

Technical Efficiency Estimation of Rubber Farming in Thailand

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Abstract

This study investigates the technical efficiency of rubber production among Thai rubber farmers and identifies the factors influencing both rubber production quantity and efficiency. A stochastic production frontier model was employed using 14 years of data from the Economic and Agricultural Household Survey, combined with sub-district weather data. The findings highlight the significant impact of agricultural production costs and plantation area on rubber production at both national and regional levels. While agricultural asset values and the number of workers were statistically insignificant, Thai rubber farmers operate at an average of 67% of their potential production efficiency. The North region exhibited the lowest efficiency, whereas both the North and Northeast demonstrated the greatest potential for improvement relative to the national frontier. Climate factors and farm practices were identified as consistent determinants of inefficiency. Policymakers can enhance rubber production efficiency by targeting key interventions, such as climate-smart agriculture practices and improved farm management, to align with the Sustainable Development Goals.

Keywords: Rubber farming, Agricultural households, Efficiency, Climate change, Irrigation, Sustainable Development Goals (SDGs).

1. Introduction

Rubber has been a vital commodity for Thailand's economy for decades. Its latex, a key ingredient in various products ranging from tires to medical supplies, generates substantial income through both domestic processing and international exports. However, the industry faces challenges such as fluctuating market prices, climate change, and inefficient farming practices.

To ensure the sustainability and competitiveness of the rubber sector, it is crucial to understand the factors influencing rubber production efficiency. This study aims to investigate the technical efficiency of rubber production among Thai farmers and identify the key determinants of both production quantity and efficiency.

Under a production function framework, the output variable is the quantity of rubber production, while the production inputs include various types of production costs, labor, and the size of the rubber cultivation area. Analyzing the productivity of rubber farmers is a critical policy concern. Studying technical efficiency and its determinants provides valuable insights for policymakers. This information can be used to develop programs that promote more efficient rubber cultivation among farmers, ultimately benefiting both their income and the overall rubber industry. To measure technical efficiency, the Stochastic Frontier Analysis (SFA) model is employed. Developed by Aigner, Lovell, and Schmidt (1977), Meeusen and van den Broeck (1977), and Battese and Coelli (1995), SFA is a robust method that utilizes maximum likelihood estimation (MLE) to account for both random errors and technical inefficiency in production. This approach has been widely adopted in agricultural economics, making it well-suited for analyzing rubber farmer productivity.

Several studies in Thailand have employed SFA to analyze the rubber production efficiency, particularly in the Northeastern region (Rungsuriyawiboon, 2012; Pongchompu and Chantanop, 2015; Kittilertpaisan et al., 2016) and the upper Northern region (Phratriya, 2008). These studies consistently identify factors, such

as, the number of workers, planting area, tapping area, and tapping time as significantly impacting rubber production (Kittilertpaisan et al. 2016; Phratriya, 2008). However, the effect of fertilizer remains inconclusive, with Phratriya (2008) finding a positive effect of fertilizer, and Kittilertpaisan et al. (2016) reporting no significant effect.

Northern studies in Thailand's Northeastern region reveal a production efficiency range of 57% to 69% (Rungsuriyawiboon, 2012; Poundchompu & Chantanop, 2015; Kittilertpaisan & Khatiwat, 2016). These studies also identify several determinants of production efficiency. Rubber tree age is a positive determinant, with older trees yielding more efficiently (Poundchompu & Chantanop, 2015; Kittilertpaisan, Kittilertpaisan, & Khatiwat, 2016). Findings on farmer education are mixed, with some studies suggesting a negative impact (Phratriya, 2008; Rungsuriyawiboon, 2012; Kittilertpaisan et al., 2016) and others finding a positive correlation (Poundchompu and Chantanop, 2015). Farmer experience generally positively impacts efficiency (Rungsuriyawiboon, 2012; Kittilertpaisan et al., 2016), although Phratriya (2008) found an opposing effect. Rainfall has a positive effect, while high temperatures negatively impact efficiency (Rungsuriyawiboon, 2012).

Existing literature reveals a significant gap in research on the technical efficiency of rubber production among rubber farmers nationwide in Thailand. This study aims to address this gap by employing a stochastic production frontier model to analyze data collected from surveys conducted by the Office of Agricultural Economics (OAE), the Ministry of Agriculture and Cooperatives. The dataset, comprising economic and social conditions of households and agricultural labor, consists of 14 years of cross-sectional agricultural household data (2006/2007-2019/2020), with 9,670 rubber-farming household samples. This nationally representative dataset enables a comprehensive nationwide analysis

of technical efficiency. Furthermore, the study will classify efficiency levels by region to gain valuable insights into regional variations.

The objective of this research project is to identify and analyze the factors that significantly impact the production of natural rubber in Thailand. This includes determining which factors have the greatest influence on both production quantity and efficiency across regions. The findings of this study will provide insights for policymakers, agricultural extension services, and farmers to develop strategies that enhance rubber production, improve farmers' livelihoods, and contribute to the overall economic growth of Thailand as one of the world's largest rubber producers.

2. Theoretical Framework

This research employs the stochastic production frontier model developed by Aigner, Lovell, and Schmidt (1977), Meeusen and van den Broeck (1977), and Battese and Coelli (1995) to analyze the economic production function of rubber production. The stochastic frontier analysis, or SFA, allows us to estimate the maximum attainable level of rubber production, which represents the highest potential output achievable given a specific set of inputs. However, various factors can hinder rubber production from reaching this maximum efficiency.

The difference between the maximum attainable production level on the frontier and the actual production level achieved by farmers represents production inefficiency. This inefficiency represents an opportunity to increase production efficiency. The MLE method separates the composite error term into two components: the uncontrollable random error term (v_i) and the one-sided *technical inefficiency* term (u_i). This allows for the measurement of agricultural production efficiency by comparing actual production to the theoretical maximum level identified by the frontier.

We considered the stochastic production frontier model in the logarithmic form as follows.

$$\ln(y_i) = \alpha + x_i'\beta - u_i + v_i, \quad i = 1, 2, \dots, n, \quad (1)$$

where $\ln(y_i)$ is the natural logarithm of the output of production unit or household i ,

α is a constant parameter representing an intercept,

β is a vector of coefficient parameters for the production factors,

x_i is a vector of production factors of production unit or household i ,

u_i is the stochastic error term representing the controllable inefficiency and can only take positive values. It is assumed to have an independent and identical exponential distribution, $u_i \sim \exp(\sigma_u)$. The term u_i in the model represents technical inefficiency, which indicates how poorly a production unit or household is using its inputs to produce outputs.

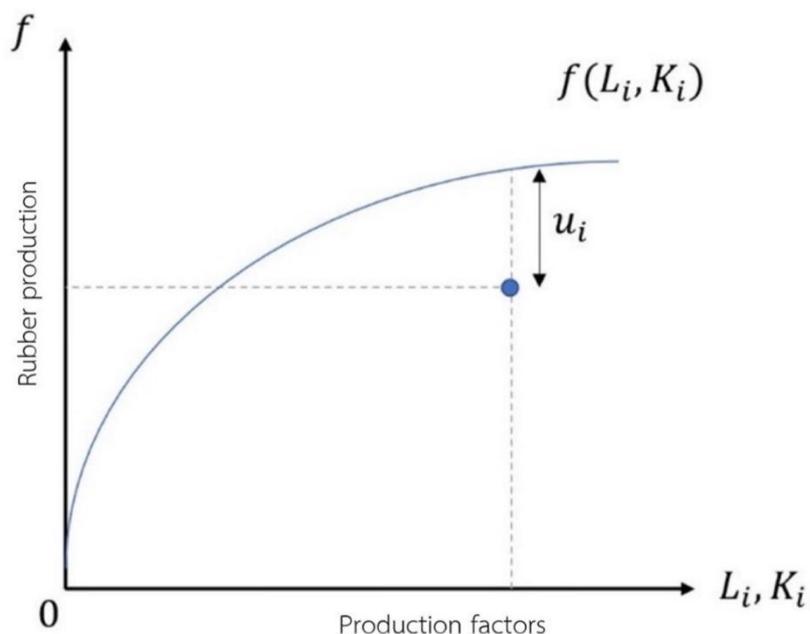
v_i is the stochastic error term representing the uncontrollable random effects, which can be positive or negative. It measures the unexpected factors impacting production. It is assumed to have an independent and identical normal distribution with a mean of zero and a constant variance, i.e. $v_i \sim N(0, \sigma_v^2)$ for all $i = 1, 2, \dots, n$ and it is also assumed to be independent with u_i .

