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Norwegian University of Life Sciences • Universitetet for miljø- og biovitenskap
Department of Economics and Resource Management
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Risk and Irrigation Investment in a Semi-Arid Economy

Risiko og vanningsinvesteringer i en tørrlands økonomi

Gebrehaweria Gebregziabher Gebrezgi

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Ås, October 2008.
Gebrehaweria Gebregziabher

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Introduction

Risk and Irrigation Investment in a Semi-Arid Economy

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1. Introduction

The northern Ethiopian highlands experience substantial agriculture production risk due to the critical problems of land degradation, soil nutrient depletion and erratic rainfall (Berg and Ruben, 2006; Hagos, 2003; Pender and Gebremedhin, 2004). This difficult situation is aggravated by low levels of agricultural input use. Smallholder rain-fed agriculture is the mainstay of the economy and accounts for about 85% of employment, 50% of GDP and more than 90% of export earnings (MoFED, 2007; World Bank, 2005; WRD, 2008). On the other hand, population pressure is increasing at an alarming rate, reducing land holdings to as small as less than one hectare (Pender and Gebremedhin, 2004). For these and other reasons, rural poverty is a widespread problem (Hagos, 2003), where most households live with an income of less than one dollar per day (Pender and Gebremedhin, 2004). Although some expansion of agricultural land may still take place in the Tigray region, it mainly occurs on more marginal lands, which leads to further environmental degradation that aggravates poverty. Therefore, agricultural intensification to produce enough food and reduce poverty become at the centre of the Ethiopian development strategy, known as “Agricultural Development Led Industrialization” (ADLI).

Since 1991, the Ethiopian government has adopted a series of pro-market policy reforms that mainly target agriculture. In the early 1990s, output and input markets were liberalized by lifting restrictions on private grain trade, compulsory delivery quotas and the farm gate price ceiling (World-Bank, 2005). These policy initiatives were meant to give price incentives to producers and improve food market integration. In the mid 1990s, however, there was a shift in policy priorities in favor of improving agricultural productivity. A green revolution-type agricultural extension program known as "Participatory Demonstration and Training Extension Systems" (PADETES) was adopted. Fertilizer, improved seed and credit together with training on input use and better agricultural practices were the main components of PADETES (World Bank, 2005). As part of the reform program, the fertilizer market was fully liberalized in 1997, when subsidies and retail price control were abolished.

The country's perennial food aid dependency, which is more serious in the Tigray region, has been largely attributed to the over-reliance on smallholder rain-fed agriculture. Recognizing the seriousness of the problem, the rural development strategy was slightly revised in 2002 to emphasize water harvesting and small-scale irrigation development as focal points of the development strategy.

In line with the national development strategy, the regional government of Tigray has embarked on an ambitious irrigation development program, especially after the establishment of the Commission for Sustainable Agricultural and Environment Rehabilitation of Tigray (CoSAERT) in 1995 (Abraha, 2003; Berg and Ruben, 2006). During the period of 1995-2006, more than 7 million Birr[1] was invested in irrigation projects, including 54 micro-dams and 106 river diversion irrigation schemes (Abraha, 2003). These collectively irrigate 3491 hectares that account for about 1.2% of irrigable land during the 2005/06 agricultural season. In addition, a number of pond and shallow well water harvesting programs were implemented

[1] Birr is the Ethiopian currency (1 USD was equal to about 8.65 Birr at the time of data collection, i.e., in 2006).

at a household level, through which about 2909 hectares was irrigated (BoNAR, 2006). Furthermore, about 15000 hectares were irrigated using traditional farmer initiated methods, making up 5% of irrigation potential (Teshome, 2003). These were mainly used to supplement rain-fed agriculture, especially when rainfall ceased early before flowering occurred. In addition to this, different local and international NGOs have also participated in the development of small-scale irrigation and water harvesting schemes.

Although the existing level of irrigation coverage is quite low compared to the potential level, considerable efforts have been made to invest in irrigation development. The purpose of this PhD dissertation is, therefore, to study a farm households' production and consumption behavior in a semi-arid environment and to examine how access to irrigation affects the households' decision behavior. Irrigation is included in the analysis to explore its impact on several factors: production risk due to weather shocks, households' input use and agricultural intensification, agricultural production, productivity, and income. Empirical evidence that comprehensively studies the impact of small-scale irrigation in Ethiopia is limited, particularly in Tigray. Even some of the empirical evidence from the same area (e.g., Berg and Ruben, 2006; Hagos, 2003; Pender et al., 2002; Pender and Gebremedhin, 2007) contains conflicting results, creating doubts about the return on irrigation investments in the region. For example, Berg and Ruben (2006) reported that irrigation had a significant effect on household level expenditures, while Pender et al. (2002) and Pender and Gebremedhin (2007) could not find a significant impact of irrigation either on input use or on farm income. Hagos (2003) found another counter-intuitive result, a negative relationship between irrigation and fertilizer use.

