Quarterly Journal of International Agriculture 51 (2012), No. 3: 203-226

Technical Efficiency of Irrigated and Rain-Fed Smallholder Agriculture in Tigray, Ethiopia: A Comparative Stochastic Frontier Production Function Analysis

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Abstract

Stochastic production frontiers of irrigated and rain-fed smallholder agriculture in Tigray, Ethiopia, were fitted to a random sample of irrigated and rain-fed plots to compare their technical efficiencies. Propensity Score Matching Method was applied to select rain-fed plots with comparable bio-physical attributes to irrigated plots that might have blurred the true efficiency differences between the two systems. Irrigated farms are on a higher production frontier with significant inefficiencies, while rain-fed farms are on a lower production frontier with high efficiency levels. Thus, there is considerable potential for increasing outputs by improving the efficiency of irrigation farms. Rain-fed systems need interventions in soil moisture management to move to a higher production frontier. The study underlines the need for correcting the sequence and mix of yield boosting technologies such as irrigation, improved seeds, and fertilizer that are promoted in arid environments such as Tigray. We recommend that water control must precede or implemented in tandem with improved seeds and fertilizer technologies. Unless soil moisture is improved by investing in moisture improving technologies, the use of seed and fertilizer in moisture stressed areas such as Tigray may have adverse effects.

Keywords: technical efficiency, stochastic frontier, inefficiency, irrigation, rain-fed, Tigray
JEL: Q12

1 Introduction

The importance of agricultural surplus for economic development has been recognized since the 1960s (HAYAMI and RUTTAN, 1971). Yet, agricultural development experiences of SSA in general and that of Ethiopia in particular has been sluggish, which was partly attributed to the farmers' resistance to take on new technologies (often for good reasons) with potential for propelling the pace of agricultural growth. SCHULTZ (1964) stated that peasants are "poor but efficient"; however, this is the case when they operate under stable conditions and have been given sufficient time to learn new technologies. This means that after the introduction of new technologies, it may take considerable time before all have adopted and learned to use the technologies efficiently.

Ethiopia has approximately 12 river basins with an annual runoff of 122 billion m^3 and with 2.6 billion m^3 of groundwater (AWULACHEW et al., 2006). With all this potential, however, it fails to produce enough food to feed its population. The country's perennial dependence on food aid has been attributed largely to an over-reliance on rain-fed smallholder agriculture. For example, only 5-6% of the 4.25 million hectares of irrigable land is currently developed through traditional, small-, medium-, and large-scale irrigation schemes (AWULACHEW et al., 2007). Of all the regions in Ethiopia, Tigray has been considered especially vulnerable to food insecurity mainly due to insufficient and highly variable rainfall, which constrains agricultural production (FDRE, 1999). Low agricultural productivity due to severe land degradation and low soil fertility is a critical problem, and one that characterizes the Ethiopian highlands in general (PENDER and GEBREMEDHIN, 2004). Hence, investment in irrigation development has been considered as one of the viable strategies for achieving food security.

Consistent with this thinking, the regional government of Tigray has embarked on a massive irrigation development program, especially after the establishment of Co-SAERT[1] in 1995. According to the Tigray Bureau of Agriculture, for example, 54 micro-dams and 106 river diversion irrigation schemes have been constructed from 1995-2006. The cost of investment was estimated to be 5.84 million Birr[2] per micro-dam that can irrigate 100 hectares, and 1.17 million Birr per river diversion project to irrigate about 45 hectares of land (ABRAHA, 2003). Despite such high investment and the lofty expectations that irrigation can shift upward the production frontier in the region, there has been no empirical study to investigate the efficiency of irrigated agriculture in the region.

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[1] Commission for Sustainable Agricultural and Environmental Rehabilitation of Tigray

[2] Birr is an Ethiopian currency. 1 USD was equal to 8.65 Birr at the time data were collected in December 2006.

Furthermore, land scarcity due to population pressure makes the expansion of agricultural land increasingly difficult, leading to small landholdings in densely populated areas. Hence, there is a need for improvements in the efficiency of existing production activity in order to foster production. Since the choice of development strategies partly depends on policymakers' conception of farmers' performance, understanding the level of efficiency of existing production activities is important for informed policymaking. Therefore, the main objectives of this paper are to: (1) investigate the level of technical efficiency of irrigated and rain-fed small-scale agriculture in the Tigray region; (2) identify, if any, the main sources of technical inefficiency; and (3) make policy recommendations for enhancing the technical efficiency of irrigated and rain-fed farming in order to achieve the food security and poverty reduction objectives of the region.

2 Literature Review

In microeconomic theory, technical efficiency is defined as the ability of a firm to produce the maximum output from a given set of inputs and technology (COELLI et al., 1998; KOOPMANS, 1951). This also implies the ability of the producer to minimize input use when producing a given amount of output (KUMBHAKAR and LOVELL, 2000). Technical efficiency analysis has been applied to a wide range of problems, while undergoing many refinements and improvements (ALI and BYERLEE, 1991; BATTESE, 1992; BRAVO-URETA and PINHEIRO, 1993; COELLI, 1995). Moreover, empirical analyses of smallholders' technical efficiency are numerous (e.g., BATTESE, 1992; BINAM et al., 2004; BRAVO-URETA and EVENSON, 1994; BRAVO-URETA and PINHEIRO, 1993; THIAM et al., 2001). However, although smallholder agriculture in developing countries depends on environmental conditions, most empirical studies estimate the effect of conventional inputs without controlling for the effect of stochastic exogenous factors in the analysis of stochastic frontier production functions.

Most of the research on the efficiency of small farmers has been triggered by the popular *'poor-but-efficient hypothesis'* (SCHULTZ, 1964), which implies that small farmers in traditional agricultural settings are reasonably efficient in allocating their resources and respond positively to price incentives. If farmers are reasonably efficient, as hypothesized by SCHULTZ, then increases in production require new inputs and technology to shift the production frontier outwards. This vision helped guide the Green Revolution and much ongoing research on improving crop production technologies in the developing world.