In summary, we can separate the disturbance into two independent parts: the part that cannot be controlled and the part that can be controlled. The controllable part represents technical inefficiency, which measures the production efficiency of farmers compared to the production that is technically efficient or at the highest level.

Figure 1 illustrates the economic production function, where f represents the production frontier or the maximum possible production level. However, there may be a production output level at the blue dot or the level of production, denoted as y_i , given certain production inputs. The difference between the production frontier and

the actual production level is the disturbance term, which indicates technical inefficiency and can be measured by the gap level of u_i .

Figure 1. An illustrative example of stochastic frontier production function



Source: Authors

The analysis of stochastic production frontier model reveals technical inefficiency, as demonstrated by Battese and Coelli (1995) who have shown that technical inefficiency can be explained by its determinants.

$$u_i = z_i' \delta + w_i, \quad i = 1, 2, \dots, n, \quad (2)$$

where z_i is the vector of exogenous factors explaining technical inefficiency,

δ is the vector of coefficient parameters for the exogenous factors,

w_i is the stochastic error term of technical inefficiency which is assumed to have an independent and identical distribution with zero mean and constant variance.

Technical efficiency (TE) can be measured as follows:

$$TE_i = \frac{y_i}{y_i^*} = \exp(-u_i), \quad i = 1, 2, \dots, n, \quad (3)$$

where y_i^* represents the output generated at full technical efficiency of production unit or household i , i.e., the output on the production frontier or the highest possible output level estimated at the combination of production factors of production unit or household i . Hence, TE values always range between zero and one.

3. Methodology

3.1 Model specification

This research employs the stochastic production frontier model to analyze the technical efficiency of rubber plantation households in Thailand. The model investigates the relationship between rubber production quantity and various production inputs, such as labor, land, and capital factors. The model is based on the Cobb-Douglas function, which is relatively simple and straightforward. The Cobb-Douglas functional form is appropriate for modeling rubber production due to its ability to capture the fundamental characteristics of agricultural production processes. Its multiplicative nature reflects the complementarity between inputs (land, labor, and capital) in rubber cultivation, while its structure accounts for diminishing marginal returns that are typical in agricultural production. The log-linear functional form provides easily interpretable elasticity coefficients. Furthermore, our finding that the null hypothesis of constant returns to scale is rejected validates the flexibility of this specification in capturing the reality of rubber production, where scale effects are significant.

This study employs a two-step stochastic production frontier approach (Huang and Liu, 1994; Rungsuriyawiboon, 2012, for example). First, we calculate

the optimal values for model parameters (such as production function coefficients and error terms) by maximizing a statistical log-likelihood function of the stochastic frontier production model. In the second step, we determine the inefficiency level of each production unit by measuring the difference between its actual output and the predicted output based on the estimated parameters. Therefore, we can regress the estimated inefficiency with the potential covariates to explore the associations between the weather, household, and farm characteristics and the production inefficiency.

The stochastic production frontier model for rubber production quantity of Thai agricultural households, using the standard Cobb-Douglas model in the natural logarithmic form. The output variable y is the quantity of rubber production measured in kilograms. There are four input variables related to production factors: number of workers, rubber plantation area measured in *rai* (~0.395 acres), cost of agricultural production for rubber, and agricultural asset value. The regression model can be expressed as:

$$\ln(y_i) = \beta_0 + \sum_{j=1}^J \beta_j \times \ln(x_i^j) + \beta_{trend} \times trend + \beta_{trend^2} \times trend^2 + (regional/provincial\ dummies\ terms) - u_i + v_i, \quad (4)$$

$$i = 1, 2, \dots, n,$$

where the beta coefficients represent the parameters to be estimated, which describe the relationships between the input variables (production factors) or control variables and the output variable, which is the rubber production quantity. These slope coefficients indicate the direction and magnitude of the relationships between each input variable and the production output. The interpretation of input slope coefficients is elasticity, because both the dependent and independent variables are logarithmically transformed into the log-log regression model. To control unobserved temporal and spatial factors, we incorporate control variables, such as time trend and its squared, and province/region dummy variables, into the first-step

model. The quadratic time trend serves as a proxy of agricultural technology progress (Attavanich and McCarl, 2014; Jithitikulchai, McCarl, & Wu, X., 2019; Jithitikulchai, 2023; Prommawin et al., 2024 among many others). The estimation of these parameters is typically done using the maximum likelihood estimation (MLE) method.

The estimated values of u_i from the above regression can be used to analyze the factors that explain the inefficiency in rubber production or cultivation among farmers. The equation represents the specification of technical inefficiency in rubber production, and the analysis of factors influencing inefficiency can be conducted using linear regressions. Following Kumbhakar, Ghosh, and McGuckin (1991) and Huang and Liu (1994), we use linear regression function as follow:

$$\ln(u_i) = \delta_0 + \sum_{k=1}^K \delta_k \ln(z_i^k) + w_i, \quad i = 1, 2, \dots, n, \quad (5)$$

where z 's are explanatory variables such as weather, household, and farm characteristics in Table 1. We explored the available variables from the survey questionnaire that fundamentally provide sensible reasoning for explaining the inefficiency and retained the statistically or conceptually significant ones. Economic theories and empirical studies have shown that factors such as production costs, asset value, and labor availability significantly influence rubber production (Phratriya, 2008; Rungsuriyawiboon, 2012; Dudu et al., 2015). There are literatures on stochastic production function using expenditure costs as inputs (Rahman et al., 2012; Bukenya et al., 2013; Tleubayev et al., 2017 among others), in addition to labor and land used for stochastic production frontier analysis of farmers. Human capital, including the characteristics of the household head (gender, age, and education), can play a role in production efficiency (Phratriya, 2008; Wijit et al., 2019). Climatic conditions, particularly temperature and rainfall, directly affect rubber growth and development (Thaiburi et al., 2021). Both access to and management of water resources, as well as agricultural practices such as integrated

farming, are also hypothesized to influence the rubber output of farmers. Some variables, such as education and climate, were previously used in Rungsuriyawiboon (2012). Because u_i is non-negative and captures inefficiency, a positive slope coefficient indicates that an increase in the covariate factor leads to an increase in inefficiency. On the other hand, a negative coefficient suggests a decrease in inefficiency. Thus, negative signs are preferable for the second-step slope coefficients.

The stochastic production frontier model estimates technical efficiency and input elasticities, allowing for variability in production inefficiencies across farmers. Key inputs considered in the model include the number of workers, rubber plantation area, agricultural production costs, and the value of agricultural assets. Elasticities of input vectors were derived from the estimated slope coefficients of the national-level model as an econometric log-linear form. To validate the model specification and assess the production technology characteristics, three statistical tests were conducted. First, a Wald test was examined for the hypothesis of constant returns to scale by testing whether the sum of input elasticities equals one (Wald, 1943). Second, the stochastic frontier estimation provided input elasticity coefficients. The delta method was applied to compute the total returns to scale and its associated standard error (Greene, 2018). Thus, we can calculate scale elasticity at means to measure how output changes when all inputs are increased proportionally at the same time. Finally, the model's specification was verified using the Ramsey Regression Equation Specification Error Test (RESET) test (Ramsey, 1969), which examines the presence of omitted variables by testing whether nonlinear combinations of the fitted values help explain the response variable. All of these enabled more confidence in evaluating the production elasticity of each input and the overall return to scale, providing insights into the factors driving productivity among Thai rubber farmers.

For inference, we used robust standard errors to account for potential heteroskedasticity (White, 1980) in equations (4)-(5) and the return to scale. As shown in Appendices, we check robustness of results from exploring combinations of covariates in both equations.

3.2 Data

The household data of rubber farmers used in this research is obtained from the Office of Agricultural Economics, Ministry of Agriculture and Cooperatives of Thailand. It is derived from the Economic and Agricultural Household Survey, covering the period from the planting year 2549/50 BE to 2562/63 BE (2006/2007 to 2019/2020). The dataset consists of 14 years of cross-sectional data, linking the sub-district level information with weather data from the ERA5 reanalysis database provided by the European Center for Medium-Range Weather Forecasts (ECMWF).

