochastic Production and Cost Frontiers." *Journal of Econometrics* 9(1979):343–66.

Schmidt, P., and R.C. Sickles. "Production Frontiers and Panel Data." *Journal of Business & Economic Statistics* 2(1984):367–74.

Schultz, T.W. *Transforming Traditional Agriculture*. New Haven: Yale University Press, 1964.

Seiford, L.M., and R.M. Thrall. "Recent Developments in DEA: The Mathematical Programming Approach to Frontier Analysis." *Journal of Econometrics* 46(1990):7–38.

Shapiro, K.H., and J. Müller. "Sources of Technical Efficiency: The Roles of Modernization and Information." *Economic Development and Cultural Change* 25(1977):293–310.

Shapiro, K.H. "Efficiency Differentials in Peasant Agriculture and Their Implications for Development Policies." *Journal of Development Studies* 19(1983):179–90.

Sidhu, S.S. "Relative Efficiency in Wheat Production in the Indian Punjab." *American Economic Review* 64(1974):742–51.

Squires, D., and S. Tabor. "Technical Efficiency and Future Production Gains in Indonesian Agriculture." *The Developing Economies* 29(1991):258–70.

Stigler, C.J. "The Xistence of X-Efficiency." *American Economic Review* 66(1976):213–26.

Taylor, T.G., and J.S. Shonkwiler. "Alternative Stochastic Specifications of the Frontier Production Function the Analysis of Agricultural Credit Programs and Technical Efficiency." *Journal of Development Economics* 21(1986):149–60.

Taylor, T.G., H.E. Drummond, and A.T. Gomes. "Agricultural Credit Programs and Production Efficiency: An Analysis of Traditional Farming in Southeastern Minas Gerais, Brazil." *American Journal of Agricultural Economics* 68(1986):110–19.

Timmer, C. "Using a Probabilistic Frontier Production Function to Measure Technical Efficiency." *Journal of Political Economy* 79(1971):776–94.

Toda, Y. "Estimation of a Cost Function When the Cost is not Minimum: The Case of Soviet Manufacturing Industries, 1958–71." *Review of Economics and Statistics* 58(1976):259–68.

Toda, Y. "Substitutability and Price Distortion in the Demand for Factors of Production: An Empirical Estimation." *Applied Economics* 9(1977):203–17.

Trosper, R.L. "American Indian Relative Ranching Efficiency." *American Economic Review* 68(1978):503–16.

Yotopoulos, P.A., and L.J. Lau. "A Test for Relative Efficiency: Some Further Results." *American Economic Review* 63(1973):214–23.