Yet the results of countless empirical studies have been mixed, with some supporting and others refuting SCHULTZ'S claim (SHERLUND et al., 2002). Those that refuted

SCHULTZ'S claim that they have found widespread technical inefficiency among smallholder producers and have consequently recommended that policymakers reallocate scarce resources toward redressing apparent obstacles to farmers' technical efficiency through such measures as improved extension work, farmer education, and land tenure reforms.

Efficiency analyses of smallholder agriculture are not extensive in Ethiopia, nor are the findings or conclusions of some of the previous studies consistent with one another. The majority of these studies observed significant inefficiencies among smallholder farmers in Ethiopia (AHMED et al., 2002; ALENE and HASSAN, 2003; BELETE et al., 1993; HAJI, 2006; SEYOUM et al., 1998; WUBENEH and EHUI, 2006), implying that significant gains can be achieved by improving the technical efficiencies of farmers. In contrast, a handful of studies found higher technical efficiencies or only a small magnitude of technical inefficiency among the sample farmers, and they concluded that improving technical efficiency cannot be a basis for sustainable growth in agricultural production in the long term (ADMASSIE and HEIDHUES, 1996; GEBREEGZIABHER et al., 2004). MAKOMBE et al. (2007) analyzed the technical efficiency of irrigated smallholder farming in the Rift Valley and compared it with the technical efficiency of rain-fed smallholder farming in the vicinity. They concluded that due to irrigation's effect of reducing crop failure and improving input use intensity, access to irrigation shifts the production frontier of smallholder farmers outwards.

The reasons for mixed results of the different technical efficiency analyses may be attributed to the differences in the location of the study and differences in the methodological approaches. The studies conducted in Ethiopia employed different analytical methodologies. BELETE et al. (1993) and HAJI (2006) used a non-parametric method, which does not consider factors that are beyond the control of the producer, attributing the entire difference between the observed output and the frontier to technical inefficiency. Moreover, all of the analyses have been done at the household level, disregarding the possible efficiency differences that may arise due to differences in bio-physical production conditions at the plot level with in a farm. Agricultural output, both at a plot and farm level depends on bio-physical conditions that are largely exogenously determined. These bio-physical circumstances in turn condition farmers' production decisions. For instance, identical producers -those possessing the same technologies and abilities -will produce different quantities of grain if faced with different conditions of rainfall, plant disease, pest or weed infestation, or other environmental production factors. Thus, farmers will adjust commonly measured inputs, such as labor, land, and fertilizer, in response to such bio-physical conditions (PENDER and GEBREMEDHIN, 2007).

SHERLUND et al. (2002) rightly attribute the lack of agreement between SCHULTZ'S '*poor but efficient'* claim and the numerous empirical studies reporting significant inefficiency among smallholder agriculture to limitations of the data and methodologies that failed to control for inter-farm (and intra-farm) heterogeneity in environmental production conditions. We share this view, given the extraordinary dependence of smallholder farmers on the underlying agro-ecology, which renders their productivity acutely sensitive to environmental production variables. However, few of the reviewed studies carried out in Ethiopia have the necessary detailed information on bio-physical production conditions. As noted correctly by SHERLUND et al. (2002), the neglect of such information raises the question of omitted variable bias, because farmers' input choices typically respond in part to bio-physical conditions. In addition, because bio-physical production conditions are rarely symmetrically distributed, their omission from efficiency models generally leads to an upward bias in the estimated technical inefficiency, as well as to biased estimates of the correlates of the estimated technical inefficiency.

3 Study Area, Data and Descriptive Analysis

3.1 Study Area and Data

Data used in this paper were obtained from a survey made to study different aspects of small-scale irrigation in the Tigray region, Ethiopia. A three-stage, stratified, random sampling procedure was used. First, all *tabias*[3] in the region that have irrigation projects were stratified based on irrigation technology, altitude, size of irrigable land, and experience (years since irrigation was started). In total, six sites were selected (i.e., two earth dam, two river diversions, and two groundwater irrigation sites). Of the two groundwater irrigation sites, one was the *Kara-Adi-Shawo* irrigation project, which uses modern irrigation systems (i.e., drip and sprinkler irrigation systems).

In the second stage, we stratified all farm households in each *tabia* based on their access to irrigation. Finally, we randomly selected 613 farm households (100 sample households from each of the five *tabias,* and 113 households from *Kara-Adi-Shawo*). The proportion of households with and without access to irrigation in the 613 sample households mirrors the proportion of households with and without access to irrigation in the *tabia*. From the total of 613 sample households, 331 of them had access to irrigation and 282 of them were purely rain-fed cultivators. The total numbers of plots operated by the sample households during the 2004-2005 production years were 2,194,

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[3] *Tabia* is the lower administrative unit in the structure of the regional government of Tigray; it usually comprises approximately four villages.

of which 426 were irrigated and 1,768 were rain-fed plots. We applied the Propensity Score Matching (PSM) technique to select rain-fed plots that are comparable to irrigated plots in their bio-physical characteristics. Consequently, only 562 rain-fed plots out of the total of 1,768 were found to be comparable to the 426 irrigated plots.

Data collection was carried out during October-December 2005. We collected data on farm input and output by asking the head of each sample household to recall her/his activities and production on a particular plot during the immediate past harvest year. A plot was defined as a distinct management unit based on the type of crop planted during 2004/2005 agricultural season. Plot size was determined by asking farmers to state it in the local unit of measurement (*tsimdi*[4]). We randomly checked prices in the nearby markets, from which we calculated average prices that we used to estimate the value of the agricultural product.

