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Production Efficiency and Diversification in Mexican Coffee-Producing Districts

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Coffee production system is analyzed for 24 municipios (districts) in Veracruz, Mexico, from 1997 to 2002. A stochastic frontier approach is used to estimate an input distance function and to evaluate production efficiency. Results show the production process to be stable over time despite global price fluctuations. Production of staple crop (corn) with either coffee or other cash crops results in increased efficiency as a result of the economies of complementarity, while production of coffee with other cash crops leads to lower efficiency. Factors contributing to higher efficiency included higher population density, road availability, and higher altitude, typically associated with production of higher-quality coffee.

Key Words: coffee production, distance function, Mexico, production systems, stochastic frontier, technical efficiency

JEL Classifications: L25, L79, O13, O18, Q12

Economic growth theories recognize the fundamental role of increases in agricultural outputs in achieving rural advancement (Johnson; Johnston and Mellor; Johnston and Nielsen; Ohkawa and Rosovsky). However, agricultural production in various regions of the world is often affected by price fluctuations at the global level. In particular, if market changes depress the prices of the main cash crop, households lacking easy access to financial and factor markets might respond to these conditions by shifting production toward food crops as a self-insurance mechanism (De Janvry, Fafchamps, and Saudolet). On the other hand, households that have easier access to input and financial markets and that produce high-quality commodities might increase their efficiency by using the best production practices, thus exploiting their comparative advantage. In addition, instead of reliance on subsistence cropping they may diversify toward commercially oriented crops driven by the market demand.

According to the International Coffee Organization (ICO), the world indicator price for coffee in 1984 was as high as $1.4463/lb. (in U.S. dollars) paid to producer countries (ICO 2004). Governmental support for coffee production in the 1980s drove farmers in developing countries to increase plantings of this commodity. In subsequent years, various forms of support intended to increase coffee productivity resulted in an oversupply of coffee that exceeded demand by 13 million bags[1] by 2000 (ICO 2004). As a result, the

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[1] One bag contains about 60 kg or 132 lb. of coffee.

average price of coffee paid to producer countries in 2000 dropped to $0.3797/lb.[2]

In Mexico, the Instituto Mexicano del Café has provided support to coffee producers since 1973 in the form of machinery, technical packages, and price floors, along with marketing and organizational structures (Salazar, Nolasco, and Olivera). However, these support mechanisms have been shown to be contributing factors in the misallocation of resources, such as land, in the resultant distorted markets (Helberger and Chavas; Saudolet and De Janvry). A consequence of these distorting policies was that many small landowners—particularly in southern Mexico (Chiapas, Veracruz, Oaxaca)—devoted most of their land to coffee production, even though environmental conditions were not suitable to the growth of quality coffee. Simultaneous production of high- and low-quality coffee resulted in the practice of mixing coffee of different grades, which in turn gave Mexico a bad reputation as a producer (Lopez).

In the early 1990s, there was a worldwide push to deregulate agriculture, particularly in developing countries. In Mexico, this process was accelerated by the signing of the North American Free Trade Agreement. One of the objectives of the market reform was to transition to free determination of market equilibrium, thus avoiding damaging distortions in factor markets. These changes, combined with elimination of the ICO production quota system in 1989, left Mexican coffee producers to face a free market that can either boost economic growth or suppress it.

There are four main coffee-producing regions in Mexico—Chiapas, Veracruz, Oaxaca, and Puebla—accounting for 85% of the country's coffee production.[3] In 2000, coffee in Mexico ranked second among the highest currency–earning agricultural products. Eighty-five percent of Mexico's coffee production was exported, generating $613.8 million in export revenues and representing 14.5% of total agricultural exports (Consejo Mexicano del Café). However, foreign currency earned from coffee production at the national level has declined from $150 million in 1998 (in U.S. dollars) to $42 million in 2001 in real prices. Figure 1 shows average monthly prices paid to Mexican coffee producers during the period extending from 1997 to 2002 (in January 1997 dollars). The graph indicates a clear declining trend, with the monthly prices dropping in real terms from the high of $1.5795/lb. in February 1997 to $0.2866/lb. in November of 2002 (ICO 2006).

Coffee production is highly fragmented, providing income for 700,000 family households in Mexico; approximately 3 million people are directly dependent on this income (México Secretaria de Agricultura). In 2000, the southeastern state of Veracruz, which is a subject of closer analysis in this paper, was the second largest producer of coffee in Mexico, with coffee representing the third most-planted agricultural product after corn and sugarcane. Recent figures for Veracruz report 67,227 small landholders owning 152,457 hectares, with an average of 2.2 hectares per producer (Consejo Veracruzano de Comercio Agropecuario). The revenue from coffee production in Veracruz has followed the declining national trend.

This study analyzes the production system of coffee producers in 24 municipios in Veracruz, Mexico, during the 1997 through 2002 growing period.[4] The municipios included in the study comprise 54% of the total land planted to coffee in the state. This region experienced rapid expansion of coffee production in the 1980s and 1990s. Most of this growth was promoted by government-introduced technologies and government subsidies. However, this support declined during the 1990s as a result of

[2] In 1984 dollar equivalent.

[3] Based on 2002 data from Mexican Secretariat for Agriculture (México Secretaria de Agricultura).

[4] A *municipio* is a unit of local administration in Mexico, similar to a county or district in other countries.

