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# The Economic Efficiency of Coffee Growers in the Department of Caldas, Colombia

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**Abstract:** This work evaluates the economic efficiency of coffee growers and the decision-making processes in the configuration of their production systems and agronomic practices over time. For these purposes, information from 136 coffee growers in the department of Caldas was analyzed. These growers systematically recorded and constructed their production costs for seven years (2015–2021) within the framework of the Business Management Program of the Departmental Committee of Coffee Growers of Caldas. Additionally, through a survey, more information on the socioeconomic types, production systems, and decision-making processes in the implementation of practices and use of technologies was obtained. Stochastic frontier analysis demonstrates that on average, these coffee farmers had an economic efficiency of 89%. The group of coffee growers with efficiency levels equal to or higher than 90% comprised 80 producers (59%). These results indicate that for the period of analysis, there are no structural inefficiencies that cannot be corrected; that is, these coffee growers can increase their efficiency and productivity levels with the available technologies.

**Keywords:** technical efficiency; productivity; coffee; technical change

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## 1. Introduction

Productivity expresses the relationship between a quantity of product obtained or task performed and the inputs or resources used to achieve this production or carry out said task. Productivity is a measure of efficiency and is a critical determinant of profitability (Bharathi and Gupta 2018).

For coffee and other crops, productivity can be measured using two types of indicators: partial productivity indicators and total productivity indicators.

Partial productivity refers to the ratio between the quantity produced or work performed and a single type of input or resource used (Doss 2018). A partial indicator for coffee is the arrobas of dry parchment coffee produced per hectare. Total productivity refers to the ratio between global production and the sum of all the resources or factors used to obtain said production (Villota et al. 2020). The cost of production per arroba of dry parchment coffee (unit cost of production) is the indicator of total productivity in coffee growing. The measurement and evaluation of productivity provide information to a company on the level of efficiency achieved in the execution of its activities (Nurwantara et al. 2018).

Efficiency, the ability to produce with the least possible investment of time, money, energy or materials, is likewise a measure of the transformation of inputs into products. This concept emphasizes that to be efficient, high productivity combined with the lowest possible costs must be sought (Tingley et al. 2005).

The production frontier represents the maximum production that can be obtained with each level of input. Therefore, it reflects the current state of technology in the productive sector. The companies in this sector operate either at this border if they are technically efficient or below it if they are not. It may be the case that companies with different levels of use in their production factors are technically efficient. A company that operates with a certain level of production may be inefficient if, technically, it can increase production to a higher level without requiring additional inputs. Companies make decisions to optimize their resource use by increasing their production and achieving economies of scale (technically optimal condition) to guarantee high levels of productivity (Coelli et al. 2005).

Over time, it is possible to identify an additional source of change in productivity called technical change. Such technological advances change the state of knowledge, representing a shift to a higher-level production frontier (Colman and Young 1989; De Janvry et al. 2005). When a company increases its productivity from one year to the next, this improvement is not only due to increased efficiency; it may be due to a technical change, exploitation of economies of scale, or a combination of all three factors (Battese and Coelli 1995).

Allocative efficiency in the selection of inputs concerns the selection of the combination of resources (for example, labor and capital) that produces a certain quantity of product at the lowest cost (given the prices of inputs). Allocative efficiency and technique combine to provide a measure of overall economic efficiency (Coelli et al. 2005).

Technology can be defined, from an economic point of view, as all the production methods that have been or can be developed based on the existing state of scientific knowledge, which is often complex. Likewise, technology represents a new input that can be transferred to farmers by organizations with proven technical experience (Ellis 1993; Duque-Orrego 2018).

The technologies generated by scientific research on coffee can be products or processes and are made available to producers as improved varieties resistant to diseases, agronomic practices for crop establishment, fertilization schemes, the integrated management of weeds, pests and diseases, and technologies concerning the control of the postharvest process. Their adoption contributes significantly to the technical changes that result in sustained increases in productivity.

Determinant practices of productivity have been identified in coffee cultivation. Among this set of variables, sowing density presents the highest partial elasticity, indicating that the greatest changes in productivity per hectare depend on the variations in the number of established plants or stems per hectare (Araque Salazar and Duque 2019), or, likewise, on variables such as chemical fertilization, organic fertilization and labor (Ngango and Kim 2019). The volume of water used, the working capital, and the area dedicated to coffee also influence crop productivity (Tran et al. 2021).

In Colombia, coffee farming is the main source of income for 542,000 coffee growers and their families, approximately 1,500,000 people (FNC 2023). Because it is a product for which approximately 90% of its production is exported, its price is set daily and externally on the New York Stock Exchange, whereby it is also subject to exchange rate effects; this situation implies a strong volatility beyond the control of these national coffee producers.

Coffee growers have at their disposal a number of technological developments that combined with the environmental offerings of their coffee-growing areas and opportunities in their work, allow them to achieve high levels of productivity.

Since 2015, according to the productive areas for coffee, an average national productivity of 18.6 bags of green coffee per hectare has been estimated, equivalent to 1400 kg of dry parchment coffee per hectare per year (FNC 2023). Frequently, farms, even in areas with similar environmental offerings, obtain productivity close to 750 kg (hectare, year), lower than the national average, while others even exceed 2500 kg per hectare, a figure that corresponds to more than 33 bags of green coffee per hectare, higher than the national average and the productivity reported for Brazil.

Efficiency in the use of factors, a consequence of the decisions made by farmers, their technologies used, their opportunities to carry out agronomic practices, and their scales of operation, among other causes, can explain these gaps in productivity (Ahearn et al. 1998).

Referencing exercises among coffee growers who construct their production costs have confirmed that differences in productivity and unit costs persist, even among coffee growers with similar scales of operation.