3.2 Descriptive Analysis

Table 1 presents summary statistics of data on production and input used in the analysis. The average size of cultivated irrigated land is 1.6 tsimdi or 0.4 hectares, while the corresponding value for rain-fed land is about 5.8 tsimdi or 1.5 hectares. The average value of production from the cultivated irrigated land is approximately 1,236 Birr, while that of rainfed is 654 Birr. The average amount of fertilizer, expenditure on seed, labor, and oxen used in the irrigated plots are: 8.4 kg, 84.1 Birr, 21 man-days of labor and 7 oxen days, respectively. The corresponding values for rain-fed plots are 7.8 kg, 53.4 Birr, 34 man-days and 8 oxen- days, respectively.

Thus, on per unit land area basis, irrigated land is about seven times more productive than rain-fed land. In addition, the input use intensities are much higher on irrigated plots. For instance, on per hectare basis, about 2.6 times more fertilizer is used in irrigated plots as compared to rain-fed plots. Moreover, the value of seed used on irrigated plots is about 5 times the value used on rain-fed plots.

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[4] *Tsimdi* is a local measure of area, which is equivalent to about 0.25 ha.

Table 1. Summary statistics of plot-level variables: irrigated and rain-fed agriculture in Tigray, Ethiopia

Variable	Variable description	Irrigation Plots		Rain-fed Plots		*t-test*
		Mean	Std.Err.	Mean	Std.Err.	
Produperha	Value of agricultural product (Birr/ha)	3013.9	333.5	451.0	23.5	-8.790***
Plotsiz	Average cultivated land size (ha)	0.41	0.007	1.45	0.05	19.546***
Produpertsi	Value of agricultural product (Birr/cultivated land)	1235.7	83.28	654.0	5.9	-8.790***
Fertzperha	Fertilizer use (kg/ha)	19.00	1.891	7.38	0.7	-6.322***
Seedperha	Seed used (Birr/ha)	179.20	26.2	38.68	4.6	-6.004***
Laboperha	Labor used (man-day/ha)	41.82	3.0	26.87	1.05	-5.184***
Oxenperha	Oxen used (oxen day/ha)	30.07	11.5	9.88	5.0	-1.747*
Litrate	Educated household members	1.50	0.074	1.63	0.07	1.313
Farasso	Access to credit	0.95	0.039	0.95	0.03	0.025
Extewdis	Walking distance to extension service (in minutes)	64.73	2.1	62.37	1.75	-0.868
Mktwalkdis	Walking distance to all weather road (in minutes)	0.93	0.013	0.93	0.011	0.315

* Significance at 10% level. ** Significance at 5% level. *** Significance at 1% level. C*ultivated land size refers to the average size of individual plot.*

Source: authors' survey

4 Analytical Framework

4.1 The Stochastic Frontier Model

In this study, we utilize the stochastic frontier production function developed by AIGNER et al. (1977), and stated as follows for a cross-section of plots:

(1) $$Y_i = f\left(X_i, \beta\right)\exp\left(V_i - U_i\right), i = 1, \ldots, N$$

Where Y_i is the output produced on the i^{th} plot, X_i is a vector of inputs used on the i^{th} plot, and β is a vector of parameters to be estimated. V_i is the random component representing factors that are beyond the control of the farm household, and left out explanatory variables assumed to be independently and identically distributed (iid). As a result, V_i is distributed $N\left(0, \sigma_v^2\right)$ and is independent of the U_i. U_i is a random variable that accounts for technical inefficiency in production and is assumed to be independently distributed, truncated at zero, and normally distributed with mean μ_i and variance σ_u^2 $\left(\left|N\left(\mu_i,\sigma_u^2\right)\right|\right)$ where

$$(2) \qquad \mu_i = \delta_0 + \sum_{m=j}^{N} \delta_{mi} z_{mi}$$

and where z is a vector of farm-specific variables that may cause inefficiency and δ represents the unknown parameters to be estimated. Since the dependent variable in Equation (2) is defined in terms of technical inefficiency, a farm-specific variable associated with the negative (positive) coefficient will have a positive (negative) impact on technical efficiency.

The stochastic production frontier at a technically efficient plot would represent the maximum attainable output $\left(Y_i^*\right)$ as:

$$(3) \qquad Y_i^* = f\left(X_i,\beta\right)\exp\left(V_i\right)$$

This can then be used to measure the technical efficiency of all other plots, relative to this efficient plot. The technical efficiency of the plot $\left(TE_i\right)$ is given by:

$$(4) \qquad TE_i = \frac{Y_i}{Y_i^*} = \exp\left(-U_i\right)$$

where TE_i may be defined as the capacity of a producer i to produce relative to a maximum output from a plot using a certain amount of input and available technology. The estimation of the stochastic production frontier function may be viewed as a variance decomposition model, which can be expressed as:

$$(5) \qquad \sigma^2 = \sigma_u^2 + \sigma_v^2$$

$$(6) \qquad \gamma = \frac{\sigma_u^2}{\sigma_u^2 + \sigma_v^2}$$

Nevertheless, a specification similar to Equation (1) identifies only the presence of technical inefficiency without modeling it on relevant explanatory variables. To overcome this problem, some have used a two-step estimation approach. In the first step of this approach, a stochastic frontier production function is estimated and used to predict farm specific technical inefficiency using Equation (1); in the second step, the result is then regressed using Equation (2). However, the two-step approach has serious limitations (BATTESE AND COELLI, 1995; KUMBHAKAR *et al.*, 1991). For example, (i) technical inefficiency may be correlated with the inputs, causing inconsistent parameter estimates and technical inefficiency; (ii) the standard ordinary least square estimation results in the second step may not be appropriate, since technical inefficiency is one-sided; and (iii) the estimated value of the inefficiency (u_i) should be non-positive for all observations, and the meaning of the residual term in the second step is unclear (KUMBHAKAR et al., 1991). In this paper, we follow the 'direct' or 'single step' approach. In the 'direct' or 'single step' approach, the exogenous factors affecting technical inefficiency are included directly in the production function and are specified as:

$$Y_i = f\left(X_i, Z_i, \beta\right)\exp\left(V_i - U_i\right) \tag{7}$$

The variables included in Equation (7) can be conveniently sorted into two: the input variables$\left(X_i\right)$, and the managerial (inefficiency) variables$\left(Z_i\right)$. However, there is a third group of variables, known as environmental production conditions, that may or may not be exogenous and are usually not included in the model. The omission of environmental production conditions has at least three consequences: biased estimates of the parameters describing the production frontier, overstatement of technical inefficiency, and biased estimates of the correlates of true technical inefficiency (SHERLUND et al., 2002). To overcome this problem, SHERLUND et al. (2002) have measured plot-specific environmental production conditions and have incorporated these into Equation (7).