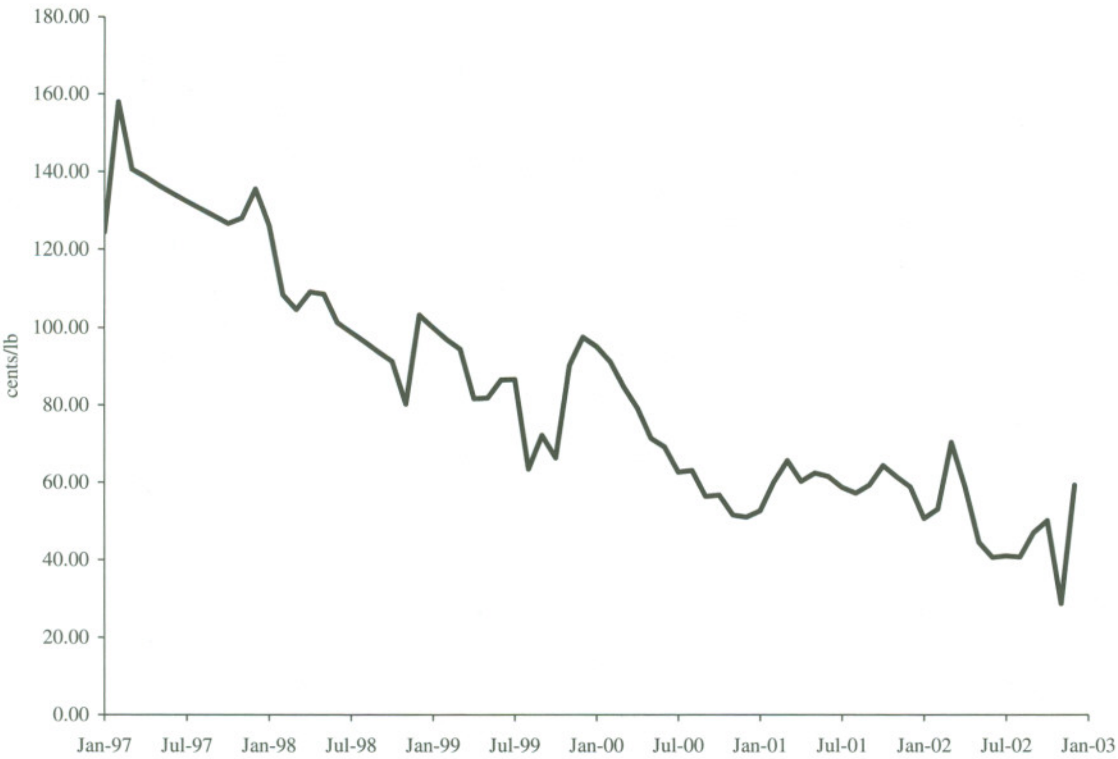

Figure 1. Monthly Prices Paid to Mexican Coffee Growers, 1997–2002 (in 1997 Dollars)

changes in the agricultural strategies of the Mexican government. The disappearance of national and international institutions supporting coffee production and increasing international supply of the commodity created an uncertain environment for coffee producers and impacted their technology, input use, and output production. Thus, the production system is analyzed during a period when governmental support had been significantly reduced and decoupled and when the pressure of decreasing international prices further burdened rural producers.

Recent studies on production efficiency and agricultural growth in developing countries include the work of Umetsu, Lekprichakul, and Chakravorty, who estimated an input-oriented Malmquist index for the 13 rice-producing regions in the post–Green Revolution (1971–1990) Philippines. Coelli and Fleming studied the role of cash crops (coffee) versus subsistence production in Papua New Guinea by using an input distance function and estimating technical efficiency. Gilligan tested for the relationship between farm size and productivity present in the sample of Honduras small coffee planters by estimating a nonparametric input–output distance function for a sample of 409 farmers during the 1993–1994 period. He used Tobit regression to estimate the relationship between technical efficiency and returns to size. Studies in both developing and developed countries indicate that economic productivity might be better explained by incorporating variables other than those related solely to production. Existing market imperfections and involvement of public services in some productive areas also have to be considered (Umetsu, Lekprichakul, and Chakravorty).

The general goal of the present study is to characterize the system of production by inputs and outputs used by the coffee producers in Veracruz, Mexico. A distance function stochastic frontier approach is used to accommodate three outputs: coffee, subsistence crops, and alternative or nontraditional cash crops (other than coffee). The specific objectives include (1) measuring the degree of technical efficiency in agricultural production; (2) assessing the existence of economies of diversification or complementarity between coffee and other crops in order to identify products that could bring more growth to the region; and (3) identifying municipio-specific characteristics (e.g., access to markets or higher altitude) that may provide comparative advantage in coffee production and determining to what extent these factors affect efficiency.

The rest of the paper is organized as follows. The second section outlines the modeling methodology, including discussion of the input distance function for the production model, the stochastic frontier approach to estimating technical inefficiency, and incorporation of hypothesized inefficiency factors. The third section describes the data set and specifications of the model to be estimated. The fourth section presents and discusses the empirical results, and the last section contains concluding comments.

Modeling Methodology

An input distance function characterizes the production technology by treating the output vector $\mathbf{y}$ as given and by looking at the minimal contraction of the input vector $\mathbf{x}$ that the producer can achieve while still producing the given output vector (Färe and Primont; Shephard). One of the main characteristics of a distance function is that it allows for multiple outputs and inputs to be considered within the same modeling framework. A general-form input distance function is given by

$$(1) \quad D(\mathbf{y},\mathbf{x}) = \max\{\lambda > 0 : (\mathbf{x}/\lambda) \in L(\mathbf{y})\},$$

where for a given output vector $\mathbf{y}$, the input set $L(\mathbf{y})$ includes all feasible input vectors ($\mathbf{x}$) that can produce $\mathbf{y}$. The distance function in (1) can be shown to be nondecreasing, homogeneous of degree one, concave, and continuous in $\mathbf{x}$ and convex and nonincreasing in $\mathbf{y}$ (Färe and Primont). The distance function may also include a time trend to capture technological changes in the production system (Hattori).