When coffee growers adopt technologies that improve their production conditions, making use of the advantages of technical changes, they focus on achieving better levels of efficiency and, therefore, on being more competitive.

In coffee growing, producers must manage the production costs represented by labor and inputs to obtain a positive gross margin after marketing their coffee at the crop's current price. It is necessary to obtain high levels of productivity to make efficient use of the production factors.

A coffee farmer makes decisions in regard to the design of his or her production system, the variety to be planted, the number of trees per hectare (planting density), and the duration of the production cycle, which is generally between 5 and 7 years. Regarding crop agronomy, from the sowing season to the appropriate moment for crop maintenance, the result of these decisions is expressed in crop yield, that is, in terms of technical efficiency and unit cost.

Achieving a lower unit cost of production (allocative efficiency) is one of the greatest challenges for producers aiming to improve the competitiveness of their coffee company. The use of partial and total productivity indicators to monitor the performance of the different agronomic tasks in their production system is a useful tool for their management (Duque-Orrego et al. 2021).

In this sense, each coffee grower must make the most appropriate decisions to structure a solid and resilient production system and must adopt the best cultivation practices at the most appropriate times. These decisions are directly related to crop productivity; it is clear that in the first instance and for agriculture in general, profitability is directly supported by productivity.

The objective of this study is thus to determine the economic efficiency of coffee growers in the department of Caldas in the period between 2015 and 2021 by identifying the changes they made to their production systems and agronomic practices during this period.

## 2. Methodology

### *2.1. Efficiency Measures*

The seminal work of Farrell (1957) assessed the agricultural sector of the United States and proposed a method of measuring efficiency via frontier production functions by accounting for several production factors at the same time. This author decomposed the efficiency of a company into two components: technical efficiency (TE), the ability to obtain the maximum output for a given level of inputs, and allocative efficiency (AE), the ability of a company to use these inputs in an optimal proportion according to their prices. Combined, these two concepts constitute economic efficiency (EE) (Coelli et al. 2005). Technical efficiency is, then, concerned with establishing how much a company can increase its production with the available inputs or how much it can reduce the use thereof while maintaining its current level of production. Economic efficiency, then, is the measure of comprehensive performance and results when multiplying technical efficiency and allocative efficiency (Coelli et al. 2005; Tingley et al. 2005). Admitting a combination of inputs to achieve production, technical efficiency (TE) is the relationship between the inputs necessary to produce and the inputs used. Allocative efficiency (EA) considers the price of the inputs that the producer can choose between the options that he considers technically viable. Finally, the total efficiency or economic efficiency (EE) is given by the product of the technical and allocative efficiencies, assuming a variable return to scale (VRS).

$$EE = TE \times AE \tag{1}$$

The stochastic (parametric) frontier model, based on regression, is derived from estimates of the inefficiency of the error terms (Farrell 1957). The work of Aigner et al. (1977) incorporates a methodology for measuring efficiency with the stochastic production frontier, improving the proposal of Meeusen and Van Den Broeck (1977) by means of the structure of the error term. This error is composed of two elements: a nonnegative random variable associated with technical inefficiency in production and a symmetric random error, outside the control of the company, which accounts for other factors, such as the measurement error in the variable, taken as a product, or errors when omitting significant variables from the model, including time or chance (Battese and Coelli 1995). Based on the theoretical definition of the stochastic production function that expresses the maximum amount of production that can be obtained with a set of inputs and a specific technology, empirical evidence is used when applying econometric techniques to stochastic frontier models, following Farrel.

A second group of nonparametric techniques known as data envelopment analysis (DEA) is applied in the unit evaluation of homogeneous units or companies, such as coffee farms. An evaluation unit, commonly known as a decision-making unit (DMU), transforms inputs into outputs. Farm performance is evaluated using an efficient frontier that is constructed by the linear combination of the farms studied (Charnes et al. 1978).

Both techniques use a sample of farms for the construction of an efficient production frontier. The border is efficient in the sense that a coffee company that operates on this border cannot increase production without increasing its production factors (inputs); otherwise, it will not be able to reduce the use of such factors without reducing production (outputs). Deviations from the frontier represent inefficiencies, called X inefficiencies, whereby production costs are not minimized (Leibenstein 1978).

To estimate efficiency in this study, first, a cost function was constructed based on the unit cost of production, cost/kg of dry parchment coffee (cps) and the technological variables that reflect the decisions made in the productive exercise. Likewise, a production function was constructed to relate productivity (kg cps/ha/year) to the technological variables of the production system. A transformed Cobb–Douglas function was used.

To estimate the β parameters, a panel data model (xtreg) was adopted in the regression using the statistical program Stata version 16.

### *2.2. Stochastic Boundary Analysis of Panel Data*

Panel data can have group effects, time effects, or both. These effects are fixed or random effects according to the way in which cross-sectional unobservable heterogeneity is considered in relation to random disturbance. Therefore, the difference between these two models lies in whether this heterogeneity is considered fixed or deterministic, or, on the contrary, is defined as the composition of a common fixed part plus a specific random part for each individual.

Stochastic frontier models for panel data can be divided into nontime variant models and time variant models concerning their solution. Green (2005) proposed the "true" models of fixed and random effects as follows:

$$Y_{it} = \alpha_i + X\prime_{it}\beta + \varepsilon_{it} \tag{2}$$

In this way, the heterogeneity of the non-time-varying firms is controlled for, separating the time-varying inefficiency from the time-varying unobserved heterogeneity of specific units. Therefore, the model does not assume constant inefficiency over time; that is, this may change from one period to another and not necessarily if a firm is the most efficient at the beginning of a period; it will continue to be so at the end of the study period.

Additionally, the random effects model assumes that the heterogeneity of the signatures should not be correlated with the explanatory variables.