In this paper, we approached the problem of omission of environmental production conditions differently than SHERLUND et al. (2002). In order to allow comparisons of technical efficiency between irrigated plots and rain-fed plots, we use a non-parametric matching method (or Propensity Score Matching Method) to identify those rain-fed plots that are relatively comparable to the irrigated plots based on their plot characteristics and agro-ecological conditions[5]. Since most of the adjustment for potentially confounding control variables is done non-parametrically, the potential for bias in comparison of technical efficiency of irrigated and rain-fed plots is substantially reduced compared to parametric analyses based on raw data (HO et al., 2007). We assume that the pre-processing procedure reduces the variance of the estimated causal effects. The argument is that in the pre-processed data, the variance with rain-fed plots is reduced to the same level as that of irrigated plots, putting them at the same "benchmark" or on the same "playing field." To the best of our knowledge, this is the first paper to adopt such a method of balancing the heterogeneous character of plots for efficiency analysis.

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[5] The STATA output of the estimation of Propensity Score Matching Method is attached in Appendix.

The following hypotheses were empirically tested in this paper:

H1: *Irrigation shifts the production frontier outwards*. The implication is that the average product of an input used in irrigated agriculture is greater than the average product of the same amount of input used in rain-fed agriculture $(AP_{iI} > AP_{iR})$, where the subscript i represents the input, and I and R refer to irrigation and rain-fed, respectively.

H2: *Technical inefficiency is greater on irrigated farm/plot than on rain-fed farm/plot*. Since irrigation technology is newer than rain-fed agricultural technologies, farmers may need more time to learn the new technology to become efficient.

4.2 Estimation Methods

We used plot- and village-level variables to match and non-parametrically generate comparable rain-fed and irrigated sample plots. We employed a nearest neighbor matching method to identify rain-fed plots that are comparable to irrigated plots. 562 of the 1,727 rain-fed plots were found to match the 426 irrigated plots. We ensured that the common support and balancing properties were satisfied (see appendix 1). The argument is that in the matched plots, the effect of exogenous physical factors on technical efficiency is similar between rain-fed and irrigated plots, allowing for comparative analysis. We assumed that matched plots are homogeneous and that comparative stochastic frontier analysis on these plots is more appropriate. In Tigray, the locations of irrigation projects were selected based on topographical and geological features, where priority was given to drought prone areas. We assumed that village- and plot-level characteristics capture factors that determine access to irrigation. In the region, irrigation projects are commonly found in lowland areas. The results of the PSM analysis concur with these observations. The major distinguishing features of irrigated plots are that they have sandy and clayey soils, characterized by plain topography, less susceptible to erosion and degradation, and have relatively good land quality (appendix 1). Thus, the selected comparable rain-fed plots share these characteristics[6].

The parameters of the stochastic production frontier model in equation (1) and those for the technical inefficiency model in equation (2) were estimated simultaneously through the maximum-likelihood estimation (MLE) method using the statistical package FRONTIER 4.1 (COELLI, 1996).

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[6] We do not claim that the selected rain-fed plots are statistically representative of the rain-fed system in Tigray region. Our aim was to compare the efficiency and productivity of irrigated and rain-fed agriculture within a comparable biophysical settings.

We specified a general form of a translog function as follows:

$$\ln(Y_i) = \beta_0 + \sum_{k=1}^{k} \beta_k \ln(X_{ik}) + \frac{1}{2}\sum_{k=1}^{k}\sum_{j=1}^{k} \gamma_{jk} \ln(X_{ij}) \ln(X_{ik}) - U_i + V_i, \tag{8}$$

$$U_i = Z_i \delta + \omega_i$$

Y = the logarithm of the value of output
X_1 = the logarithm of the size of cultivated plot (in tsimdi)
X_2 = the logarithm of the total amount of fertilizer used (in kg)
X_3 = the logarithm of the total amount of seed (Birr)
X_4 = the logarithm of total labor used (man- days)
X_5 = the logarithm of total oxen used (oxen days)

The farm-specific inefficiency variables are:
Z_1 = education (number of literate household members)
Z_2 = access to credit
Z_3 = access to an extension service
Z_4 = access to an all-weather road (as a proxy for access to a market)

We performed a likelihood ratio test to test whether the two full translog stochastic frontier production functions could be reduced to Cobb-Douglas or to one of the partial translog functional forms (see table 2). The likelihood ratio (LR) test is specified as:

$$LR = -2(L_R - L_U) \tag{9}$$

Where L_R and L_U are the restricted and unrestricted likelihood functions, respectively. If the calculated χ^2 (LR) value is less than the tabulated upper 5% point of the critical value, we accepted the specified null hypothesis at a 5% level of significance (KODDE AND PALM, 1986).

As reported in table 2, tests 1 and 2 examine the null hypotheses that the stochastic frontier production functions of irrigation and rain-fed agriculture, respectively, reduce to Cobb-Douglas or to one of the partial translog functional forms (with interaction or square terms). The null hypotheses were accepted at the 5% level in favor of Cobb-Douglas for irrigated stochastic frontier production functions, and in favor of partial translog (with interaction terms) for rain-fed stochastic frontier production functions. Due to a problem of multicollinearity, however, we specified both production functions as Cobb-Douglas production functions. In fact, in a technical efficiency analysis, functional specification has a small impact (KOPP and SMITH, 1980); therefore, our decision to use the Cobb-Douglas form is reasonable.