Technical efficiency can be defined as a condition $D(\mathbf{y},\mathbf{x}) = 1$. For estimation purposes, the distance function in Equation (1) is replaced by a stochastic frontier distance function so that $\varepsilon D(\mathbf{y},\mathbf{x}) = 1$, where ε is a random disturbance. The latter can be further decomposed so that $\varepsilon = v - u$, where the random term $u > 0$ measures the degree of inefficiency and is producer-specific, while the second error term v allows for measurement errors and the impacts of various events, such as weather, that affect productivity but are outside of the producer's influence (Battese and Coelli; Hattori). The estimated distance function reflects the best management practices represented in the data set. That is, given available inputs, the most-efficient producer will determine an efficiency boundary from which the producers not using the best management practices will deviate. The degree of technical inefficiency of individual producers can then be evaluated by measuring these deviations from the efficiency frontier.

Following Battese and Coelli, we assume that the producer-specific random terms u_i are drawn from a truncated normal distribution $N^{+}(\mu_i, \sigma^2)$, with the mean μ_i expressed as a linear function of a vector of explanatory variables z_i, so that $\mu_i = \delta_i z_i$. In the rest of the paper, we refer to these additional variables as *inefficiency variables*, as they help to explain deviations of individual producers from the efficiency frontier. The estimation of a distance function also provides coefficients and measures of economies of diversification that describe the production process.

The transcendental logarithmic (or translog) function is a commonly used functional form for the input distance function. It does not impose restrictions on substitution elasticities and is more flexible than a Cobb–Douglas specification (Christensen, Jorgenson, and Lau; Fuss, McFadden, and

Mundlak). Therefore, we use the translog function to represent a multi-output technology that allows for direct estimation of economies of diversification. A general-form stochastic frontier translog distance function for K inputs and M outputs can be written as

$$\begin{aligned}\ln D(\mathbf{y},\mathbf{x}) = {} & \alpha_0 + \sum_{m=1}^{M} \beta_m \ln y_m \\ & + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \beta_{mn} \ln y_n \ln y_m \\ & + \sum_{k=1}^{K} \alpha_k \ln x_k \\ & + \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \alpha_{kl} \ln x_k \ln x_l \\ & + \sum_{k=1}^{K}\sum_{m=1}^{M} \chi_{km} \ln x_k \ln y_m \\ & + v - u.\end{aligned} \tag{2}$$

Homogeneity and symmetry properties of the input distance function require that the parameters of the translog function satisfy the conditions

$$\begin{aligned} & \sum_{k=1}^{K} \alpha_k = 1, \\ & \sum_{k=1}^{K} \alpha_{kl} = 0, \qquad l = 1,\ldots,K, \\ & \sum_{k=1}^{K} \chi_{km} = 0, \qquad m = 1,\ldots,M, \end{aligned} \tag{2a}$$

$$\begin{aligned} & \beta_{mn} = \beta_{nm}, \qquad m,n = 1,\ldots,M, \\ & \alpha_{kl} = \alpha_{lk}, \qquad k,l = 1,\ldots,K. \end{aligned} \tag{2b}$$

For the translog function to represent a production technology, it must also satisfy regularity conditions (i.e., be nondecreasing and concave in inputs and nonincreasing and convex in outputs). The monotonicity conditions imply

$$\frac{\partial D(\mathbf{y},\mathbf{x})}{\partial x_k} \geq 0, \qquad k = 1,\ldots,K \quad \text{and} \quad \frac{\partial D(\mathbf{y},\mathbf{x})}{\partial y_m} \leq 0, \qquad m = 1,\ldots,M. \tag{2c}$$

The concavity with respect to inputs requires the Hessian

$$H^I = \left\{ \frac{\partial^2 D(\mathbf{y},\mathbf{x})}{\partial x_k \partial x_l} \right\}_{k,l=1}^{K-1} \tag{2d}$$

to be negative-definite, while the convexity with respect to the outputs requires the Hessian

$$H^O = \left\{ \frac{\partial^2 D(\mathbf{y},\mathbf{x})}{\partial y_m \partial y_n} \right\}_{m,n=1}^{M} \tag{2e}$$

to be positive-definite.[5]

As suggested by Lovell et al., the homogeneity condition in Equation (2a) imposed on Equation (2) can be used to normalize the distance function with respect to an arbitrary input. By defining a new input vector $\mathbf{x}^* = (x_k/x_K)$, $k = 1, \ldots, K-1$, we can obtain a transformed distance function $D'(\mathbf{y},\mathbf{x}^*) = x_K^{-1} D(\mathbf{y},\mathbf{x})$ and estimate it instead of Equation (2). We also include a time trend in order to measure changes in the production system over time (if there are any). The final model to estimate is then given by

$$\begin{aligned}\ln D'(\mathbf{y},\mathbf{x}^*) = {} & -\ln x_K + \ln D(\mathbf{y},\mathbf{x}) \\ = {} & \alpha_0 + \alpha_t t + \sum_{m=1}^{M} \beta_m \ln y_m \\ & + \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{M} \beta_{mn} \ln y_n \ln y_m \\ & + \sum_{k=1}^{K-1} \alpha_k \ln x_k^* \\ & + \frac{1}{2}\sum_{k=1}^{K-1}\sum_{l=1}^{K-1} \alpha_{kl} \ln x_k^* \ln x_l^* \\ & + \sum_{k=1}^{K-1}\sum_{m=1}^{M} \chi_{km} \ln x_k^* \ln y_m \\ & + v - u.\end{aligned} \tag{3}$$

The efficiency condition $D(\mathbf{y},\mathbf{x}) = 1$ now implies $x_K^{-1} = D'(\mathbf{y},\mathbf{x}^*)$, and the random term u again measures the degree of deviation from

[5] Note that the Hessian for inputs includes partial derivatives only with respect to $K-1$ inputs, because the full Hessian with respect to all inputs has a zero determinant as a result of homogeneity conditions.

the efficiency frontier.[6] Therefore, the technical efficiency for the ith producer can be calculated based on the point estimates $\hat{u}_I = \mathbf{E}(u_i \mid \varepsilon)$ as

$$(4) \quad TE_i = \exp(-\hat{u}_i)$$

(Jondrow et al.).