The historical reanalysis data used in this research provides weather conditions at a spatial resolution of 0.1 degrees, which is approximately 9 square kilometers. The data is averaged at the sub-district level, and the frequency of the data is annually, corresponding to the start and end periods of each survey year. These time intervals align with the agricultural planting season of the surveyed household sample in the Economic and Agricultural Household Survey conducted by the Office of Agricultural Economics (Prommawin et al., 2022).

This paper aims to utilize data on the socio-economic conditions of households and agricultural characteristics. The data includes detailed information on the agricultural households, such as production output, number of workers, plantation area, and relevant cost expenditure for agricultural activities such as crop cultivation. This data also includes household demographics and other farm characteristics,

Data on rubber cultivation households used for the nationwide study consists of a total of 9,670 households, covering four regions of Thailand: Central, North,

Northeastern, and Southern. When considering the Southern region, this research has divided the area based on meteorological conditions according to the Center for Agricultural and Agro-Industrial Emergency Management and Solution of the Ministry of Agriculture and Cooperatives. It is divided into:

- (i) Eastern coast of the Southern region or the Gulf of Thailand coast,
- (ii) Western coast of the Southern region or the Andaman Sea coast.

This division is appropriate for examining the rubber cultivation quantity in relation to rainfall patterns, because the Eastern coast of the Southern region tends to have higher rainfall compared to the Western coast of the Southern region.

To ensure comparability over time, all monetary variables are expressed in constant 2019 Thai Baht. This accounts for changes in input prices affecting production costs. Costs associated with agricultural production and land used exclusively for rubber production are identified by the rubber product survey classification code.

We included years of the country-wide effects of the 2011 major flood and 2015 severe drought as dummy variables. Given that one-fifth of rubber farm households in our sample also engage in rice cultivation and considering the Thai government's frequent interventions in the rice market, we incorporated a dummy variable indicating whether rubber farmers have rice production in their crop portfolio.

Table 1 presents the descriptive statistics of the rubber production output variable, the four production factors, and other variables employed in the inefficiency study. The data are organized into panels, including production quantity, inputs, weather conditions, household characteristics, and farm characteristics which collectively contribute to understanding rubber production.

Table 1. Descriptive statistics of rubber production variables in all regions of Thailand

Variables	N	Mean	SD	Min	Max
<i>Panel A: Production quantity</i>					
Rubber production quantity (kilograms)	9,670	5,032	17,918	1	1,522,800
<i>Panel B: Inputs</i>					
Number of workers	9,670	2.23	0.99	1	8
Rubber plantation area (rai/~0.395 acres)	9,670	16.8	16.9	0.5	400.0
Cost of agricultural production for rubber (2019 THB)	9,670	62,788.9	118,298.3	59.7	3,847,832.5
Agricultural asset value (2019 THB)	9,670	84,117.6	429,351.8	12.0	30,218,702.0
<i>Panel C: Annual weather (Efficiency regression)</i>					
Average annual temperature (°C)	9,451	26.0	0.8	22.2	28.1
Total annual rainfall (inches)	9,451	1,200.6	343.0	478.1	2,668.9
Number of hot days (max temp>32.22°C)	9,451	1.1	3.5	0	33
Number of wet days (total precipitation>1 inch)	9,451	1.8	1.9	0	23
<i>Panel D: Household characteristics (Efficiency regression)</i>					
Gender of household head (female=1)	9,451	20%	40%	0%	100%
Elderly household head (age over 65=1)	9,451	22%	42%	0%	100%
Education of household head (complete lower secondary or higher=1)	9,451	32%	47%	0%	100%
Household size	9,451	4.4	1.7	1.0	14.0
<i>Panel E: Farm characteristics (Efficiency regression)</i>					
Cultivation Year 2014/2015	9,451	8%	28%	0%	100%
Cultivation Year 2011/2012	9,451	7%	25%	0%	100%
Proportion of land accessed for irrigation (percentage)	9,451	7%	23%	0%	100%
Main water source (rainwater=1)	9,451	93%	25%	0%	100%
Main water source (pond/reservoirs/wells=1)	9,451	7%	25%	0%	100%
Main water source (extracted from natural sources=1)	9,451	7%	25%	0%	100%
Practice monoculture (rubber plantation only=1)	9,451	35%	48%	0%	100%
Engage in growing rice (yes=1)	9,451	22%	41%	0%	100%
Share of rented land (percentage)	9,451	2%	10%	0%	100%
Agricultural debt (has debt = 1)	9,451	43%	50%	0%	100%
BAAC (membership=1)	9,451	46%	50%	0%	100%

Co-operative Members (membership=1)	9,451	7%	26%	0%	100%
Agricultural/Saving Group (membership=1)	9,451	9%	29%	0%	100%

Note: The unit of observation is household. THB was approximately 31 USD in 2019. BAAC stands for the Bank for Agriculture and Agricultural Cooperatives.

Source: Authors' calculations.

4. Estimation Results

The data used in this study covers rubber production across Thailand from 2006/2007 to 2019/2020 (2549/50 BE to 2562/63 BE), spanning 14 years. The data includes variables representing rubber production quantity, production factors, and external temporal and spatial factors influencing rubber production.

Production Frontier Analysis

Our models incorporate input variables for rubber plantations, such as the number of workers, land area of rubber plantation, cost expenditure for rubber, and agricultural machinery and equipment. Table 1 presents these output and input variables, which are valuable for informing decisions on adjusting production factor proportions to optimize rubber production yields. To ensure statistical robustness, we conducted control variable combinations testing and included location and time controls for spatial and temporal heterogeneity.

The estimation results of the Cobb-Douglas production function in logarithmic form, presented in Table 2, indicate that rubber production in Thailand is primarily driven by the area of rubber plantations and agricultural production costs, both of which exhibit a strong positive impact across regions. While the elasticity of plantation area remains consistently high, the significance of production costs varies, suggesting that financial inputs play a crucial role in certain regions. Moreover, the number of workers and the value of agricultural assets demonstrate less consistent or significant impacts on rubber production.

Nationally, rubber production shows a declining trend over time, although a small positive quadratic term suggests a potentially slowing decline. Regionally, time trends vary, with some regions experiencing positive or negative effects. The Southeast region exhibits a negative linear trend, contributing significantly to the national decline. In contrast, the Central region shows a positive linear trend with a slight downward slope, while the North region demonstrates a strong positive trend.

Our findings align with previous research by Wijit et al. (2019), Dudu, H. (2015), Phratriya (2008), and Rungsuriyawiboon (2012). These studies consistently found positive coefficients for agricultural expenses, capital variables, and specific input costs like seed, electricity, and animal feed. Our results validate that increases in these variables are significantly associated with higher agricultural production.

Table 2. Estimation results of the stochastic production frontier function

Dependent variable: ln (Rubber production quantity)	Thailand	Central	Northeast	Southeast	Southwest	North
Time	-0.019* (0.019)	0.084** (0.007)	0.011 (0.595)	-0.043*** (<0.001)	0.026 (0.142)	0.766*** (<0.001)
Time, squared	0.003*** (<0.001)	-0.004* (0.034)	0.003** (0.010)	0.004*** (<0.001)	-0.001 (0.588)	-0.032** (0.003)
ln (Number of workers)	0.027 (0.094)	-0.035 (0.546)	0.009 (0.780)	0.052* (0.022)	0.050 (0.125)	-0.082 (0.687)
ln (Rubber plantation area)	0.697*** (<0.001)	0.689*** (<0.001)	0.690*** (<0.001)	0.698*** (<0.001)	0.637*** (<0.001)	0.963*** (<0.001)
ln (Cost of agricultural production)	0.064*** (<0.001)	0.102*** (<0.001)	0.086*** (<0.001)	0.059*** (<0.001)	0.072*** (<0.001)	0.012 (0.883)
ln (Agricultural asset value)	0.005 (0.279)	0.008 (0.679)	0.013 (0.183)	0.006 (0.323)	-0.007 (0.546)	0.009 (0.816)
N (sample households)	9,670	897	2,628	4,153	1,710	282

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. All regression models include region/province dummy variables. Robustness checks are available in Tables A1-A6 in Appendix I. Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Technical Efficiency Analysis

The efficiency of rubber cultivation in Thailand and its regions can be assessed using the stochastic production frontier model. This model enables us to calculate technical efficiency (TE), a metric ranging from 0 to 1 that evaluates how effectively rubber farmers utilize their inputs to produce output. A TE value of 1 indicates optimal efficiency, while a TE value of 0 signifies the lowest level of efficiency.