This work focuses on the representation of a stochastic cost frontier model for a balanced data panel. Each observation $i$ corresponds to each of the 136 Caldas coffee growers analyzed for the period between 2015 and 2021. The cost function is defined as follows:

$$y_{it} = \alpha + \beta' + v_{it} + u_{it} \tag{3}$$

$$i = 1 \ldots 136 \; t = 2015 \ldots 2021 \quad (4)$$

This function defines a lower limit for the production costs that are budgeted and executed with the objective of producing a given vector of outputs; these correspond to the productivity and tasks that make up the cost structure in which a coffee grower operates in this productive exercise. Alpha and beta are parameters that must be estimated.

Because stochastic frontier analysis is based on a composite error model, the term $v_{it}$ captures noise disturbance (symmetrical), and $u_{it}$ represents inefficiency in the cost of production of coffee growers. Both terms of the error are assumed to be independent. The sign of the term is positive because it describes a cost function.

The use of a data panel that corresponds to the period between 2015 and 2021 supposes a set of data that allows a better estimation of inefficiencies. The model with the greatest adjustment is that of variable inefficiencies over time; therefore, $u_i = u_{it}$.

Estimates are made using the "true" random effects model of Greene to isolate unobserved individual heterogeneity and allow time-varying efficiency measures. The changes in the results of the model are compared by assuming seminormal and exponential distributions.

### *2.3. Location and Study Area*

This study was carried out in 22 of the 25 coffee municipalities in the department of Caldas with the following extreme geographic coordinates: 04°48′32″ and 05°46′43″ North latitude; 74°37′44″ and 75°55′52″ West longitude. Figure S1 shows the number of coffee growers per municipality that participated in the study.

### *2.4. Study Population*

The population under study comprised 136 coffee growers with farms located in the department of Caldas participating in the Business Management program with a systematic record of production cost information for 7 years without interruption. Since we worked with all the coffee growers that met this criterion, we did not carry out sampling but rather a census.

### *2.5. Information Capture*

To meet the objective of this research, the costs recorded by the coffee growers in the application "My Costs on the Web" of the Departmental Committee of Coffee Growers of Caldas for the calendar years 2015–2021 were used as sources of information. The Coffee Information System (SICA) managed by the Technical Management of the National Federation of Coffee Growers was consulted to comprehend the coffee growing structure of the sampled farms for each of the focal years. Additional information on the socioeconomic nature of and decision making in these coffee farms regarding their agronomic work and application of inputs (frequency, opportunity and amounts applied) was collected, via the Extension Service of the Coffee Growers Committee, through a survey of the focal coffee growers.

The records for each farm, obtained from these different sources of information, were consolidated and refined in a database to proceed with the analyses.

A balanced data panel was created with information on the production costs and production systems, as well as the socioeconomic data, of the 136 coffee growers for the focal period of seven years.

Descriptive univariate analysis of this information was performed and included measures of central tendency and dispersion in continuous variables and frequency analysis for nominal variables.

### *2.6. Research Variables*

To determine the allocation of resources and the economic result of the decisions made by the focal producers over time (during the years studied), in addition to their productivity (arrobas of dry parchment coffee per hectare), this study analyzed the costs of the tasks involved in the production process—renovation, weed management, fertilization, CBB control, harvesting, benefit process (postharvest)—as well as their administrative expenses and, finally, their unit cost of production (Table S1). All securities were indexed to 2018 prices with the base index published by the Departamento Administrativo Nacional de Estadística (DANE 2023).

The variables used to explain the contribution to efficiency of the use of production techniques and practices are listed in Table S2. In the work of Araque Salazar and Duque (2019), density, age, and fertilization are established as determining variables of productivity. These variables enable assessing technical efficiency; in this study, they show how a production system is configured to explain its different levels of productivity and technical changes in the seven years of analysis. Likewise, technological variables such as fertilization, weed management, cultivated variety, and increased area provide relevant information on the allocation of resources in the productive exercise of a farm.

The characterization of the producers and their farms was complemented with socioeconomic variables such as age, education level, and coffee growing experience. This information allowed the evaluation of specific aspects of decision-making in allocating resources across the productive exercises of the coffee growers.

Additionally, an aptitude index was constructed based on the geophysical component elaborated by Siachoque et al. (2022) with information on the variables of precipitation (mm), thermal time (°C), solar brightness (hr) and water balance (deficit) to establish whether environmental variables have conditioned the technical efficiency of the coffee growers.

## 3. Results

The statistical results of the multiple regression model applied to the Caldas coffee growers who participated in the study in the 2015–2021 period are listed in Table S3 for the 952 observations and 136 groups (individuals) that comprise the data panel. The probability of the joint significance test (F) of the model is 0.0000, indicating that the regressors as a whole explain the dependent variable. In the model, the variables (LProductivity, LCost harvest, LCost fertilization, LCost pest control, LCost crop renewal, LCost weed management, and LAdministrative expenses) significantly affect the dependent variable; that is, its coefficients ($\beta$) are significant, but its aptitude and scale variables are not, confirming that the environmental variables in this case did not affect productive exercise from an economic point of view. Likewise, in Table S3, the F test of individual effects allows rejecting the null hypothesis, justifying the use of panel data that considers this type of effect; moreover, rho indicates the proportion of joint effects ($\alpha_i + u_{it}$), which derive from the individual effects. A total of 35.04% of the composite error of the model is due to individual effects. Additionally, the Breusch–Pagan/Cook–Weisberg heteroskedasticity test was applied (Ho: Constant variance; Variables: fitted values of LUnit cost), which resulted in: Chi2(1) = 1.76; Prob > chi2 = 0.1848 (Halunga et al. 2017). Table 1 presents the descriptive statistics of the abovementioned variables for the period of analysis.