Following Coelli and Fleming, we also calculate the measure of diversification economies

$$(5) \quad \frac{\partial^2 \ln D}{\partial \ln y_m \partial \ln y_n} = \beta_{mn} = \beta_{nm}.$$

The latter reflects the change of input shares when the outputs m and n are produced together (i.e., measures output complementarity) (Coelli and Fleming). Whenever this measure is positive, output complementarity exists in the sense that simultaneous production of the two outputs increases efficiency as a result of a relative decrease in input use.

Data Specification and Expected Outcomes

Data used in this study were collected by one of the authors from the statistical yearbooks published by the Secretary of Finance and Economics (SFE) in the state of Veracruz, Mexico (Consejo Veracruzano de Comercio Agropecuario). The yearbooks provide information on the value of outputs produced and inputs used, as well as environmental and socio–demographic information at the municipio level. However, the data do not include costs of inputs and are highly aggregated for certain variables. As a result of data limitations, the analysis at the household level was not possible. The smallest unit of aggregation available in the data set—and thus chosen for the analysis—was a *municipio* (a district), which is a basic unit of local government administration.

A total of 24 municipios were included in the sample, accounting for 54% of the total area planted under coffee in Veracruz. The demographic characteristics of the municipios, as well as area planted to coffee, are presented in Table 1. The available data for each municipio include use of fertilizers and land, availability of technical assistance, value of all outputs produced, and demographic variables. Table 2 provides descriptions of the variables included in the model and their sample statistics. The SFE database included data for five growing seasons, namely 1997/1998, 1998/1999, 1099/2000, 2000/2001, and 2001/2002. Therefore, a total of 120 observations were used in a pooled cross-section, time-series analysis.

The model in Equation (3) was estimated with three outputs and four inputs. The outputs are corn, coffee, and "other crops." Traditionally, corn is the main staple crop produced in Mexico and is considered separately in order to account for self-consumption agriculture. Corn output is measured as a constant value of production by each municipio in an agricultural year.[7] Coffee is the main cash crop of interest in this study. Coffee output is also measured as a constant value of production in an agricultural year. Finally, the "other crops" variable accounts for all cash crop production other than coffee and varies widely across municipios. However, "other crops" mainly includes export-oriented crops, such as mango, passion fruit, lime, tangerine, banana, oranges, and pineapple. The output of "other crops" is also measured as a constant value of production in an agricultural year.[8]

[6] Note that despite similar appearance, the model in Equation (3) should not be interpreted as that explaining area planted for coffee (i.e., the normalizing input). Decomposition of the error term into $v - u$ and distributional assumptions about v and u are what distinguishes the stochastic frontier approach used here from a conventional OLS estimation. The transformation from Equation (2) to Equation (3) is performed only to facilitate estimation and does not change the meaning of the estimated coefficients. In particular, even though the transformed model in Equation (3) includes normalized inputs, the effects measured by the estimated coefficients reflect the influence of the actual inputs on the untransformed distance function (cf., for example, Coelli and Fleming).

[7] Consumer Price Index base 1997.

[8] Technically, the distance function reflects the relationship between levels of inputs and outputs, and it is those inputs and outputs that have to be used for estimation. However, in our case, the constant values of production are obtained by multiplying corresponding volumes of output by a fixed price factor (i.e., essentially representing volumes up to a constant multiplier). Thus, the inefficiency results of our analysis can be interpreted to be applied to volumes rather than monetary values of the outputs.

Table 1. Coffee-Producing Districts: Demographic Data

Municipio	Area, km²	Population[a]	% Rural Population	Rural Population Density per km²	Area Planted Under Coffee, ha
Alto Lucero	725.48	27,188	63.7	23.86	1,626.86
Atoyac	171.09	22,619	27.3	36.10	3,001.54
Atzalan	543.70	48,179	94.4	83.65	5,048.61
Chumatlan	36.19	3,438	100.0	95.00	199.40
Coatepec	255.81	73,536	19.9	57.34	9,578.86
Comapa	319.97	17,094	74.6	39.86	2,907.91
Coxquihui	86.37	14,423	74.8	124.88	550.09
Coyutla	312.56	21,105	63.2	42.66	800.10
Emiliano Zapata	394.82	44,580	67.9	76.63	5,264.37
Jilotepec	72.38	13,025	49.7	89.51	1,438.34
Misantla	537.90	60,771	62.6	70.69	4,182.53
Naolinco	123.38	18,097	55.4	81.26	772.00
Omealca	225.37	22,085	83.1	81.41	605.48
Soteapan	528.07	27,486	43.6	22.72	2,243.44
Tenampa	69.92	5,900	100.0	84.38	2,082.70
Teocelo	54.29	14,900	39.2	107.53	2,796.40
Tepatlaxco	99.53	7,844	100.0	78.81	2,510.08
Tezonapa	351.00	51,006	82.5	119.90	13,972.22
Tlachichilco	291.18	11,067	100.0	38.01	2,678.21
Tlaltetela	266.50	13,339	69.5	34.79	3,208.11
Tlapacoyan	142.30	51,877	32.8	119.70	1,873.74
Xico	176.85	28,762	26.7	43.35	3,388.81
Yecuatla	74.03	12,500	75.0	126.57	2,998.40
Zongolica	347.33	39,841	84.2	96.56	5,969.94

The input variables included areas planted under coffee and corn, fertilizer use, and technical support. The planted areas are measured in hectares. The fertilizer variable is measured in kilograms of fertilizer used per agricultural year and includes both organic and inorganic fertilizers. The technical support is measured as the total area that received outreach support (e.g., through visits by outreach agents per agricultural year). The area planted to coffee was used as a normalizing input to transform the input distance function from Equation (2) to Equation (3).