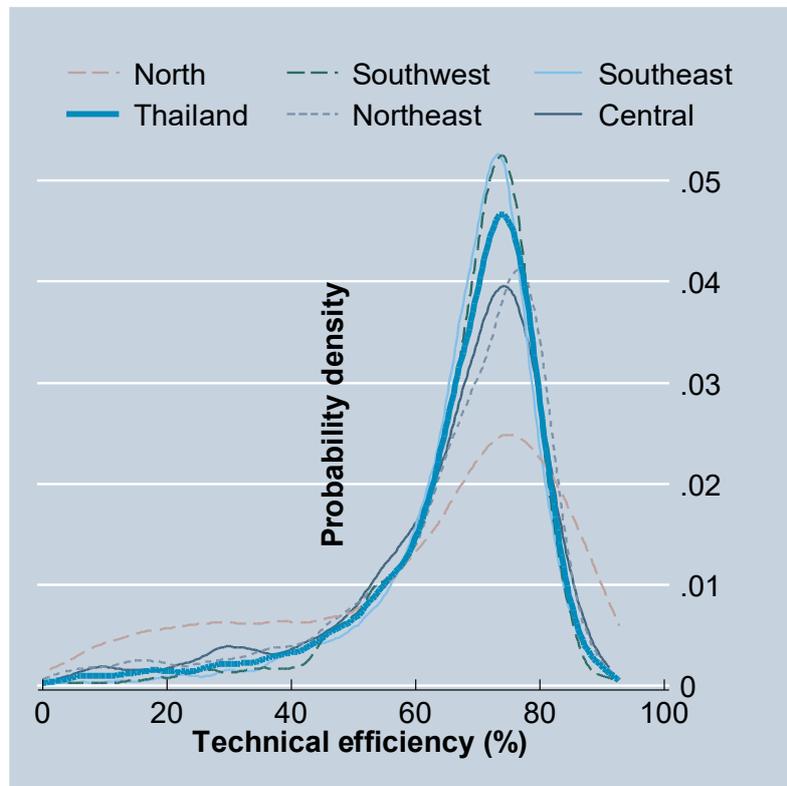
The average TE of rubber production in Thailand is approximately 67%, with a median value of 71%. This indicates an average potential for efficiency improvement of around 33%, suggesting a significant gap between current production levels and the maximum attainable output, based on an average technical efficiency of approximately 67%.

The production efficiency of each region is summarized in Table A7 in Appendix II. The table reveals that the significant regional variations. The North region exhibits the lowest average efficiency at 61%, while both the North and Northeast regions demonstrate the greatest potential for improvement. Although the overall median efficiency is relatively consistent at 70%, targeting the underperforming farmers in the North and Northeast could substantially enhance national productivity, as these regions lag behind other regions.

The maximum–minimum efficiency gap further underscores significant regional disparities, particularly in the North, where efficiency ranges from a low of 6% to a high of 92%. This wide range highlights unequal access to resources and practices. Both the North and Northeast regions share notable inefficiencies at the lower end of distributional percentiles, with some farmers performing poorly compared to their peers in other regions. Addressing these regional disparities by focusing on underperforming areas could help bridge the efficiency gap and improve overall productivity in Thailand's rubber farming sector. The distribution pattern of

technical efficiency on a regional basis, compared to Thailand, can be illustrated through kernel density estimates plotted in Figure 2.

Figure 2. Probability density function estimates of technical efficiency



Note: Kernel density estimates using Epanechnikov kernel with optimal bandwidth.
 Source: Authors' calculation.

The estimated value of technical inefficiency in rubber cultivation by farmers, denoted as \hat{u}_i , can be analyzed to identify factors influencing inefficiency using regression analysis. Factors influencing technical inefficiency in rubber production are assessed based on the estimated slope coefficients derived from the inefficiency equation (5). A negative slope coefficient suggests that the corresponding factor reduces technical inefficiency in rubber production. Conversely, a positive slope coefficient indicates that the factor contributes to increasing technical inefficiency.

Key findings from Table 3 reveal that technical inefficiency in rubber production is influenced by several factors. Average annual temperature significantly reduces inefficiency in Thailand, particularly in the Northeast and

Southeast regions, where higher temperatures (within the range of 22.2-28.1 °C) are beneficial. However, a diminishing returns effect is evident, as the squared term of temperature shows a positive relationship. Rainfall exhibits mixed effects, with only slight significance in certain regions. The number of hot days generally reduces inefficiency in the Central and Northeast regions, while the number of wet days is not significant. The impacts of the 2011 major flood and 2015 severe drought on inefficiency vary across regions.

Farm practices like monoculture and growing rice also impact inefficiency, with monoculture generally reducing inefficiency. Additionally, factors such as the gender of the household head, membership in cooperative groups, and the main water source contribute to technical inefficiency, although their effects vary by region. Overall, climate factors and farm practices emerge as the most consistent determinants of inefficiency in rubber production.

Table 3. Estimation results of the technical inefficiency regression

Dependent variable: ln (Technical inefficiency)	Thailand	Central	Northeast	Southeast	Southwest	North
Average annual temperature (Celsius)	-1.370*** (0.001)	-1.504 (0.091)	-2.593*** (0.001)	-1.537* (0.016)	1.042 (0.421)	0.647 (0.623)
Average annual temperature squared (Celsius squared)	0.026*** (0.001)	0.029 (0.090)	0.051*** (0.001)	0.030* (0.015)	-0.021 (0.403)	-0.013 (0.622)
Total annual rainfall (Inch)	-0.006* (0.025)	0.009 (0.322)	-0.009 (0.145)	0.010* (0.037)	0.004 (0.684)	0.021 (0.496)
Total annual rainfall squared (Inch squared)	0.000* (0.047)	-0.000 (0.289)	0.000 (0.180)	-0.000 (0.156)	-0.000 (0.783)	-0.000 (0.421)
Number of hot days in a year	-0.004 (0.068)	-0.065** (0.009)	-0.009** (0.002)	-0.028 (0.559)	n.a.	0.008 (0.485)
Number of wet days in a year	-0.001 (0.740)	0.006 (0.601)	-0.011 (0.276)	-0.006 (0.192)	0.008 (0.339)	0.005 (0.841)
Cultivation Year 2014/2015	-0.012 (0.572)	-0.046 (0.414)	-0.098* (0.013)	-0.006 (0.820)	0.101 (0.053)	0.312* (0.028)