### *Economic Efficiency*

In efficiency measurement analysis, a producer may operate under conditions of technical efficiency but may be inefficient in managing production costs. Production functions can measure technical efficiency insofar as the quantities of inputs are given and can be assigned in a nonoptimal way. Cost functions measure the sum of technical inefficiency and allocation (Greene 2008).

This analysis was carried out according to the principles of the theory of production and costs, which posits duality between production functions and cost functions; thus, the production process can be studied empirically, using both one function and the other, to evaluate the efficiency of the focal technology.

**Table 1.** Descriptive statistics of the variables for the period 2015–2021.

| Variable | Average | Standard Deviation | Maximum | Minimum |
|---|---|---|---|---|
| Unit cost | USD 1.44 | USD 0.22 | USD 2.32 | USD 1.17 |
| Productivity | 2585.75 kg cps | 1027.21 kg cps | 7785.63 kg cps | 438.5 kg cps |
| Crop renewal | USD 0.04 | USD 0.05 | USD 0.23 | USD 0.18 |
| Weed management | USD 0.10 | USD 0.05 | USD 0.56 | USD 0.01 |
| Fertilization | USD 0.20 | USD 0.09 | USD 0.82 | USD 0.05 |
| Pest control | USD 0.03 | USD 0.03 | USD 0.22 | USD 0.00 |
| Harvest | USD 0.69 | USD 0.10 | USD 1.27 | USD 0.47 |
| Postharvest | USD 0.08 | USD 0.04 | USD 0.58 | USD 0.00 |
| Administrative expenses | USD 0.16 | USD 0.12 | USD 0.66 | USD 0.01 |

When such analysis is carried out using the cost frontier approach, economic efficiency is measured as the difference between the observed costs and the minimum cost (with a set of inputs), which corresponds to the border (optimal); costs (of other companies or coffee farms) far from this border are inefficient.

The efficiency model with the best fit was determined to be the true random effects model, which considers inefficiency variation over time. Below, Table 2 presents the results of this model, assuming a seminormal distribution. For the calculation, Stata *sfpanel* command was used (Belotti et al. 2013).

The output of Table 2 shows that the random effects model proposed by Greene is appropriate for measuring stochastic efficiency because it allows rejecting the null hypothesis $Ho : \gamma = \frac{\sigma_u^2}{\sigma_{u\varepsilon}^2} = 0$, which measures the contribution of the variance in $u$ to the variance in the error $\varepsilon$.

The value of lambda ($\lambda$) is significant in the model, indicating that it is appropriate to include technical inefficiency in the unit cost function of coffee production for the Caldas producers who participated in the study.

Given that lambda assumes values between 5.69 and 5.71, higher than the stochastic deviations, technical inefficiency is the main cause of deviation from the cost frontier.

A review of the individual contributions of the variables considered shows that the logarithm of productivity (LProductivity) presents a significant coefficient of negative sign; that is, as productivity increases, unit cost decreases, coinciding with the results of Araque Salazar and Duque (2019); i.e., the actions undertaken to increase productivity result in a decrease in the cost of production and, therefore, an increase in economic benefits.

The variable cost of collection (LCost harvest) presented the coefficient with the greatest weight in the formation of the cost of production. Therefore, percentage increases in the cost of collection will imply proportional increases in the unit cost of production. As the collection of coffee in Colombia is performed manually, it generates a high demand for labor.

Fertilization is another variable of great importance in the cost structure of coffee production. Here, the logarithm of fertilization (LCost Fertilization) has a significant positive influence, indicating that percentage increases in fertilization drive percentage increases in the cost of production. Administrative expenses also significantly determine production cost and are essential in decision making on the allocation of resources in the different production tasks for the crop.

Other variables, such as weed management, postharvest, crop renewal, pest control and scale of operation, also have a significant influence on the cost of production. The environmental variables represented in the aptitude index (aptitude), constructed with geophysical information from the Rural Agricultural Planning Unit (UPRA; Siachoque et al. 2022), were not significant in the model and, therefore, did not influence efficiency. Of the 136 farms analyzed, 134 were classified as having a high aptitude for coffee cultivation. In Brazil, a study has analyzed the influence of climatic variables on the technical efficiency of coffee growers in the Cerrado and southern regions of Minas Gerais by conditioning the choice of inputs according to weather conditions. Estimating a stochastic production frontier, its results indicate that climatic variables have little effect on the average efficiency of coffee growers (de Paula et al. 2014).