Inefficiency Variables

In order to account for differences in technical efficiency of production across municipios, four variables are introduced—rural population density, roads, ratio of other crops planted to coffee, and altitude. The variable for rural population is introduced to capture some of the effects that labor availability may play in determining production efficiency. In the area studied, agricultural production is labor intensive, and, hence, we expect that an increase in the rural population working in the agricultural sector would impact positively the technical efficiency of production.

To capture how mobility and access to markets impacts efficiency of production, the variable "roads" is used. This variable is measured in kilometers of paved roads in the municipio. Availability of a good road network affects efficiency in two ways. On the one hand, road infrastructure facilitates trade, as the municipios have easier access to markets and can sell agricultural products in a wider area. On the other hand, increased mobility allows for diversification into other economic activities. Since the model presented does not account for economic activities other than agricultural production, we expect that the sign of the roads variable will depend on

Table 2. Variables Description and Sample Statistics

Variable	Description	Units	Mean	SD	Min.	Max.
Inputs						
Co_H	Planted area, corn	Hectares	2,620.67	2,825.43	111	11,671
Fer	Area fertilized	Hectares	7,477.30	6,477.89	0	30,918
Tch	Area receiving technical support	Hectares	4,644.49	4,967.03	0	22,394
Cf_H[a]	Planted area, coffee	Hectares	3,333.02	2,933.16	200	15,000
Outputs						
Co	Constant value of corn production	Pesos	11,344.89	12,572.57	255.53	51,516.47
Cf	Constant value coffee production	Pesos	26,175.37	35,948.2	512.68	218,632.9
Oc	Constant value of other cash crop production	Pesos	35,935.14	74,381.9	43.09	466,350.5
Inefficiency Variables						
Dens	Rural population density	Persons/ha^2	0.740	0.324	0.227	1.266
Roads	Length of road network	km	65.70	48.13	2.00	175.70
MIX	Ratio of other cash crops to coffee	—	0.022	0.052	0.000	0.230
Altitude	Growing altitude	1 for altitudes above 800 m; 0 otherwise	0.583	0.495	0	1

[a] Normalizing input. SD is standard deviation; Min. is minimum; Max. is maximum.

how market-oriented agriculture is affected by access to markets.

The ratio of cash crops produced to coffee captures diversification of municipios toward production of export-oriented crops other than coffee. This variable is included in the model in order to assess how such diversification affects technical efficiency of agricultural production within municipios.

Finally, the altitude of the coffee plantations proxies coffee quality. Growing high-quality arabica species of coffee usually requires planting at an altitude of 800 m or higher above sea level. Production at lower elevations is typically associated with robusta varieties and lower-quality arabicas used in soluble or instant coffee mixes. In Veracruz this distinction is particularly important, as government subsidies and support led to expansion of coffee production into lower-altitude regions in the 1970s and 1980s. The producers in those regions did not have enough experience in growing coffee and often planted coffee varieties not intended for that particular area, resulting in poor quality of produced coffee. Plantations at higher altitudes, on the other hand, have a longer history of coffee production (usually within the same household) and utilize more-established coffee varieties, which results in production of higher-quality coffee.

Altitude in the model is a dummy variable that has a value of one for altitudes greater than 800 m and a value of 0 otherwise. While other variables could possibly be used to reflect coffee quality (e.g., proportions of certain varieties in the total production), data at this level of detail were not available. However, using altitude as an approximation to quality is consistent with the most commonly used approach to classify high-quality coffee (de Graaff). This criterion is also used by the Mexican government to distinguish high- and low-quality producers (México Secretaria de Agricultura).

Empirical Results

The homogeneity and symmetry conditions in Equations (2a) and (2b) were imposed on model Equation (3) for estimation purposes. Imposing the monotonicity and concavity/convexity conditions in Equations (2c) through (2e) would require rather complex constrained maximization of the likelihood function. Therefore, we opted to estimate the unconstrained model in Equation (3) and then test the constraints implied by Equations (2c) through (2e). The error terms v in Equation (3) were assumed to be normally distributed $N(0, \sigma_v^2)$ with zero mean and variance σ_v^2. The distribution of the error terms u_i was assumed to be truncated normal $N^+(\mu, \sigma_v^2)$ with variance σ^2 and the mean $\mu_i = \delta_i z_i$ represented as a linear combination of the four inefficiency variables described in the previous section.

The resulting translog distance function with the time trend and inefficiency variables was estimated in STATA 8 for the data set comprising five annual observations in each of the 24 municipios (120 observations total). Estimated coefficients, standard errors, t-statistics, and corresponding p-values are presented in Table 3. Note again that the transformation from Equation (2) to Equation (3) is identical (i.e., the coefficients estimated in Equation (3) are exactly the same as the coefficients in Equation (2) and have to be interpreted as such).

The time coefficient is negative but not significantly different from zero, which indicates that the productivity of the municipios remained roughly the same during the period considered. Since the translog function is nonlinear, the effects of other explanatory variables on the distance function include both first- and second-order terms. Therefore, the marginal effects of inputs and outputs were calculated by taking partial derivatives of the estimated distance function and evaluating those at the geometric means of the corresponding variables. The results are summarized in Table 4.

As expected, the table indicates that an increase in any input increases the distance function, i.e., has a positive effect on efficiency. However, the estimated coefficient for technical support is not significantly different from zero. On the output side, all coefficients are negative and significant, i.e., an increase in any output results in a decrease in the distance function (has a negative effect on efficiency).