Dependent variable: ln (Technical inefficiency)	Thailand	Central	Northeast	Southeast	Southwest	North
Cultivation Year 2011/2012	0.098*** (<0.001)	0.125 (0.066)	0.234*** (0.001)	0.033 (0.204)	-0.080* (0.040)	0.187 (0.311)
Gender of household head (female=1)	0.034* (0.012)	0.050 (0.183)	0.014 (0.650)	0.033 (0.054)	0.045 (0.157)	-0.128 (0.190)
Elderly household head (age over 65=1)	0.022 (0.098)	-0.020 (0.578)	0.035 (0.255)	0.023 (0.194)	0.014 (0.626)	0.027 (0.777)
Education of household head (complete lower secondary or higher=1)	-0.018 (0.160)	-0.022 (0.583)	-0.031 (0.280)	0.005 (0.742)	-0.049 (0.054)	-0.013 (0.847)
Household size	0.002 (0.565)	-0.006 (0.566)	0.010 (0.161)	-0.001 (0.873)	-0.004 (0.626)	-0.005 (0.755)
Proportion of land accessed for irrigation (percentage)	0.003 (0.896)	-0.117 (0.173)	0.098 (0.266)	0.026 (0.386)	-0.051 (0.414)	0.003 (0.980)
Main water source (rainwater=1)	0.050 (0.057)	-0.066 (0.322)	-0.153 (0.104)	0.096** (0.003)	-0.018 (0.775)	0.203* (0.048)
Main water source (pond/reservoirs/wells=1)	0.052* (0.030)	0.013 (0.797)	0.005 (0.931)	0.052 (0.095)	-0.025 (0.765)	0.070 (0.595)
Main water source (extracted from natural sources=1)	0.052* (0.040)	0.084 (0.145)	0.136* (0.047)	0.004 (0.888)	-0.114 (0.102)	0.062 (0.339)
Practice monoculture (rubber plantation only=1)	-0.026* (0.032)	-0.085* (0.042)	-0.134*** (<0.001)	-0.015 (0.334)	-0.015 (0.556)	-0.002 (0.991)
Engage in growing rice (yes=1)	0.052** (0.001)	-0.014 (0.846)	0.093*** (0.001)	0.014 (0.526)	0.005 (0.910)	-0.110 (0.122)
Share of rented land (percentage)	0.035 (0.537)	0.130 (0.330)	0.010 (0.908)	0.044 (0.564)	-0.185 (0.198)	-0.032 (0.862)
Agricultural debt (has debt = 1)	0.007 (0.550)	-0.004 (0.905)	-0.015 (0.556)	-0.001 (0.961)	-0.007 (0.788)	0.027 (0.731)
BAAC (membership=1)	0.003 (0.840)	-0.047 (0.218)	-0.052 (0.074)	0.025 (0.116)	0.009 (0.723)	-0.020 (0.836)
Co-operative Members (membership=1)	-0.001 (0.974)	-0.049 (0.376)	-0.109* (0.025)	0.056 (0.065)	-0.035 (0.499)	-0.055 (0.621)
Agricultural/Saving Group (membership=1)	-0.001 (0.960)	-0.077 (0.145)	-0.027 (0.669)	0.038 (0.094)	-0.045 (0.332)	-0.329* (0.018)

Dependent variable: ln (Technical inefficiency)	Thailand	Central	Northeast	Southeast	Southwest	North
N (sample households)	9,451	874	2,539	4,078	1,680	281

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. BAAC=Bank for Agriculture and Agricultural Cooperatives. Robustness checks are available in Tables A8-A13 in Appendix III.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.

Return to Scale Analysis

Table 4 reports that the Wald test strongly rejects constant returns to scale (p -value < 0.001). Table 5 reports that the scale elasticity, i.e. sum of input elasticities, is 0.792, indicating decreasing returns to scale. This means that a 1% increase in all inputs would lead to only about 0.79% increase in output.

Table 4. Wald test of constant return to scale

Ho: Constant Return to Scale (the sum of the input elasticities equals one)

Test statistic	Value	Degree of freedom	p -value
Wald test statistic: Chi ²	144.78	1	<0.001

Note: Slope coefficients are based on the stochastic production frontier model for Thailand (Table 2).

Table 5 also reveals that land is by far the most important input factor. The low labor elasticity suggests possible labor surplus or inefficient labor use. Specifically, rubber plantation area has the largest impact with elasticity of 0.697 and highly significant. On the other hand, labor input as the number of workers has a marginal effect at 0.027 with a borderline significance (p -value = 0.094). In addition, production costs have a small but significant effect at 0.064. But physical capital as measured by the agricultural asset value appears to have a minimal impact on production with no statistical significance.

Table 5. Input-output relationships from stochastic frontier analysis

Input	Elasticity (Slope coefficient)	Robust standard error	t-statistic	p -value
Number of workers	0.027	0.016	1.7	0.094
Rubber plantation area	0.697	0.011	60.7	<0.001
Cost of agricultural production	0.064	0.006	9.9	<0.001
Agricultural asset value	0.005	0.005	1.1	0.279
Total / Return to scale	0.792	0.017	45.9	<0.001

Note: Slope coefficients are based on the stochastic production frontier model for Thailand (Table 2). The scale elasticity is calculated using the delta-method.

Table 6 provides a Ramsey RESET test to check for potential model misspecification due to omitted variables, incorrect functional form, or errors in variables. The null hypothesis is that the model has no omitted variables. It suggests no statistically significant evidence of model misspecification, because the Ramsey RESET test fails to reject the null hypothesis. This indicates the model is likely well-specified with no major omitted variables.

Table 6. Ramsey RESET test of omitted variables

Ho: Model has no omitted variables

Test statistic	Value	Degree of freedom	p-value
F statistic	1.70	(3, 9598)	0.1642

Note: The test is based on the stochastic production frontier model for Thailand (Table 2).

5. Conclusion and Policy Implications

This present study applied the stochastic production frontier model to analyze rubber cultivation among agricultural households in Thailand at both the national level and across five regions. Data for this study was sourced from the Household Socioeconomic and Agricultural Labor Survey conducted by the Ministry of Agriculture and Cooperatives. The dataset included 9,670 rubber cultivation households categorized into five regions: Central (897 households), Northeastern (2,628 households), Eastern coast of Southern (4,153 households), and Western coast of Southern (1,710 households), and North (282 households). The study period spanned from the planting year 2006/2007 to 2019/2020.

Furthermore, our research integrated agricultural household survey data with sub-district-level climate data of the ERA5 reanalysis dataset to assess the technical efficiency of rubber production nationwide. This study aimed to understand the factors influencing technical inefficiency in rubber cultivation in Thai rubber farmers.

Rubber production in Thailand is largely driven by the area of rubber plantations and agricultural production costs, both of which exhibit a strong positive impact across regions. While plantation area consistently influences production, the significance of production costs varies, suggesting that financial input is crucial in certain regions. Conversely, labor and agricultural assets have relatively minor impacts on rubber production.

Nationally, there is a negative trend in rubber production over time, though this decline is moderated by a small positive quadratic term, suggesting a potential slowdown. Regionally, time trends are mixed: the Southeast shows a negative trend that drives the national decline, while the Central region exhibits a positive trend with a slight downturn, and the North demonstrates a strong positive trend in production.

The average efficiency among rubber farmers in Thailand is 67%, with notable regional disparities. The North has the lowest average efficiency at 61%, and along with the Northeast, shows the greatest potential for improvement. Targeting underperforming farmers in the North and Northeast regions could significantly improve national productivity. The efficiency gap in the North is particularly striking, ranging from 6% to 92%, reflecting uneven access to resources and practices. By addressing these disparities and targeting support to underperforming areas, Thailand can close the efficiency gap and enhance overall productivity in its rubber farming sector.

Average annual temperature has a significant negative effect on inefficiency in Thailand, particularly in the Northeast and Southeast regions, where higher temperatures within the 22.2-28.1 °C range are associated with reduced inefficiency. However, caution is warranted when interpreting this relationship, as temperature is generally increasing over time. Rainfall also exhibits a significant impact in reducing inefficiency, while the number of hot days generally reduces inefficiency in the Central and Northeast regions.

Farm practices like monoculture and rice cultivation also influence inefficiency, with monoculture typically reduces it, but engaging in rice growing increases it. Other factors, such as cooperative group membership and main water sources also play roles in technical inefficiency, though their effects vary regionally. Overall, climate factors and farm practices are the most consistent determinants of inefficiency in rubber production.

The analysis shows significant decreasing returns to scale in Thailand's rubber production, with scale elasticity at 0.792, indicating that a 1% increase in inputs results in only a 0.79% increase in output. The rubber plantation area is the most impactful input, while labor and agricultural capital contribute minimally, with labor likely in surplus or inefficiently utilized. The Wald test strongly rejects constant returns to scale, and the Ramsey RESET test confirms the model's specification accuracy, suggesting no significant omitted variable bias.

We acknowledge data constraints in our study. First, while labor is crucial for rubber production, we could only use worker headcount rather than the preferred "man-days" measure due to limited information on actual working hours and days. Second, regarding rice cultivation, we used a simple dummy variable indicating household engagement in rice farming. However, detailed plot-specific data would be preferable. Third, for cooperative and agricultural savings membership, we included these as basic categorical variables due to the absence of detailed information about specific training programs or knowledge transfer activities associated with membership. Furthermore, we acknowledge the absence of tapping age and planting density variables. Despite these limitations, our analysis provides valuable insights into rubber production among Thai farmers.