**Table 2.** Stochastic frontier, assuming seminormal distribution in the Caldas coffee growers data panel.

| **True Random-Effects Model (Half-Normal) Group Variable Farmer Code** | | | | | **Number of Obs = 952 Number of Groups = 136** | |
|---|---|---|---|---|---|---|
| Time variable: Year | | | | | Obs per group: | |
| | | | | | Min = 7 | |
| | | | | | Avg = 7 | |
| | | | | | Max = 7 | |
| Log-simulated likelihood = 1211.9535 | | | | | Prob > chi2 = 0.0000 | |
| | | | | | Wald chi2(10) = 7295.21 | |
| Number of Pseudo-Random Draws = 250 | | | | | | |
| LUnit cost | Coef. | Std. Err | z | P > \|z\| | [95% Conf. Interval] | |
| Frontier | | | | | | |
| LProductivity | −0.022411 | 0.0069812 | −3.21 | 0.001 | −0.0360939 | −0.0087282 |
| LCost harvest | 0.5777314 | 0.0169494 | 34.09 | 0.000 | 0.5445112 | 0.6109517 |
| LCost postharvest | 0.0271037 | 0.0038555 | 7.03 | 0.000 | 0.019547 | 0.0346604 |
| LCost fertilization | 0.1625467 | 0.0067318 | 24.15 | 0.000 | 0.1493526 | 0.1757409 |
| LCost pest control | 0.0016984 | 0.0004773 | 3.56 | 0.001 | 0.0007629 | 0.0026339 |
| LCost crop renewal | 0.0086642 | 0.0006207 | 13.96 | 0.000 | 0.0074477 | 0.0098808 |
| LCost weed management | 0.0816932 | 0.0052962 | 15.42 | 0.000 | 0.0713128 | 0.0920735 |
| LAdministrative expenses | 0.1159822 | 0.0047837 | 24.25 | 0.000 | 0.1066064 | 0.125358 |
| Aptitude | −0.0002715 | 0.0079998 | −0.03 | 0.973 | −0.0159508 | 0.0154078 |
| Scale | 0.0196376 | 0.0041571 | 4.72 | 0.000 | −0.0408214 | 0.0234594 |
| _cons | 1.636146 | 0.1867383 | 8.76 | 0.000 | 1.741275 | 2.726517 |
| Usigma _cons | −4.397366 | 0.0678828 | −64.78 | 0.000 | −4.530414 | −4.264318 |
| Vsigma _cons | −7.87959 | 0.3001687 | −26.25 | 0.000 | −8.46791 | −7.29127 |
| Theta _cons | 0.236709 | 0.002594 | 9.13 | 0.000 | 0.0185868 | 0.0287551 |
| Sigma_u | 0.1109492 | 0.0037658 | 29.46 | 0.000 | 0.1038086 | 0.118581 |
| Sigma_v | 0.0194522 | 0.0029195 | 6.66 | 0.000 | 0.014495 | 0.0261048 |
| lambda | 5.703683 | 0.0058315 | 978.09 | 0.000 | 5.692253 | 5.715112 |

The value of theta, the standard deviation of the unobserved heterogeneity, considered random in this model, is significant. In this way, it is possible to distinguish inefficiency that varies over time from the heterogeneity that is not observed and that does not vary over time for some coffee farms. Table 3 shows the output of the model, assuming an exponential distribution.

The model assuming an exponential distribution is also significant and suitable for modeling the allocative and technical efficiency of the focal coffee growers. As in the previous model, all the variables are significant individually except for the environmental variables (aptitude). The variables cost of collection, fertilization, and administrative expenses presented the coefficients with the most significant weight in the formation of the cost of production. Likewise, it is assumed that there is no correlation between the regressors and the effects of specific units; the lower the value of the theta coefficient is, the lower the correlation of the explanatory variables and the effects of specific units. The value of theta, the standard deviation of the unobserved heterogeneity, considered random in this model is significant. In this way, it is possible to distinguish inefficiency that varies over time from the heterogeneity that is not observed and that does not vary over time for some coffee farms.

**Table 3.** Stochastic frontier, assuming exponential distribution in the Caldas coffee growers data panel.

| **True Random-Effects Model (Exponential) Group Variable Farmer Code** | | | | | **Number of Obs = 952 Number of Groups = 136** | |
|---|---|---|---|---|---|---|
| Time variable: Year | | | | | Obs per group: | |
| | | | | | Min = 7 | |
| | | | | | Avg = 7 | |
| | | | | | Max = 7 | |
| Log-simulated likelihood = 1248.6408 | | | | | Prob > chi2 = 0.0000 | |
| | | | | | Wald chi2(10) = 7982.28 | |
| | Number of Pseudo-Random Draws = 250 | | | | | |
| LUnit cost | Coef. | Std. Err | z | P > \|z\| | [95% Conf. Interval] | |
| Frontier | | | | | | |
| LProductivity | −0.0240747 | 0.0063699 | −3.78 | 0.000 | −0.0365594 | −0.0115899 |
| LCost harvest | 0.5760682 | 0.0157167 | 36.65 | 0.000 | 0.5452641 | 0.6068724 |
| LCost postharvest | 0.055658 | 0.0052729 | 10.56 | 0.000 | 0.0453233 | 0.0659926 |
| LCost fertilization | 0.1639617 | 0.0062411 | 26.27 | 0.000 | 0.1517294 | 0.176194 |
| LCost pest control | 0.0018981 | 0.0004255 | 4.46 | 0.000 | 0.0010641 | 0.0027321 |
| LCost crop renewal | 0.0078804 | 0.0004956 | 15.90 | 0.000 | 0.006909 | 0.0088517 |
| LCost weed management | 0.0772404 | 0.0050419 | 15.32 | 0.000 | 0.0673585 | 0.0871223 |
| LAdministrative expenses | 0.1102238 | 0.0045316 | 24.32 | 0.000 | 0.101342 | 0.1191056 |
| Aptitude | −0.0006008 | 0.0074631 | −0.08 | 0.936 | −0.0152283 | 0.0140266 |
| Scale | 0.0168867 | 0.0037464 | 4.51 | 0.000 | 0.0095438 | 0.0242295 |
| _cons | 1.532464 | 0.1735522 | 8.83 | 0.000 | 1.192308 | 1.872621 |
| Usigma _cons | −5.36782 | 0.09581 | −56.03 | 0.000 | −5.555604 | −5.180036 |
| Vsigma _cons | −7.354975 | 0.1740003 | −42.27 | 0.000 | −7.696009 | −7.013941 |
| Theta _cons | −0.0222747 | 0.0023655 | −9.42 | 0.000 | −0.0269111 | −0.0176383 |
| Sigma_u | 0.0682956 | 0.0032717 | 20.87 | 0.000 | 0.062175 | 0.0750187 |
| Sigma_v | 0.0252864 | 0.0021999 | 11.49 | 0.000 | 0.0213222 | 0.0299876 |
| lambda | 2.700879 | 0.0047524 | 568.32 | 0.000 | 2.691565 | 2.710194 |

The value of lambda ($\lambda$) is significant in the model, indicating that it is appropriate to include technical inefficiency in the unit cost function of coffee production for the Caldas producers who participated in the study. Given that lambda assumes values between 2.69 and 2.71, higher than the stochastic deviations, technical inefficiency is the main cause of deviation from the cost frontier.