Regularity Conditions

We tested the regularity conditions following the methodology outlined in Lau. The inequality constraints on estimated coefficients implied by the monotonicity conditions in Equation (2c) are essentially constraints on the signs of marginal effects reported in Table 4. The monotonicity conditions are satisfied for all inputs, with all but one inequality constraint significantly positive. The inequality constraint for technical support is positive, but not significantly different from zero. The monotonicity constraints are also satisfied for all outputs, with all inequality constraints significantly negative.

The constraints implied by the negative-definiteness of Hessian in Equation (2d) and positive-definiteness of Hessian in Equation (2e) were derived using Cholesky factorization of the Hessians and by imposing appropriate constraints on the diagonal elements (Cholesky values) of the resulting matrices (Lau). The factorization was performed analytically using Mathematica 5.0. The estimates of the derived Cholesky values are reported in Table 5.[9]

Two out of three inequality constraints corresponding to conditions of concavity with respect to the inputs have the correct signs, although only one of them is significant. One inequality constraint has an incorrect sign but is not significantly different from zero. Therefore, we cannot reject negative-semidefiniteness of the Hessian. The inequality constraints implied by the conditions of convexity with respect to the outputs all have the correct sign, although only one is significantly positive. Therefore, we also cannot reject positive-semidefiniteness of the corresponding Hessian.

[9] The analytical formulas used to calculate the estimates are too cumbersome to include in the paper and are available from the authors upon request.

Table 3. Estimation Results, Untransformed Distance Function

Coefficient		Variable	Estimate	SE	*t*-Statistics	*p*-Value
	α_0	Constant	8.933	2.415	3.700	0.000
	α_t	Time	−0.154	0.215	−0.716	0.237
Outputs	β_1	ln(*Co*)	−3.467	0.543	−6.380	0.000
	β_2	ln(*Cf*)	0.620	0.368	1.690	0.092
	β_3	ln(*Oc*)	0.051	0.149	0.340	0.732
Output–Output	β_{11}	0.5×ln(*Co*)×ln(*Co*)	0.237	0.061	3.870	0.000
	β_{12}	ln(*Co*)×ln(*Cf*)	0.131	0.047	2.810	0.005
	β_{13}	ln(*Co*)×ln(*Oc*)	−0.061	0.019	−3.240	0.001
	β_{22}	0.5×ln(*Cf*)×ln(*Cf*)	−0.251	0.067	−3.760	0.000
	β_{23}	ln(*Cf*)×ln(*Oc*)	0.044	0.017	2.530	0.011
	β_{33}	0.5×ln(*Oc*)×ln(*Oc*)	0.012	0.012	0.980	0.327
Inputs	α_1	ln(*Co_H*)	3.448	0.475	7.260	0.000
	α_2	ln(*Fer*)	−0.660	0.498	−1.330	0.185
	α_3	ln(*Tch*)	0.097	0.287	0.340	0.737
	α_4	ln(*Cf_H*)	−1.884	0.555	−3.400	0.001
Input–Input	α_{11}	0.5×ln(*Co_H*)×ln(*Co_H*)	0.126	0.061	2.080	0.037
	α_{12}	ln(*Co_H*)×ln(*Fer*)	−0.184	0.083	−2.220	0.027
	α_{13}	ln(*Co_H*)×ln(*Tch*)	−0.028	0.033	−0.840	0.399
	α_{14}	ln(*Co_H*)×ln(*Cf_H*)	0.086	0.091	0.940	0.345
	α_{22}	0.5×ln(*Fer*)×ln(*Fer*)	0.059	0.016	3.640	0.000
	α_{23}	ln(*Fer*)×ln(*Tch*)	−0.003	0.009	−0.330	0.743
	α_{24}	ln(*Fer*)×ln(*Cf_H*)	0.128	0.078	1.640	0.101
	α_{33}	0.5×ln(*Tch*)×ln(*Tch*)	−0.002	0.014	−0.160	0.875
	α_{34}	ln(*Tch*)×ln(*Cf_H*)	0.033	0.035	0.950	0.341
	α_{44}	0.5×ln(*Cf_H*)×ln(*Cf_H*)	−0.248	0.159	−1.560	0.119
Input–Output	χ_{11}	ln(*Co_H*)×ln(*Co*)	−0.273	0.042	−6.410	0.000
	χ_{12}	ln(*Co_H*)×ln(*Cf*)	−0.120	0.050	−2.410	0.016
	χ_{13}	ln(*Co_H*)×ln(*Oc*)	0.068	0.021	3.300	0.001
	χ_{21}	ln(*Fer*)×ln(*Co*)	0.234	0.090	2.600	0.009
	χ_{22}	ln(*Fer*)×ln(*Cf*)	−0.113	0.070	−1.630	0.103
	χ_{23}	ln(*Fer*)×ln(*Oc*)	−0.030	0.021	−1.390	0.165
	χ_{31}	ln(*Tch*)×ln(*Co*)	0.032	0.031	1.020	0.306
	χ_{32}	ln(*Tch*)×ln(*Cf*)	−0.048	0.031	−1.550	0.122
	χ_{33}	ln(*Tch*)×ln(*Oc*)	0.011	0.011	0.970	0.330
	χ_{41}	ln(*Cf_H*)×ln(*Co*)	0.007	0.100	0.070	0.948
	χ_{42}	ln(*Cf_H*)×ln(*Cf*)	0.281	0.087	3.240	0.001
	χ_{43}	ln(*Cf_H*)×ln(*Oc*)	−0.049	0.024	−2.040	0.041
Inefficiency Variables	δ_0	Constant	3.300	0.609	5.420	0.000
	δ_1	*Dens*	−2.381	0.403	−5.910	0.000
	δ_2	*Roads*	−0.015	0.003	−5.640	0.000
	δ_3	*MIX*	1.831	0.657	2.790	0.005
	δ_4	*Altitude*	−0.206	0.102	−2.020	0.043
Log-Likelihood		28.0964	$\chi^2(28)$	1,505.39	*p*-value	0.000

Note: SE is standard error.