Policy Implications

By employing a stochastic production frontier model and analyzing a comprehensive dataset, we have identified key factors influencing both production quantity and efficiency. Our findings underscore the importance of agricultural production costs, plantation area, and climate factors in determining rubber production outcomes.

The Rubber Authority of Thailand (RAOT) has implemented a policy to limit land expansion, a measure that contrasts with the empirical findings that land is the input with the highest return in rubber production. Despite RAOT's policy, the data shows that expanding plantation area significantly enhances rubber output, making land one of the most crucial factors for increasing productivity. Therefore, based on these empirical results, this study suggests the following recommendations:

1. *Prioritize Efficiency Improvement:* While expanding cultivation areas can increase production, this study suggests focusing on efficiency improvements. Government support for improving efficiency on existing farms, such as extension services, training programs, and access to new technologies, could significantly boost output.

2. *Targeted Support for North and Northeastern:* The study revealed lower production efficiency among low-capacity farmers in the North and Northeast regions. The government should urgently implement targeted income security programs, like weather-based crop insurance schemes. This aims to enhance rubber production efficiency, bringing it closer to the levels observed in other regions.

Enhancing the efficiency of rubber production from its industrial upstream necessitates fostering sustainable development practices in rubber plantations. To support these efforts, the government should establish key targets related to poverty reduction, sustainable development, and climate resilience. By prioritizing sustainable practices, the government can increase the competitiveness of the rubber

industry, improve the livelihoods of rubber farmers, and contribute to broader economic, social, and environmental development outcomes, aligning with the Sustainable Development Goals (SDGs).

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Appendices

Appendix I. Robustness in Stochastic Production Frontier Models

Table A1. Estimation results of the stochastic production frontier model (Thailand)

Dependent variable: ln (Rubber production quantity)	Model 1	Model 2	Model 3	Model 4	Model 5
Time	-0.010 (0.337)	-0.008 (0.350)	-0.059*** (<0.001)	-0.004 (0.704)	-0.019* (0.019)
Time, squared	0.002** (0.001)	0.002*** (<0.001)	0.005*** (<0.001)	0.002** (0.003)	0.003*** (<0.001)
ln (Number of workers)	0.197*** (<0.001)				0.027 (0.094)
ln (Rubber plantation area)		0.755*** (<0.001)			0.697*** (<0.001)
ln (Cost of agricultural production)			0.291*** (<0.001)		0.064*** (<0.001)
ln (Agricultural asset value)				0.097*** (<0.001)	0.005 (0.279)
N (sample households)	9670	9670	9670	9670	9670

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. All regressions include region and province dummy variables.

Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Table A2. Estimation results of the stochastic production frontier model (Central)

Dependent variable: ln (Rubber production quantity)	Model 1	Model 2	Model 3	Model 4	Model 5
Time	0.073 (0.078)	0.089** (0.003)	0.055 (0.123)	0.099* (0.014)	0.084** (0.007)
Time, squared	-0.004 (0.171)	-0.004* (0.023)	-0.003 (0.212)	-0.005 (0.072)	-0.004* (0.034)
ln (Number of workers)	0.219** (0.005)				-0.035 (0.546)
ln (Rubber plantation area)		0.792*** (<0.001)			0.689*** (<0.001)
ln (Cost of agricultural production)			0.359*** (<0.001)		0.102*** (<0.001)
ln (Agricultural asset value)				0.142*** (<0.001)	0.008 (0.679)
N (sample households)	897	897	897	897	897

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. All regressions include province dummy variables.

Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Table A3. Estimation results of the stochastic production frontier model (Northeast)

Dependent variable: ln (Rubber production quantity)	Model 1	Model 2	Model 3	Model 4	Model 5
Time	-0.009 (0.675)	0.031 (0.112)	-0.087*** (<0.001)	-0.009 (0.688)	0.011 (0.595)
Time, squared	0.004** (0.005)	0.002 (0.092)	0.007*** (<0.001)	0.004** (0.003)	0.003** (0.010)
ln (Number of workers)	0.175*** (<0.001)				0.009 (0.780)
ln (Rubber plantation area)		0.741*** (<0.001)			0.690*** (<0.001)
ln (Cost of agricultural production)			0.388*** (<0.001)		0.086*** (<0.001)
ln (Agricultural asset value)				0.087*** (<0.001)	0.013 (0.183)
N (sample households)	2628	2628	2628	2628	2628

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. All regressions include province dummy variables.

Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Table A4. Estimation results of the stochastic production frontier model (Southeast)

Dependent variable: ln (Rubber production quantity)	Model 1	Model 2	Model 3	Model 4	Model 5
Time	-0.025 (0.105)	-0.033** (0.002)	-0.067*** (<0.001)	-0.016 (0.270)	-0.043*** (<0.001)
Time, squared	0.003** (0.009)	0.003*** (<0.001)	0.005*** (<0.001)	0.002* (0.030)	0.004*** (<0.001)
ln (Number of workers)	0.253*** (<0.001)				0.052* (0.022)
ln (Rubber plantation area)		0.761*** (<0.001)			0.698*** (<0.001)
ln (Cost of agricultural production)			0.274*** (<0.001)		0.059*** (<0.001)
ln (Agricultural asset value)				0.105*** (<0.001)	0.006 (0.323)
N (sample households)	4153	4153	4153	4153	4153

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. All regressions include province dummy variables.

Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Table A5. Estimation results of the stochastic production frontier model (Southwest)

Dependent variable: ln (Rubber production quantity)	Model 1	Model 2	Model 3	Model 4	Model 5
Time	0.038 (0.066)	0.045** (0.008)	-0.026 (0.176)	0.048* (0.022)	0.026 (0.142)
Time, squared	-0.002 (0.244)	-0.002 (0.131)	0.002 (0.129)	-0.002 (0.125)	-0.001 (0.588)
ln (Number of workers)	0.146** (0.001)				0.050 (0.125)
ln (Rubber plantation area)		0.710*** (<0.001)			0.637*** (<0.001)
ln (Cost of agricultural production)			0.275*** (<0.001)		0.072*** (<0.001)
ln (Agricultural asset value)				0.082*** (<0.001)	-0.007 (0.546)
N (sample households)	1710	1710	1710	1710	1710

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001. All regressions include province dummy variables.

Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Table A6. Estimation results of the stochastic production frontier model (North)

Dependent variable: ln (Rubber production quantity)	Model 1	Model 2	Model 3	Model 4	Model 5
Time	1.039*** (<0.001)	0.779*** (<0.001)	1.128*** (<0.001)	1.041*** (<0.001)	0.766*** (<0.001)
Time, squared	-0.047*** (<0.001)	-0.033** (0.002)	-0.051*** (<0.001)	-0.047*** (<0.001)	-0.032** (0.003)
ln (Number of workers)	-0.034 (0.880)				-0.082 (0.687)
ln (Rubber plantation area)		0.967*** (<0.001)			0.963*** (<0.001)
ln (Cost of agricultural production)			0.231* (0.013)		0.012 (0.883)
ln (Agricultural asset value)				0.051 (0.274)	0.009 (0.816)
N (sample households)	282	282	282	282	282

Note: p -values are shown in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. All regressions include province dummy variables.

Sources: Authors' calculations using the stochastic production frontier model with robust standard errors.

Appendix II. Estimated Efficiency of Stochastic Production Frontier

Table A7. Estimated efficiency and regional disparities

	Thailand	Regions					Regions (relative to Thailand)					Regional
		C	NE	SE	SW	N	C	NE	SE	SW	N	Max-Min
Number of households	9,451	873	2,539	4,078	1,680	281						
Mean	67%	66%	66%	68%	68%	61%	-1%	-1%	1%	1%	-6%	7%
SD	15%	16%	17%	12%	12%	23%						
1st percentile	12%	9%	7%	22%	24%	6%	-3%	-6%	10%	12%	-6%	18%
5th percentile	36%	29%	26%	43%	46%	16%	-6%	-10%	7%	10%	-20%	30%
10th percentile	48%	43%	42%	53%	53%	21%	-5%	-6%	5%	5%	-27%	32%
25th percentile	62%	60%	60%	64%	64%	48%	-3%	-2%	1%	1%	-15%	16%
50th percentile	71%	70%	71%	71%	71%	69%	0%	0%	0%	0%	-2%	3%
75th percentile	76%	76%	77%	76%	76%	78%	0%	1%	-1%	0%	2%	3%
90th percentile	80%	80%	81%	80%	80%	83%	0%	1%	0%	-1%	3%	3%
95th percentile	83%	83%	83%	82%	82%	85%	0%	1%	0%	-1%	2%	3%
99th percentile	87%	87%	88%	88%	85%	92%	0%	0%	0%	-2%	4%	7%

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001, *n* = 9,670. C=Central, NE=Northeast, SE=Southeast, SW=Southwest, and N=North. Sources: Authors' calculations using the national stochastic production frontier model from Table A1.