Table 2. Generalized likelihood-ratio tests of hypotheses for model specifications and parameters of technical inefficiency

Null Hypothesis	**Calculated χ^2 Statistics**	**Degrees of freedom**	**Critical Value of χ^2_{df},0.95**	**Decision**
IRRIGATION				
Model specification: The Stochastic Frontier Production Function for Irrigation Reduces to a Cobb-Douglas				
1) $H_0 : \beta_6 = \beta_7 = \beta_8 =,...,= \beta_{20} = 0$	22.064	15	24.996	Accept H_0
Inefficiency parameters				
3) $H_0 : \gamma = \delta_0 =,...,\delta_4 = 0$	33.793	6	11.911	Reject H_0
4) $H_0 : \gamma = 0$	23.902	4	8.761	Reject H_0
5) $H_0 : \delta_1 =,...,\delta_4 = 0$	31.922	4	9.488	Reject H_0
RAIN-FED				
Model specification: The Stochastic Frontier Production Function for Rain-fed Reduces to a Partial Translog Without Square Terms				
2) $H_0 : \beta_6 = \beta_7 = \beta_8 =,...,= \beta_{10} = 0$	9.755	5	11.071	Accept H_0
Inefficiency parameters				
6) $H_0 : \gamma = \delta_0 =,...,\delta_4 = 0$	46.139	6	11.911	Reject H_0
7) $H_0 : \gamma = 0$	33.631	4	8.761	Reject H_0
8) $H_0 : \delta_1 =,...,\delta_4 = 0$	4.991	4	9.488	Accept H_0

The critical values for the tests involving $\gamma = 0$ are obtained from table 1 of KODDE and PALM (1986).
Source: authors' survey

We have made a series of likelihood ratio tests concerning the inefficiency parameters. Tests 3 and 6 in table 2 assume that all irrigated and rain-fed plots, respectively, are technically efficient. The restrictions required for testing these are that all the parameters of the inefficiency variables (δ) and the variance parameter (γ) are equal to zero. Both tests are rejected in favour of the alternative hypotheses that at least one irrigated and one rain-fed plot are not fully technically efficient. Tests 4 and 7 imply that the variance parameter is equal to zero$(\gamma = 0)$ in the irrigation and rain-fed stochastic frontier production functions, respectively. Here again, the likelihood ratio test accepts that the inefficiency effects are stochastic, implying that$\gamma \neq 0$. If the opposite were accepted, it would mean that both the irrigation and rain-fed stochastic frontier production functions could have been reduced to traditional mean response functions, in which case the inefficiency variables could have been included in the stochastic frontier production functions. The critical values for the test statistics are obtained from a mixed Chi-square distribution[7] with four degrees of freedom.

Test 5 and 8 examine whether the inefficiency variables have no effect on the level of technical inefficiencies. This implies that all the δ parameters, except the intercept, are equal to zero. The test result for the stochastic frontier production function of irrigated plots suggests that in combination, access to credit, number of educated household members, access to a market, and access to extension have statistically significant effect on the inefficiency of irrigated agriculture. However, the individual effect of some of these variables may not be significant. On the other hand, the likelihood ratio test confirms that inefficiency of rain-fed agriculture in Tigray is not a function of the effect of a combination of access to credit, education, access to a market, and access to an extension service, although the individual effect of some of these variables can be significant.

Finally, we estimated an OLS regression on agricultural output, controlling for the effect of village and plot characteristics. The OLS regression results are consistent with the maximum likelihood frontier estimates, implying that the effect of bio-physical factors on the technical efficiency of smallholders was well-controlled in the preprocessed data.

5 Analytical Results and Discussion

The results of the Cobb-Douglas stochastic frontier production functions of irrigated and rain-fed plots are presented in table 3. Among inputs used in the stochastic frontier production function of irrigated agriculture land ($P<0.001$), seed ($P<0.01$), Fertilizer ($P<0.1$) and oxen ($P<0.001$) are significantly different from zero. On the other hand land ($p<0.001$), seed ($P<0.1$), labor ($P<0.01$) and oxen ($P<0.1$) were found to be statistically significant in the stochastic frontier production function of rain-fed agriculture. But the effect of seed and chemical fertilizer on the stochastic frontier production function of rain-fed agriculture was found to be negative although the fertilizer effect is not statistically significant. The implications are that: (1) the performance of improved seed is inferior to local seeds under-moisture stressed rain-fed production conditions, and (2) yield response to chemical fertilizer under moisture-stressed rain-fed production condition is poor. This is consistent with findings of previous study from Niger (ABDOULAYE and SANDERS, 2005).

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[7] The likelihood ratio test statistic, $\gamma = -2\left\{\log\left[Likelihood\left(H_0\right)\right] - \log\left[Likelihood\left(H_1\right)\right]\right\}$ has approximately chi-square distribution with a degree of freedom equal to the number of parameters assumed to be zero in the null hypothesis, H_0, provided H_0 is true (BATTESE AND COELLI, 1995). The mixed $\chi^2_{v,0.95}$ values are taken from KODDE and PALM (1986).