Technical Efficiency

Technical efficiency as defined in Equation (4) is a measure that ranges from 0 to 1, with all municipios compared to the most technically efficient municipio in the sample. Higher measures of technical efficiency (with values closer to 1) mean more efficient municipios,

Table 4. Marginal Effects and Monotonicity Conditions

Variable	Marginal Effect	Monotonicity Condition	Estimate	SE	t-Statistics	p-Value
Inputs						
Co_H	$\partial D(\mathbf{y},\mathbf{x})/\partial x_1$	≥ 0	0.057	0.010	5.780	0.000
Fer	$\partial D(\mathbf{y},\mathbf{x})/\partial x_2$	≥ 0	0.024	0.007	3.420	0.001
Tch	$\partial D(\mathbf{y},\mathbf{x})/\partial x_3$	≥ 0	0.003	0.004	0.690	0.493
Cf_H	$\partial D(\mathbf{y},\mathbf{x})/\partial x_4$	≥ 0	0.070	0.013	5.540	0.000
Outputs						
Co	$\partial D(\mathbf{y},\mathbf{x})/\partial y_1$	≤ 0	−0.055	0.008	−7.200	0.000
Cf	$\partial D(\mathbf{y},\mathbf{x})/\partial y_2$	≤ 0	−0.034	0.006	−5.690	0.000
Oc	$\partial D(\mathbf{y},\mathbf{x})/\partial y_3$	≤ 0	−0.035	0.009	−3.760	0.000

Notes: Marginal effects are evaluated at geometric means of corresponding variables. The derivatives of the untransformed distance function in Equation (2) are reported. SE is standard error.

Table 5. Concavity and Convexity Conditions

Condition	Estimate	SE	t-Statistics	p-Value
Concavity with Respect to Inputs				
$H_1^I < 0$	−0.100	0.052	−1.910	0.056
$H_2^I < 0$	0.071	0.204	0.350	0.727
$H_3^I < 0$	−0.026	0.036	−0.730	0.467
Convexity with Respect to Outputs				
$H_1^O > 0$	0.805	0.109	7.400	0.000
$H_2^O > 0$	0.026	0.117	0.220	0.824
$H_3^O > 0$	0.089	0.778	0.110	0.909

Notes: H_k^I and H_k^O are Cholesky factors of the corresponding Hessians of the distance function (Equations (2d) and (2e)). All constraints are evaluated at geometric means of corresponding variables. SE is standard error.

while lower values (those closer to zero) indicate possibilities for improvement in input use. The calculated measures of technical efficiency are shown in Table 6. Note that these results reflect technical efficiency relative to the best practice used in this sample.

The results presented in Table 6 indicate that technical efficiency, on average, remained virtually flat, increasing overall between 1997 and 2002 by 1.70% (from 0.8754 to 0.8903). During the 1997/1998 growing period (first period in the sample), inefficiencies[10] among individual villages ranged from 0.14% (most efficient) to 59.8% (least efficient). This spread remained virtually unchanged in the subsequent periods. While some of the municipios are very close to the efficiency frontier, the producers in the least-efficient municipio (Coyutla) could still decrease their input usage by 59.2% during the 2001/2002 growing period to produce at the best practice frontier. Note also that the relative efficiency of individual municipios changed little over time, with Tenampa and Coyutla remaining the most- and least-efficient municipios, respectively, during the five growing periods included in the sample. Thus, despite changes in the market conditions caused by fluctuation of coffee prices and elimination of government support, the Veracruz municipios included in the study did not substantially change their production technology during the period considered.

[10] Inefficiency here is defined as the difference between the maximum efficiency of one and the calculated measures reported in Table 5.

Table 6. Technical Efficiency of Individual Municipios, 1997–2002

	Growing Period				
Municipio	1997/1998	1998/1999	1999/2000	2000/2001	2001/2002
Alto Lucero	0.4321	0.5330	0.5415	0.4885	0.5301
Atoyac	0.9972	0.9973	0.9972	0.9972	0.9972
Atzalan	0.9668	0.9720	0.9671	0.9648	0.9662
Chumatlan	0.9977	0.9977	0.9977	0.9977	0.9977
Coatepec	0.7306	0.7352	0.7225	0.7410	0.7468
Comapa	0.5202	0.5198	0.5281	0.5158	0.5218
Coxquihui	0.9972	0.9972	0.9972	0.9972	0.9972
Coyutla	0.4023	0.4045	0.4069	0.3996	0.4071
Emiliano Zapata	0.9955	0.9954	0.9954	0.9953	0.9953
Jilotepec	0.7731	0.7759	0.7771	0.7903	0.7659
Misantla	0.5021	0.6076	0.6000	0.5344	0.5582
Naolinco	0.9854	0.9849	0.9843	0.9846	0.9850
Omealca	0.9979	0.9978	0.9978	0.9978	0.9978
Soteapan	0.9978	0.9978	0.9978	0.9978	0.9978
Tenampa	0.9986	0.9986	0.9986	0.9985	0.9986
Teocelo	0.9978	0.9979	0.9979	0.9979	0.9979
Tepatlaxco	0.9582	0.9465	0.9652	0.9626	0.9581
Tezonapa	0.9971	0.9971	0.9971	0.9971	0.9972
Tlachichilco	0.7806	0.9735	0.9645	0.9691	0.9698
Tlaltetela	0.9975	0.9975	0.9975	0.9975	0.9975
Tlapacoyan	0.9971	0.9972	0.9971	0.9971	0.9971
Xico	0.9968	0.9969	0.9969	0.9968	0.9969
Yecuatla	0.9958	0.9960	0.9959	0.9957	0.9959
Zongolica	0.9937	0.9942	0.9943	0.9939	0.9940
Average	0.8754	0.8921	0.8923	0.8879	0.8903
Inefficiency, min	0.0014	0.0014	0.0014	0.0015	0.0014
Inefficiency, max	0.5977	0.5955	0.5931	0.6004	0.5929

Note: Inefficiency is measured as the difference between 1 and the efficiency reported in the table. min is minimum; max is maximum.