With respect to the model with a seminormal distribution, the estimation of the deviation of the inefficiency term (sigma_u) is lower in the model with an exponential distribution.

In order to offer a comparative perspective regarding the coefficient estimates in Table S4, the estimates of the "true" fixed effects model can be seen.

## 4. Discussion

### *4.1. Classification of Producers by Level of Productivity*

The focal coffee growers were classified by their productivity level as follows: low productivity (CP), 31 producers (23%), with an average productivity lower than 1812.5 kg/cps; medium productivity (PM), 39 coffee growers (29%), with an average productivity below 2450 kg/cps; and high productivity (PA), 66 producers (49%), with a productivity above 2450 kg/cps.

In total, the focal group of coffee growers (136) between 2015 and 2021 presented an average productivity of 2587.5 kg/cps, higher than the national average (1400 kg/cps) reported by FNC (2023) in the same period.

### *4.2. Efficiency Scores*

The efficiency predictions were obtained with the statistics u, u0, jlms and the bc estimator (Battese and Coelli 1995). For each observation of the data panel, the bc estimator showed a high correlation with both distributions (mean-normal and exponential), with the jlms estimator when inefficiency was estimated with the exponential distribution and with the u statistic with the mean-normal distribution. The efficiency ranking presented a more stable ordering with the bc exponential distribution statistic.

Table 4 shows that the average economic efficiency of the coffee growers was 89.6%. Two classes, 85–90% and 91–100%, contained 94% of the producers, 35% and 59%, respectively.

**Table 4.** Frequency distribution of the economic efficiency scores of the coffee growers studied in Caldas, 2015–2021.

| Classes | Frequency | % | % Accumulated | |
|---|---|---|---|---|
| 0.75–0.80 | 3 | 2% | 2% | |
| 0.81–0.85 | 5 | 4% | 6% | |
| 0.85–0.90 | 48 | 35% | 41% | |
| 0.91–1.00 | 80 | 59% | 100% | |
| Average | Median | Standard deviation | Minimum | Maximum |
| 0.8969 | 0.9052 | 0.3036 | 0.7724 | 0.9464 |

When reviewing classification by productivity, it was found that the classes of lower efficiency grouped coffee growers with lower levels of productivity; likewise, producers with efficiency scores higher than 85% presented mostly medium and high productivity (Figure 1). In Brazil, Freire et al. (2011) have found a similar distribution of coffee growers in the south of Minas Gerais, i.e., economic efficiency scores between 80% and 100% when productivity is medium and high.

Additionally, in Figure 1, it can be seen that the classes with the lowest economic efficiency scores, from 0.75 to 0.85, are composed of producers with the lowest productivity levels. It is also observed that the classes with the highest scores, from 0.86 to 1.00, are primarily (83%) coffee growers with medium and high productivity, a situation similar to that reported by (Freire et al. 2012).

However, it is essential to remember that coffee growers (17%) with low productivity for this study, located in the higher efficiency classes, present an average of 1679 kg/cps, a value 20% higher than the national coffee growing average, which is 1400 kg/cps. One of the most important reasons why their level of productivity is lower than that of other more efficient producers is that despite having solid agronomic production systems, the unproductive area dedicated to crop renewal is proportionally more significant than the recommended area. Moreover, that affects their production levels, even making appropriate decisions regarding agronomic tasks.