Table 3. Maximum likelihood estimates of the stochastic production frontier and technical inefficiency models for irrigation and rain-fed production functions

Variable	Description	Parameter	Irrigation (N = 426)	Rain-fed (N = 562)
Stochastic Frontier				
LnQ	Gross value of output in Birr			
cons	Intercept	β_0	7.319*** (0.175)	5.673*** (0.138)
LnA	Land (tsimdi = 0.25 ha.)	β_1	0.269*** (0.010)	0.246 (0.036)***
LnF	Chemical fertilizer (kg)	β_2	0.023* (0.014)	-0.002 (0.006)
LnS	Seed (Birr)	β_3	0.136*** (0.040)	-0.045* (0.026)
LnL	Labor (man-days)	β_4	0.071 (0.064)	0.113 (0.042)***
LnO	Oxen (oxen days)	β_5	0.242*** (0.064)	0.092* (0.049)
	Returns to Scale		0.741	0.403
Variance parameters				
	$\sigma_s = \sigma_u^2 + \sigma_v^2$		0.898 (0.048)	0.898 (0.048)
	$\gamma = \sigma_u^2 / \left(\sigma_u^2 + \sigma_v^2\right)$		0.005 (0.012)	0.005 (0.012)
Inefficiency effects				
cons	Intercept	δ_0	1.173*** (0.396)	-214.208*** (0.071)
Farasso	Access to credit from farmer association (1 = yes,)	δ_1	-0.350*** (0.100)	-29.434 (21.238)
Litrate	Number of literate household members	δ_2	-0.063** (0.033)	15.347** (6.159)
Allwthrodwdis	Walking distance to all-weather road in minutes	δ_3	-0.004*** (0.001)	-0.909*** (0.239)
Extewdis	Walking distance to extension service in minutes	δ_4	0.014*** (0.003)	2.006*** (0.480)
hhage	Household age (Proxy for farming experience)	δ_5	0.014 (0.019)	-6.753** (3.157)
Hhage2	Square of the household head age	δ_6	-0.00007 (0.0001)	0.071**
Log likelihood Function		-561.427	-2368.610	

* Significance at 10% level. ** Significance at 5% level. *** Significance at 1% level. Figures in parentheses are standard errors.

Source: authors' survey

5.1 Average and Marginal Products

Table 4 presents the average and marginal products of inputs used in the stochastic frontier production models of irrigated and rain-fed agriculture. The results confirm our first hypothesis (H1), which states that irrigation shifts the production frontier of smallholder agriculture outwards. Irrigated agriculture requires approximately 1.6 *tsimdi* of land, 8.4 kg of fertilizer, 84 Birr worth of seed, 21.1 man-days of labor, and 6.8 oxen days to produce 1,235.7 Birr worth of agricultural product. On the other hand, in rain-fed agriculture 5.8 *tsimdi* of land, 7.8 kg of fertilizer, 53.4 Birr worth of seed, 33.6 man-days of labor, and 8.0 oxen days was required to produce about 654.0 Birr worth of product. This indicates that, as expected, the production frontier of irrigated agriculture is higher than that of rain-fed agriculture.

Table 4. Average and marginal product of input used in irrigated and rain-fed agriculture (in Birr)

Type of input	Irrigation			Rain-fed		
	Amount of input used	Average Product	Marginal product	Amount of input used	Average Product	Marginal product
Total Average product (Birr)[a]		**1,235.7**			**654.0**	
Land (*tsimdi*)	1.64	753.5	202.6	5.78	113.2	27.8
Fertilizer (kg)	8.36	147.8	3.42	7.77	84.2	-0.20
Seed (Birr)	84.12	14.7	2.00	53.42	12.2	-0.55
Labor (man days)	21.12	58.5	4.15	33.57	19.5	2.20
Oxen (oxen days)	6.84	180.7	43.75	7.96	82.2	7.53

[a] The total average product shows the value of the agricultural product produced on a cultivated plot. The average size of cultivated irrigated and rain-fed plots is 0.41 and 1.45 hectares, respectively.

Source: authors' survey

The marginal products of all inputs are positive in irrigated agriculture, while the marginal products of fertilizer and seed are negative in rain-fed agriculture. A negative marginal product implies the poor yield response to seed and fertilizer technologies under moisture stress. Experimental studies indicate that, under soil moisture stress, increased fertilizer application will induce rapid plant growth which will enhance the rate of evapotranspiration and the depletion of the limited soil moisture and consequently results in reduced dry matter production (ZAKIA et al., 2008; GRANT et al., 1991). These results explain the reasons behind the reluctance of farmers in Ethiopia and in Tigray in particular to adopt improved seed and fertilizer technologies under moisture stressed rain-fed production conditions. Fertilizer use and expenditure on improved seed per unit area in Tigray is very low by any standards (HAGOS, 2003; PENDER and GEBREMEDHIN, 2004). At national level, despite more than decades of policies placing high priority on cereal intensification backed by high rate of public expenditure on seed-fertilizer technologies, Ethiopia has not seen payoffs in terms of higher and more stable cereal yields (BYERLEE et al., 2007).

5.2 Technical Efficiency

We hypothesized (**H2**) that farmers are less efficient on irrigated plots than on rain-fed plots because of the relative skill and knowledge needs of irrigated agriculture. Table 5 presents a summary of the average technical efficiency and potential output that can be gained by improving technical efficiency.

Table 5. Technical efficiency and actual and potential output levels of irrigated and rain-fed agriculture

	Irrigation	Rain-fed
Average Technical Efficiency (%)	0.45	0.82
Minimum Technical Efficiency (%)	0.25	0.40
Maximum Technical Efficiency (%)	1.00	1.00
Actual average value of Gross Output (Birr)/average size of cultivated land[a]	1235.7	654.0
Potential Output (Birr)/average size of cultivated land	2362.7	721.5
Potential Increment in Output (Birr)/average size of cultivated land	1127.0	67.5

[a] The average size of cultivated irrigated and rain-fed plots is 0.41 and 1.45 hectares, respectively.