Complementarity

The measures of diversification economies calculated according to Equation (5) are reported in Table 7. These coefficients indicate the degree of complementarity among outputs resulting in increases in efficiency. The results demonstrate the existence of strong economies of complementarity between coffee and corn. In other words, during the time period considered, producers planting the traditional crops (coffee and corn) were more efficient as a result of lower input shares used in production. In particular, a 1% increase in corn production by coffee producers resulted in an 0.13% increase in efficiency as a result of a decrease in input use.

Table 7. Measures of Output Complementarity

	Corn	Other Crops
Coffee	0.131	−0.061
Other crops	0.044	

Note: All coefficients are significant at the 95% confidence level.

Production of other cash crops resulted in small diseconomies of complementarity (negative sign) when planted together with coffee and small economies of complementarity (positive sign) when planted together with corn. Despite relatively small magnitude, all three complementarity effects were found to be significantly different from zero (cf. Table 3). These results indicate that Veracruz municipios can achieve higher production efficiency either by maintaining the traditional crop production system (coffee/corn) or through a complete shift to production of alternative cash crops along with the staple crop (corn). However, diversification toward production of both coffee and alternative cash crops would decrease efficiency.

Inefficiency Variables

The explanatory variables included in the model to explain mean inefficiencies of individual municipios included rural population density, roads, ratio of other crops to coffee, and altitude. The estimated coefficients for these variables are presented in Table 3 and all are significant at the 99% confidence level, except for altitude, which is significant at the 95% confidence level. Note that the signs of the coefficients reflect the effect of the explanatory variables on the mean inefficiency, so that a negative sign actually means a positive effect on efficiency, and vice versa.

The estimated coefficient of rural population is negative, implying that an increase in rural population density decreases the mean deviation from the efficiency frontier and thus increases efficiency. This result was expected, as the municipios under consideration are characterized by labor-intensive agricultural production. This is also consistent with the results of other studies that have found that higher population density positively affects the efficiency of agricultural production (Johnson).

The availability of roads was also found to be positively related to agricultural productivity. While the magnitude of the effect was relatively small, it was significantly different from zero. This result confirmed the hypothesis that road availability, and thus access to markets, increases the efficiency of market-oriented production.

The municipios producing a higher ratio of other cash crops to coffee were found on average to be less technically efficient. This result is consistent with the statistically significant diseconomy of scale in simultaneous production of coffee and other cash crops discussed earlier. This finding indicates that municipios would benefit either from concentration on the traditional corn/coffee rotation or from shifting to corn/cash crop production. Such shifts may provide a way to diversify from the current heavy dependence on coffee production, especially at times during which coffee prices are low or volatile. However, diversification into production of other cash crops while simultaneously planting coffee actually decreases efficiency of production and should be avoided.

Finally, the altitude variable, which was used as a proxy to coffee quality, showed a significant and negative impact on the mean inefficiency (i.e., the technical efficiency was, on average, higher in the municipios located at altitudes above 800 m). This is consistent with the documented fact that coffee producers in higher-altitude locations in Mexico exhibit more commercially oriented behavior in comparison with their lower-altitude counterparts, partly because they know that the markets will pay a premium for their higher-quality coffee (Altobello and de Valdivia). As discussed in the previous section, another important phenomenon that is captured by the altitude variable is a longer family history of cultivating coffee in municipios with better environmental conditions and better land quality, which would allow for better methods of production and organization.

Implications and Conclusions

The agricultural production system in the state of Veracruz, Mexico, was analyzed for a 5-year period for 24 coffee-producing municipios by estimating a stochastic frontier translog distance function with four inputs and three outputs. The results show that overall technical efficiency increased only marginally during the period considered, despite coffee price fluctuations in the global market. Efficiency of individual municipios also changed little over time, with relative rankings of individual municipios virtually unchanged. Strong economies of complementarity have been found between coffee and staple crops (represented by corn) and between staple crops and other cash crops. On the other hand, simultaneous production of coffee and other cash crops resulted in lower overall efficiency of production.

Higher population density, higher altitude, and road availability positively contribute to the efficiency of regional production systems. A higher ratio of other cash crops to coffee, on the other hand, was found to decrease efficiency, thus confirming the results obtained from the analysis of economies of complementarity.

Our measure of producer efficiency is based on total production: that is, quality and differentiation of products are not explicitly considered. Data limitations also affected our choice of inefficiency variables, as well as the units of measurement for outputs. Relatively short data series may also have affected our results. Nevertheless, few studies on productivity at the local level have been conducted for agricultural production in Mexican regions. Collection of data for micro-regions in Mexico is a recent effort, and further opportunities may be exploited as more data become available.

The modeling approach developed here can serve as a framework for analysis of agricultural production comparing different coffee producers within Mexico or around the world. These findings can be then considered part of an effort that can be extended to contribute to the creation of suitable policies focused at a regional or district level. Information on types of farm organization, types of coffee, specific cash crops, human capital, and value produced can be used to find better measures of efficiency and its determinants. Further analysis can also be enriched by utilizing longer data series and additional data related to off-farm activities.

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