Appendix III. Robustness in Technical Inefficiency Regression Models

Table A8. Estimation results of the technical inefficiency regression (Thailand)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Average annual temperature (Celsius)	-1.389*** (0.001)	-1.335*** (0.001)	-1.354*** (0.001)	-1.370*** (0.001)
Average annual temperature squared (Celsius squared)	0.027*** (0.001)	0.026*** (0.001)	0.026*** (0.001)	0.026*** (0.001)
Total annual rainfall (Inch)	-0.008** (0.003)	-0.006* (0.020)	-0.008** (0.003)	-0.006* (0.025)
Total annual rainfall squared (Inch squared)	0.000* (0.013)	0.000* (0.042)	0.000* (0.014)	0.000* (0.047)
Number of hot days in a year	-0.003 (0.168)	-0.004 (0.067)	-0.003 (0.156)	-0.004 (0.068)
Number of wet days in a year	0.000 (0.943)	-0.001 (0.853)	0.001 (0.856)	-0.001 (0.740)
Cultivation Year 2014/2015	-0.007 (0.724)	-0.011 (0.585)	-0.007 (0.747)	-0.012 (0.572)
Cultivation Year 2011/2012	0.107*** (<0.001)	0.098*** (<0.001)	0.107*** (<0.001)	0.098*** (<0.001)
Gender of household head (female=1)	0.031* (0.022)			0.034* (0.012)
Elderly household head (age over 65=1)	0.021 (0.112)			0.022 (0.098)
Education of household head (complete lower secondary or higher=1)	-0.017 (0.175)			-0.018 (0.160)
Household size	0.004 (0.209)			0.002 (0.565)
Proportion of land accessed for irrigation (percentage)		0.002 (0.940)		0.003 (0.896)
Main water source (rainwater=1)		0.050 (0.058)		0.050 (0.057)
Main water source (pond/reservoirs/wells=1)		0.051* (0.031)		0.052* (0.030)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Main water source (extracted from natural sources=1)	0.052*			0.052*
	(0.040)			(0.040)
Practice monoculture (rubber plantation only=1)	-0.026*			-0.026*
	(0.031)			(0.032)
Engage in growing rice (yes=1)	0.053**			0.052**
	(0.001)			(0.001)
Share of rented land (percentage)	0.030			0.035
	(0.588)			(0.537)
Agricultural debt (has debt = 1)			0.009	0.007
			(0.441)	(0.550)
BAAC (membership=1)			0.000	0.003
			(0.988)	(0.840)
Co-operative Members (membership=1)			-0.001	-0.001
			(0.951)	(0.974)
Agricultural/Saving Group (membership=1)			-0.001	-0.001
			(0.957)	(0.960)
N (sample households)	9451	9451	9451	9451

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.

Table A9. Estimation results of the technical inefficiency regression (Central)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Average annual temperature (Celsius)	-1.083 (0.231)	-1.410 (0.112)	-1.065 (0.236)	-1.504 (0.091)
Average annual temperature squared (Celsius squared)	0.021 (0.227)	0.027 (0.110)	0.021 (0.232)	0.029 (0.090)
Total annual rainfall (Inch)	0.007 (0.399)	0.011 (0.213)	0.008 (0.346)	0.009 (0.322)
Total annual rainfall squared (Inch squared)	-0.000 (0.370)	-0.000 (0.178)	-0.000 (0.330)	-0.000 (0.289)
Number of hot days in a year	-0.028 (0.064)	-0.055* (0.011)	-0.035* (0.024)	-0.065** (0.009)
Number of wet days in a year	0.007 (0.562)	0.008 (0.493)	0.007 (0.584)	0.006 (0.601)
Cultivation Year 2014/2015	-0.045 (0.415)	-0.034 (0.546)	-0.042 (0.451)	-0.046 (0.414)
Cultivation Year 2011/2012	0.154* (0.039)	0.121 (0.068)	0.142* (0.048)	0.125 (0.066)
Gender of household head (female=1)	0.041 (0.265)			0.050 (0.183)
Elderly household head (age over 65=1)	-0.012 (0.734)			-0.020 (0.578)
Education of household head (complete lower secondary or higher=1)	-0.015 (0.707)			-0.022 (0.583)
Household size	-0.004 (0.686)			-0.006 (0.566)
Proportion of land accessed for irrigation (percentage)		-0.123 (0.145)		-0.117 (0.173)
Main water source (rainwater=1)		-0.067 (0.308)		-0.066 (0.322)
Main water source (pond/reservoirs/wells=1)		0.011 (0.824)		0.013 (0.797)
Main water source (extracted from natural sources=1)		0.072 (0.204)		0.084 (0.145)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Practice monoculture (rubber plantation only=1)		-0.076 (0.062)		-0.085* (0.042)
Engage in growing rice (yes=1)		-0.013 (0.853)		-0.014 (0.846)
Share of rented land (percentage)		0.111 (0.402)		0.130 (0.330)
Agricultural debt (has debt = 1)			0.015 (0.644)	-0.004 (0.905)
BAAC (membership=1)			-0.034 (0.355)	-0.047 (0.218)
Co-operative Members (membership=1)			-0.027 (0.627)	-0.049 (0.376)
Agricultural/Saving Group (membership=1)			-0.074 (0.154)	-0.077 (0.145)
N (sample households)	874	874	874	874

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.

Table A10. Estimation results of the technical inefficiency regression (Northeast)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Average annual temperature (Celsius)	-2.939*** (<0.001)	-2.494** (0.001)	-2.906*** (<0.001)	-2.593*** (0.001)
Average annual temperature squared (Celsius squared)	0.058*** (<0.001)	0.049** (0.001)	0.057*** (<0.001)	0.051*** (0.001)
Total annual rainfall (Inch)	-0.006 (0.358)	-0.009 (0.156)	-0.006 (0.294)	-0.009 (0.145)
Total annual rainfall squared (Inch squared)	0.000 (0.461)	0.000 (0.187)	0.000 (0.402)	0.000 (0.180)
Number of hot days in a year	-0.009*** (0.001)	-0.009** (0.002)	-0.009** (0.001)	-0.009** (0.002)
Number of wet days in a year	-0.012 (0.234)	-0.011 (0.290)	-0.013 (0.208)	-0.011 (0.276)
Cultivation Year 2014/2015	-0.073 (0.061)	-0.093* (0.019)	-0.071 (0.069)	-0.098* (0.013)
Cultivation Year 2011/2012	0.251*** (<0.001)	0.233*** (0.001)	0.270*** (<0.001)	0.234*** (0.001)
Gender of household head (female=1)	0.026 (0.387)			0.014 (0.650)
Elderly household head (age over 65=1)	0.040 (0.196)			0.035 (0.255)
Education of household head (complete lower secondary or higher=1)	-0.024 (0.411)			-0.031 (0.280)
Household size	0.012 (0.090)			0.010 (0.161)
Proportion of land accessed for irrigation (percentage)		0.095 (0.277)		0.098 (0.266)
Main water source (rainwater=1)		-0.149 (0.113)		-0.153 (0.104)
Main water source (pond/reservoirs/wells=1)		0.009 (0.884)		0.005 (0.931)
Main water source (extracted from natural sources=1)		0.134* (0.049)		0.136* (0.047)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Practice monoculture (rubber plantation only=1)		-0.129*** (0.001)		-0.134*** (<0.001)
Engage in growing rice (yes=1)		0.097*** (<0.001)		0.093*** (0.001)
Share of rented land (percentage)		-0.001 (0.991)		0.010 (0.908)
Agricultural debt (has debt = 1)			-0.011 (0.675)	-0.015 (0.556)
BAAC (membership=1)			-0.054 (0.063)	-0.052 (0.074)
Co-operative Members (membership=1)			-0.109* (0.026)	-0.109* (0.025)
Agricultural/Saving Group (membership=1)			-0.042 (0.496)	-0.027 (0.669)
N (sample households)	2539	2539	2539	2539

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.