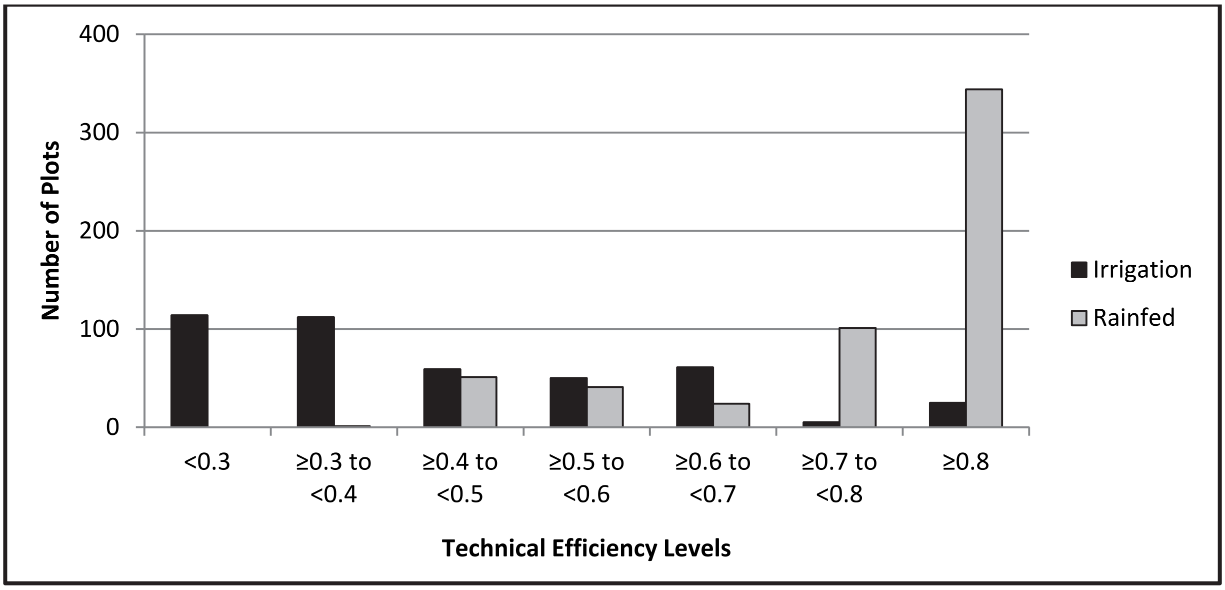
Source: authors' survey

The frequency distribution of technical efficiency levels are presented in figure 1. The result shows a wide range in the level of technical efficiencies across plots. The average technical efficiencies of irrigated and rain-fed plots are 45% and 82%, respectively. These figures indicate that rain-fed agriculture operates close to its production frontier, while irrigated agriculture produces at less than 50% of its potential. The proportion of plots with an efficiency score of at least 80% is significantly higher in rain-fed agriculture than in irrigated agriculture, whereas the opposite is true for the proportion of plots having an efficiency score below 30%. For example, if an average rain-fed plot increases its efficiency to that of the most efficient rain-fed plot, its level of output can merely increase by 67.5 Birr.

The production frontier of irrigated plots is on higher level than that for rain-fed plots, meaning that the productivity of irrigated plots is higher than that of rain-fed crops.

This supports our hypothesis that farmers are technically efficient on their rain-fed plots as compared to irrigated plots. Because irrigation is new production technology for smallholder farmers in Tigray, they may need more time to learn and make efficient use of irrigation water.

Figure 1. Frequency distribution of technical efficiency indices for irrigated and rain-fed farms



Source: authors' survey

On the other hand, if an average irrigated plot increases its efficiency level to the level of the most efficient irrigated plot, its level of output can increase by 1,127 Birr without any additional input or cost. The sample mean of technical efficiencies indicates that, on average, output falls short of the maximum level by 47.5% in irrigated agriculture and by 9.4% in rain-fed agriculture. The already high technical efficiency of rain-fed agriculture in Tigray indicates that there is limited scope for increased agricultural production through improving the technical efficiency of the exiting rain-fed systems alone. Thus, substantial improvement in rain-fed farming systems can only be made through introducing new technologies including soil moisture conservation measures. On the other hand, improving the efficiency of existing irrigated agriculture can be a policy option.

5.3 Technical Inefficiencies

Given the data and model specification, the results indicate that variables included in the technical inefficiency model contribute significantly to the explanation of technical inefficiencies of rain-fed and irrigated agriculture both as a group and individually.

The technical inefficiencies are consistent with the results of maximum likelihood estimation, summarized in the lower panel of table 3. As expected, access to credit (*farasso*) and number of literate household members (*litrate*) reduce the technical inefficiency of irrigated agriculture. The effect of access to credit on the inefficiency of irrigated and rain-fed agriculture was as expected but not significant. Also as walking distance to extension service, which is a proxy for access to extension, decreases inefficiency decreases and this particularly so for rain-fed agriculture.

We used farmers' age as a proxy for learning-by-doing and experience variable. We expected a non-linear relationship between inefficiency and farmers' age, i.e., as the farmers' age increases inefficiency decreases but only up to a certain point beyond which inefficiency increases as farmers get older and older. Our expectation was found to be true for the rain-fed inefficiency model. The result for irrigation inefficiency model is unexpected but not statistically significant. The effect of the number of literate household members used here as a proxy for level of education or managerial skill was significant but unexpected for rain-fed model, which is in contrast to its effect in the irrigation model. Note the substitution possibility between formal education and experience as exemplified by the switch in the direction of effect and statistical significance of literacy (Literate) and household age variables. The implication is that for rain-fed agriculture experience is more important in explaining in-efficiency while in irrigated agriculture formal education is the most important.

Education may enhance farmers' ability to interpret and make good use of information about markets and prices in environments where such attributes are particularly necessary (AHMED et al., 2002).

Walking distance to all weather roads in minute was used as a proxy for market access. However, the direction of effects is unexpected in both irrigated and rain-fed models. The probable explanation for this anomaly is that the walking distance to extension service variable may have explained both the effects of market access and extension services.

6 Conclusions and Recommendations

In this paper, we used a single-step analysis to estimate both the stochastic frontier and inefficiency models simultaneously. This analysis is innovative in that it used Propensity Score Matching method to select rain-fed plots that are similar in characteristics to irrigated plots. This process eliminated the effect of plot/farm level biophysical characteristics that blur the true differences in the technical efficiencies between irrigated and rain-fed farms or fields. The potential to increase production by improving technical efficiency is immense in irrigated agriculture, while rain-fed agriculture seems to be producing close to its production frontier. Average input productivities are higher for irrigated agriculture than for rain-fed agriculture, suggesting that irrigation shifts the production frontier of smallholders outwards. The returns to scale, though diminishing both under irrigated and rain-fed smallholder agriculture in Tigray, is higher under irrigated agriculture.