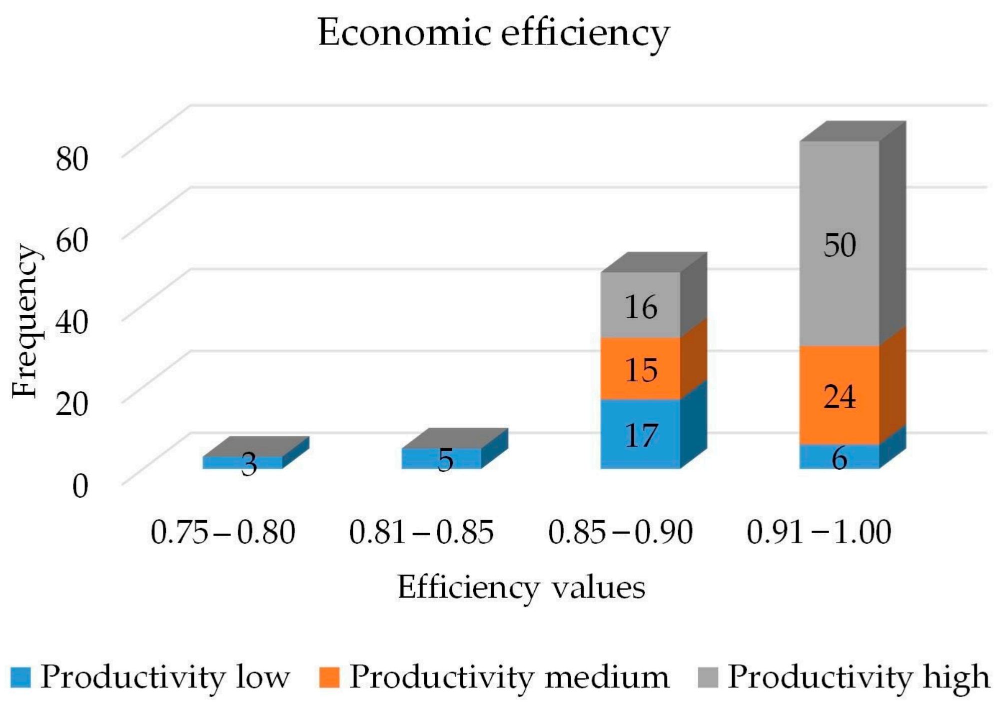


**Figure 1.** Distribution by efficiency class of coffee growers, grouped by productivity level, in Caldas, 2015–2021.

### *4.3. Economic Efficiency and Productivity*

#### 4.3.1. Economic Efficiency Less Than 85%

This group of eight coffee growers (6%), with an average age of 57 years, coffee growing experience of 37 years and 9 years of education, obtained an average efficiency of 81% with a deviation of 0.029, a minimum of 77% and a maximum of 84%. Its productivity levels were the lowest for the period of analysis (2015–2021), on average 1586.5 kg of dry parchment coffee per hectare (21 bags of green coffee per hectare); however, these levels were higher than the national average of 1400 kg/cps/ha.

- Characteristics of production systems. The average area of the farms established with resistant varieties was 82%, the average planting density was 5655 trees per hectare, the average age of the trees was 3.63 years, and the average percentage of area for renewed coffee (unproductive stage) was 16%.
- Resource allocation. The application of 807 kg of fertilizer per hectare per year stands out, an amount 32% lower than the application of the group of coffee growers with an efficiency greater than 90%, but at a cost greater than 21% due to their criteria for carrying out this work—mainly, the sources of fertilizer used and a greater fractionation (frequency) of application. The coffee growers grouped at this level of efficiency stated that they did not apply lime to adjust the acidity of the soil.

Due to lower planting densities and the lack of replanting to replace lost sites, weed management had a resource allocation 64% higher than the value invested by coffee growers with a higher level of efficiency.

Despite having a higher proportion of area in varieties susceptible to rust, the resources destined for phytosanitary control were 35% lower than those of the other producers.

The plant material used for renewal by sowing was mainly commercial colino, seed extracted from the lots of the farms and other colinos supplied by the Committee of Coffee Growers.

Finally, the unit cost of production in the study period (2015–2021) was higher by 10% and 19% compared to the intermediate and higher efficiency groups, respectively (Perdomo et al. 2007). Data envelope analysis, whose purpose was to determine the efficiency of coffee producers in the central coffee zone, showed generally low levels of productivity and high production costs, mainly due to errors in the allocation of resources.

4.3.2. Economic Efficiency Greater Than 85% and Less Than 90%

In total, 35% percent of the coffee growers (48) studied were classified in this efficiency range, with an average of 88%, a deviation of 0.013, a minimum of 85% and a maximum of 89.9%. The average productivity of this group was 2260.25 kg/cps/ha (30 bags of green coffee/ha).

- Characteristics of production systems. The average area sown with resistant varieties was 91%, the average planting density was 6615 trees per hectare, the average age of the trees was 3.65 years, and the average area for renewed coffee (vegetative growth) was 18%.
- Resource allocation. The coffee growers grouped at this level of economic efficiency applied 964 kg of fertilizer on average per hectare per year, mainly using fertilizers with a recommended grade for coffee cultivation and physical mixtures of urea, dap and KCl. They performed soil analysis every 2 years; based on these results, they corrected the acidity of the soils using dolomite lime. For renewal by sowing and replanting, they used plant material supplied by the Coffee Growers Committee (28%) and certified seed (72%) for the purpose of preparing the seedlings on their farms.

4.3.3. Economic Efficiency Greater Than 90%

The average productivity for this group was 2881.13 kg/cps/ha (38 green coffee bags/ha). Eighty coffee growers (59%) obtained efficiency scores of 91.5% on average with a deviation of 0.009, a minimum of 90.05% and a maximum of 94.6%. This result is higher than that reported in a study in Brazil, where 28.2% of the coffee growers studied reached levels of economic efficiency greater than 90% (Freire et al. 2011). The same study performed data envelopment analysis (DEA), establishing an average economic efficiency of 64.08% where the proportion of producers who reached levels of efficiency equal to or greater than 90% was 13.4% (Freire et al. 2012).

- Characteristics of production systems. The following averages were found: established area with resistant varieties, 96%; average planting density, 6695 trees per hectare; average age of trees, 3.27 years; and average area for renewed coffee, 21%. These figures reflect production systems with a lower risk of coffee rust and greater productive potential due to their greater number of trees per hectare and the lower age of these trees, confirmed by production cycles defined in fifths due to their renovated area or in lift. In northern Rwanda (Ngango and Kim 2019), the use of resistant varieties mainly has a positive effect on the technical efficiency of coffee growers. The characteristics of this group with higher levels of productivity and efficiency coincide with the results of Araque Salazar and Duque (2019), i.e., maximum partial elasticities correspond to the variables coffee plantation density (trees/ha) and fertilization level (kg ha-year-1 of fertilizer). Likewise, crop age, the percentage of resistant varieties and the growing area are determinants of productivity for the group of coffee farms analyzed. The results for this group of efficient coffee growers coincide with the technical characteristics of small coffee growers in Vietnam who have developed sustainable coffee farming and for whom the renewal of crops and the use of resistant varieties and fertilization practices are fundamental in the productive performance and economic efficiency of their crops (Hung Anh et al. 2019).
- Resource allocation. This group presented the highest amounts of fertilizer (1067 kg), applied on average per hectare per year; however, its fertilization costs were 21% and 10% lower than those of the coffee growers with low and medium efficiencies, respectively. Fertilization decisions were based on the results of soil analysis and the recommendations of an extension service technician (79%). The application of fertilizer was divided into two applications during the year, and the sources used were mainly a mixture of urea, dap, KCl and formulas with degrees for the cultivation of coffee

(78%). In the same sense, decisions on the execution of agronomic practices such as the renewal of coffee plantations, replanting, weed management, sanitary management, correction of soil acidity, and the opportunities to apply them, among this group of coffee growers were framed by technical recommendations.