Table A11. Estimation results of the technical inefficiency regression (Southeast)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Average annual temperature (Celsius)	-1.554*	-1.610*	-1.556*	-1.537*
	(0.014)	(0.012)	(0.014)	(0.016)
Average annual temperature squared (Celsius squared)	0.031*	0.032*	0.031*	0.030*
	(0.013)	(0.011)	(0.013)	(0.015)
Total annual rainfall (Inch)	0.011*	0.011*	0.011*	0.010*
	(0.015)	(0.022)	(0.021)	(0.037)
Total annual rainfall squared (Inch squared)	-0.000	-0.000	-0.000	-0.000
	(0.079)	(0.093)	(0.099)	(0.156)
Number of hot days in a year	-0.035	-0.029	-0.034	-0.028
	(0.470)	(0.547)	(0.494)	(0.559)
Number of wet days in a year	-0.005	-0.005	-0.005	-0.006
	(0.225)	(0.273)	(0.223)	(0.192)
Cultivation Year 2014/2015	-0.006	-0.007	-0.003	-0.006
	(0.822)	(0.794)	(0.919)	(0.820)
Cultivation Year 2011/2012	0.040	0.029	0.039	0.033
	(0.119)	(0.271)	(0.125)	(0.204)
Gender of household head (female=1)	0.030			0.033
	(0.084)			(0.054)
Elderly household head (age over 65=1)	0.019			0.023
	(0.285)			(0.194)
Education of household head (complete lower secondary or higher=1)	0.005			0.005
	(0.772)			(0.742)
Household size	0.000			-0.001
	(0.952)			(0.873)
Proportion of land accessed for irrigation (percentage)		0.023		0.026
		(0.430)		(0.386)
Main water source (rainwater=1)		0.096**		0.096**
		(0.003)		(0.003)
Main water source (pond/reservoirs/wells=1)		0.051		0.052
		(0.105)		(0.095)
Main water source (extracted from natural sources=1)		0.004		0.004
		(0.887)		(0.888)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Practice monoculture (rubber plantation only=1)		-0.013 (0.380)		-0.015 (0.334)
Engage in growing rice (yes=1)		0.014 (0.528)		0.014 (0.526)
Share of rented land (percentage)		0.032 (0.671)		0.044 (0.564)
Agricultural debt (has debt = 1)			-0.003 (0.830)	-0.001 (0.961)
BAAC (membership=1)			0.023 (0.155)	0.025 (0.116)
Co-operative Members (membership=1)			0.053 (0.081)	0.056 (0.065)
Agricultural/Saving Group (membership=1)			0.038 (0.087)	0.038 (0.094)
N (sample households)	4078	4078	4078	4078

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.

Table A12. Estimation results of the technical inefficiency regression (Southwest)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Average annual temperature (Celsius)	1.116 (0.386)	1.041 (0.417)	1.233 (0.336)	1.042 (0.421)
Average annual temperature squared (Celsius squared)	-0.022 (0.370)	-0.021 (0.398)	-0.024 (0.321)	-0.021 (0.403)
Total annual rainfall (Inch)	0.003 (0.779)	0.003 (0.761)	0.002 (0.804)	0.004 (0.684)
Total annual rainfall squared (Inch squared)	-0.000 (0.885)	-0.000 (0.862)	-0.000 (0.901)	-0.000 (0.783)
Number of hot days in a year	n.a.	n.a.	n.a.	n.a.
Number of wet days in a year	0.008 (0.334)	0.009 (0.276)	0.009 (0.259)	0.008 (0.339)
Cultivation Year 2014/2015	0.104* (0.044)	0.097 (0.061)	0.102* (0.048)	0.101 (0.053)
Cultivation Year 2011/2012	-0.078* (0.045)	-0.080* (0.042)	-0.076 (0.054)	-0.080* (0.040)
Gender of household head (female=1)	0.044 (0.163)			0.045 (0.157)
Elderly household head (age over 65=1)	0.017 (0.555)			0.014 (0.626)
Education of household head (complete lower secondary or higher=1)	-0.048 (0.056)			-0.049 (0.054)
Household size	-0.003 (0.700)			-0.004 (0.626)
Proportion of land accessed for irrigation (percentage)		-0.052 (0.408)		-0.051 (0.414)
Main water source (rainwater=1)		-0.015 (0.816)		-0.018 (0.775)
Main water source (pond/reservoirs/wells=1)		-0.027 (0.748)		-0.025 (0.765)
Main water source (extracted from natural sources=1)		-0.110 (0.112)		-0.114 (0.102)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Practice monoculture (rubber plantation only=1)		-0.012 (0.628)		-0.015 (0.556)
Engage in growing rice (yes=1)		-0.003 (0.948)		0.005 (0.910)
Share of rented land (percentage)		-0.181 (0.206)		-0.185 (0.198)
Agricultural debt (has debt = 1)			-0.012 (0.646)	-0.007 (0.788)
BAAC (membership=1)			0.005 (0.856)	0.009 (0.723)
Co-operative Members (membership=1)			-0.039 (0.464)	-0.035 (0.499)
Agricultural/Saving Group (membership=1)			-0.047 (0.316)	-0.045 (0.332)
N (sample households)	1680	1680	1680	1680

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.

Table A13. Estimation results of the technical inefficiency regression (North)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Average annual temperature (Celsius)	0.110 (0.936)	0.550 (0.673)	0.502 (0.707)	0.647 (0.623)
Average annual temperature squared (Celsius squared)	-0.002 (0.939)	-0.011 (0.666)	-0.010 (0.707)	-0.013 (0.622)
Total annual rainfall (Inch)	0.028 (0.357)	0.025 (0.435)	0.032 (0.268)	0.021 (0.496)
Total annual rainfall squared (Inch squared)	-0.000 (0.310)	-0.000 (0.360)	-0.000 (0.250)	-0.000 (0.421)
Number of hot days in a year	0.004 (0.716)	0.009 (0.448)	0.008 (0.479)	0.008 (0.485)
Number of wet days in a year	0.004 (0.880)	0.008 (0.773)	0.000 (0.989)	0.005 (0.841)
Cultivation Year 2014/2015	0.270* (0.044)	0.287* (0.039)	0.297* (0.026)	0.312* (0.028)
Cultivation Year 2011/2012	0.070 (0.685)	0.151 (0.400)	0.108 (0.542)	0.187 (0.311)
Gender of household head (female=1)	-0.117 (0.190)			-0.128 (0.190)
Elderly household head (age over 65=1)	0.029 (0.756)			0.027 (0.777)
Education of household head (complete lower secondary or higher=1)	-0.012 (0.856)			-0.013 (0.847)
Household size	0.002 (0.917)			-0.005 (0.755)
Proportion of land accessed for irrigation (percentage)		-0.000 (0.999)		0.003 (0.980)
Main water source (rainwater=1)		0.207* (0.043)		0.203* (0.048)
Main water source (pond/reservoirs/wells=1)		0.066 (0.609)		0.070 (0.595)
Main water source (extracted from natural sources=1)		0.054 (0.394)		0.062 (0.339)

Dependent variable: ln (Technical inefficiency)	Model 6	Model 7	Model 8	Model 9
Practice monoculture (rubber plantation only=1)		-0.009 (0.950)		-0.002 (0.991)
Engage in growing rice (yes=1)		-0.111 (0.109)		-0.110 (0.122)
Share of rented land (percentage)		-0.037 (0.845)		-0.032 (0.862)
Agricultural debt (has debt = 1)			0.055 (0.473)	0.027 (0.731)
BAAC (membership=1)			-0.003 (0.975)	-0.020 (0.836)
Co-operative Members (membership=1)			-0.032 (0.774)	-0.055 (0.621)
Agricultural/Saving Group (membership=1)			-0.286* (0.046)	-0.329* (0.018)
N (sample households)	281	281	281	281

Note: *p*-values are shown in parentheses. * *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001.

Sources: Authors' calculations using the ordinary least squares (OLS) regression with robust standard errors.