Agricultural production on irrigated land can be more than doubled without additional inputs, if the following interventions are implemented to improve production efficiency of irrigated plots in the study areas:

- Provision of training for farmers to improve their skills in irrigation agronomy, on-farm water management, and general farm management capabilities.
- Provision of credit services to allow timely procurement of complementary inputs. The availability of affordable and timely credit solves liquidity constraints of the farm household. In fact, access to credit can have a twofold effect. First, it shifts the production frontier upward through its effect on the capacity of the producer to invest in inputs. Second, it indirectly affects the level of production through its effect on technical inefficiency.
- Improving the marketing systems. Access to market favors the production of high-value cash crops, which are usually associated with irrigated agriculture.
- Improving irrigation scheme level management to improve water allocation and distribution and reliability.

The farmers seem to manage well their rain-fed systems given the circumstances and the pay-off from improvements in efficiency is limited. Thus, improving the soil moisture may push the production frontier upwards by enhancing the yield contribution of critical inputs such as improved seeds and fertilizer.

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Appendix. Propensity Score Matching Regression Result

Algorithm to estimate the propensity score			
The treatment	is irrigation		
type of plot,			
1=irrigated			
, 0=rainfed	Freq.	Percent	Cum.
rain-fed	1,727	80.21	80.21
irrigated	426	19.79	100.00
Total	2,153	100.00	

Estimation of the propensity score

Iteration 0: log likelihood = -1070.9587
Iteration 1: log likelihood = -1000.8779
Iteration 2: log likelihood = -996.22233
Iteration 3: log likelihood = -996.09776
Iteration 4: log likelihood = -996.0974

Logistic regression Number of obs = 2153
LR chi2(14) = 149.72
Prob > chi2 = 0.0000
Log likelihood = -996.0974 Pseudo R2 = 0.0699
Source: authors' survey

irrigation	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
ownership1 (ownership of land 1=owned, 0=otherwise)	.3925052	.1704408	2.30	0.021	.0584474	.726563
ownership2 (ownership of land 1=rented in, 0=otherwise)	.4099115	.3728426	1.10	0.272	-.3208465	1.14067
Ownership3 (ownership of land 1=sharecropped in, 0=otherwise)	Control variable (Omitted)					
soiltype1 (soil type, 1=sandy loam, 0=otherwise)	-.0442967	.1801247	-0.25	0.806	-.3973346	.3087412
soiltype2(soil type, 1=clay, 0=otherwise)	.4359981	.155088	2.81	0.005	.1320313	.739965
soiltype3 (soil type (1=sandy, 0=otherwise)	.6398343	.1635901	3.91	0.000	.3192035	.9604651
Soiltype4 (soil type (1=clay loam, 0=otherwise)	Control variable (omitted)					
soildept1 (soil depth, 1=deep, 0=shallow)	.6527585	.1687156	3.87	0.000	.3220821	.983435
slope1 (Slope, 1=plain, 0=steep)	-.4360765	.1972914	-2.21	0.027	-.8227607	-.0493924
landqual1(Land quality, 1=good, 0=poor)	.4376706	.1823276	2.40	0.016	.080315	.7950262
suscepti1 (susceptibility to land erosion, 1=high, 0=otherwise)	-.3207419	.5001139	-0.64	0.521	-1.300947	.6594633
degreeso1 (Degree of land degradation, 1=no degradation, 0=degraded)	.9488908	.3963284	2.39	0.017	.1721015	1.72568
agroecology1(1=highland, 0=otherwise)	-.2003768	.1778889	-1.13	0.260	-.5490326	.1482791
agroecology2 (1=midland, 0=otherwise)	-.0587315	.1310939	-0.45	0.654	-.3156709	.1982079
Agroecology3 (1=lowland, 0=otherwise)						
Cv (Rainfall coefficient of variance)	-.5386024	.4880896	-1.10	0.270	-1.49524	.4180356
Hheadsex (Household head gender, 1=mail, 0=female)	-.0978094	.1424242	-0.69	0.492	-.3769558	.1813369
_cons (constant)	-3.25166	.5059899	-6.43	0.000	-4.243382	-2.259938

Note: the common support option has been selected.

The region of common support is [.04767298, .3983292].

Description of the estimated propensity score in region of common support.

Estimated propensity score.
Source: authors' survey

Percentiles	Smallest			
1%	.0558018	.047673		
5%	.0662152	.047673		
10%	.0861477	.047673	Obs	2053
25%	.1122256	.047673	Sum of Wgt.	2053
50%	.2059637	Mean	.2043473	
	Largest	Std. Dev.	.0973518	
75%	.2713475	.3983292		
90%	.3554216	.3983292	Variance	.0094774
95%	.3630154	.3983292	Skewness	.2375364
99%	385921	.3983292	Kurtosis	1.884494

****

Step 1: identification of the optimal number of blocks

Use option detail if you want more detailed output.

****

The final number of blocks is 4.

This number of blocks ensures that the mean propensity score is not different for treated and controls in each blocks.

****

Step 2: test of balancing property of the propensity score

Use option detail if you want more detailed output.

****

The balancing property is satisfied.

This table shows the inferior bound, the number of treated and the number of controls for each block.

type of plot,		
Inferior	1=irrigated,	
of block	0=rainfed	
of pscore	rain-fed irrigated	Total
.047673	143 7	150
.0714286	472 49	521
.1428571	703 211	914
.2857143	309 159	468
Total	1,627 426	2,053

Note: the common support option has been selected.

****

End of the algorithm to estimate the pscore

****

Source: authors' survey