### 4.4. Socioeconomic Characteristics and Resource Allocation

For the three efficiency levels in which the coffee growers were grouped, the socioeconomic characteristics of age, coffee growing experience and years of schooling were similar: the average age was 57 years in the lowest efficiency group (<85%), 65 years in the intermediate group (85–90%) and 61 years in the group of coffee growers with efficiency greater than 90%. For all three groups, the average experience in coffee farming was 37 years, while the average years of schooling were 9 years for the least efficient group and 8 years for the two more efficient groups.

These socioeconomic variables did not constitute a differentiating factor that conditioned economic efficiency. In contrast, in Poudel et al.'s (2015) study in Nepal concerning the technical efficiency of organic and conventional coffee growers, when relating these performance levels with their production systems, the authors find that any variations in efficiency were mainly due to the educational level and coffee experience of the producers, reflected in their access to extension services and credit.

Likewise, Tran et al. (2021), evaluating the efficiency in the use of water for irrigation among 194 coffee growers in Lam Dong Province in Vietnam, have shown that the amount of water used could be reduced by 25% without reducing the productivity of robusta coffee and that coffee growing experience, education level and contact with extension significantly affect levels of efficiency.

The allocation of resources among the group of coffee growers in Caldas in the evaluated period was more conditioned according to the criteria used to define the production systems, the opportunity in the performance of agronomic practices, and the selection of inputs, especially fertilizers, such as the use of available technologies. Similarly, Ho et al. (2022), analyzing 900 farms in Vietnam, have determined that the appropriate use of the technologies available for irrigation (sprinkling, microsprinkling, and microbasins) is more decisive in water efficiency than sustainable coffee certification, education level or coffee growing experience. Furthermore, farms that use sprinkler systems show higher efficiencies than those that use microbasin irrigation.

Another aspect to highlight regarding the 136 coffee growers is that all of them referred to the support of an extension service. However, when determining planting density, the time and type of renewal and the sources and fractionation of the crop, the fertilization coffee growers with efficiency levels lower than 85% stated that their coffee growing experience prevailed in their decision making. Likewise, 100% of the coffee growers stated that they had access to credit, although 20% of them did not use it during the study period.

Studies carried out in Vietnam and Rwanda underscore the need for improvements in education, support extension services, and access to credit; these additional measures could contribute to strengthening the management capacity of coffee growers and, in this way, allow them to achieve higher efficiency levels (Hung Anh et al. 2019; Ngango and Kim 2019).

## 5. Conclusions

The results obtained suggest that the technical inefficiency in the production cost function of the focal Caldas coffee growers and the estimation of an efficiency frontier should be considered.

The model that presents the best fit is that proposed by Green (2005). The "true" random effects model assumes that all inefficiency of coffee growers is susceptible to variation over time, since the allocation of resources changes each year according to the management of the coffee company, whereby there are no structural inefficiencies that cannot be corrected during the analysis period.

Importantly, the results of the estimations have not established the effect of the environmental variables grouped in the aptitude index on technical efficiency; 96% of the farms registered a high aptitude for coffee cultivation.

Classification by efficiency allows us to conclude that the coffee growers in the study with efficiency values higher than 90% have an average productivity level 82% and 27% higher than those of the coffee growers with efficiencies lower than 85% and between 85% and 90%, respectively, indicating that a planned and precise allocation of resources results in higher productivity and lower unit production costs.

The age of the coffee growers, their years of schooling and their years of coffee growing experience were similar among all the coffee growers that made up the three efficiency categories.

Differences were observed in the allocations of resources, both to define the production systems and for the execution of agronomic tasks, among the coffee growers in the different categories of economic efficiency.

The least efficient coffee growers (<85%) presented higher unit costs, by 19.6%, and their productivity represented 55%, compared to the figures obtained by the most efficient coffee growers in the study period.

The characteristics of the production systems, mainly planting density, percentage of the area established with resistant varieties, percentage of area in harvest, and average age of trees, conditioned the technical efficiency of the coffee growers.

The resources allocated to the collection of coffee, to the fertilization of the crop—especially in the sources of fertilizer used and in the fractionation in the applications—to administrative expenses, and to weed management significantly influenced the allocative efficiency of the producers.

Defining the production systems by considering the perennial condition of the crop supposes long-term decisions that combined with agronomic practices condition productive performance.

With the available technologies, the focal coffee growers have the ability to increase their levels of efficiency and productivity, reducing their unit production costs.

The results of this work may be useful in focusing the accompaniment of the extension service and the educational work strategies in such a way that they contribute to the decision making of the coffee growers in their allocations of the resources available to them, enabling improvements in efficiency and in productivity while reducing production costs.

Although the findings of the work contribute to the understanding of the problem of efficiency in coffee production, they cannot be generalized. A limiting factor for the development of the work was having more producers who recorded information on their production costs (one of the primary sources of information on the work) over the years.

Therefore, future research should consider a larger sample of farmers covering all provinces in Colombia.

In future work, it is advisable to delve deeper into constructing indices with environmental variables that can differentiate between the different areas dedicated to coffee production and measure their effect on technical efficiency.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/economies11100255/s1, Figure S1. Number of coffee growers per municipality that participated in the study; Table S1. Economic variables of coffee production; Table S2. Technological variables considered in the study; Table S3. Multiple regression results of the selected model for coffee growing in Caldas for the period 2015/2021; Table S4. Stochastic frontier, true fixed-effects model (exponential) in the Caldas coffee growers data panel.

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