Therefore, the objective of this dissertation is to investigate the following research questions.

- How does the land rental market in combination with irrigation contribute to mitigate households' temporary consumption pressure and enhance household food security?
- How does production risk affect households' fertilizer adoption? How do food deficit households respond to production risk? Does access to irrigation stimulate fertilizer adoption?
- Does access to irrigation increases the smallholders' production frontier? Is there any difference in the level of technical efficiency of farmers on irrigated plots as compared to rain-fed plots? Is there room to increase agricultural production given the current input use and technology?
- Does investment in irrigation increase household income and reduce poverty? Does the type of irrigation technology affect the ability of irrigation to increase household income, off-farm activity and income?

This PhD dissertation consists of four articles that independently address the four set of research questions using various econometric methods on household and plot level survey data[2]. The summaries of results are presented in section 6 below.

2. Overall Theoretical Framework: Production risk, Market imperfections, Institutions and Household Behavior

2.1. General Background: Institutions and Markets

In recent years, two strands of economic theories (i.e., the transaction cost and imperfect information schools) have been developed and challenge the neoclassical paradigm. The neoclassical framework argues that markets (including future markets) for all goods and risks

[2] Data was collected by the PhD student. A summarized part of the questionnaire that was use for data collection is attached as an Appendix.

exist and, therefore, market-clearing prices determine economic relationships (Bardhan, 1989; Hoff *et al.*, 1993). This analysis, however, fails to explain what happens if market are missing and prices do not adjust to market clearing levels. Furthermore, the neoclassical argument is inconsistent with many observations. For example, it fails to provide an explanation why sharecropping and cost sharing exist, and why cost sharing differs from output shares (Stiglitz, 1986). It also fails to recognize that many individuals cannot buy insurance against many important risks that have important implications on their behavior (Stiglitz, 1986). Therefore, the transaction costs and imperfect information schools emerged largely in response to the absence of markets for many goods and services and the fact that many transactions of goods and services are based on many non-price factors. Both theories oppose the Walrasian neoclassical economics on the basis that the transaction cost and imperfect information are important determinants of contracts in economic transactions (Bardhan, 1989).

The transaction cost literature argues that a price system is intrinsically limited because transaction costs (mainly information and enforcement costs) lead some markets to fail and to be non-competitive (Hoff et al., 1993). Hence, allocation of resources (property rights) becomes difficult with high transaction costs. Accordingly, institutions that evolve to reduce such costs (such as the cost of information, negotiation, monitoring, and enforcement of contracts) are, therefore, the key to economic performance (Bardhan, 1989; Hoff et al., 1993). Unlike neoclassical arguments, both the transaction cost and imperfect information arguments assume that institutions are endogenous, and are defined as rules that constrain the kinds of exchanges and incentives in the transactions of goods that are determined by contracts and social norms. These rules have important implications for the economics of rural organizations (Akerlof, 1970; Cheung, 1969; Stiglitz, 1974). For example, Cheung

(1969) stated that sharecropping emerged due to its risk dispersion effect at lower transaction costs than other alternative contracts (such as insurance or fixed rental contracts). Furthermore, the transaction cost literature emphasized the importance of contracting costs in shaping the institutional arrangements. For instance, Akerlof (1970) argues that in developing countries, the limited role of price systems and informational problems leading to adverse selection and moral hazards have implications in the credit and insurance markets. Asymmetric information also leads to pervasive market imperfections (Ray, 1998). On the other hand, if monitoring costs are significant in wage contracts, sharecropping contracts might emerge as a response to imperfect markets for the tenants' effort and for risk (Stiglitz, 1974). Hence, this implies that institutions are adaptable and endogenous (Stiglitz, 1986).

The Imperfect Information theory is used to model many agrarian institutions that substitute for missing markets (such as credit and insurance markets) in an environment where risk, information asymmetry and moral hazard are pervasive (Bardhan, 1989). For example, Stiglitz (1986) argues that the efficiency of a market economy depends on certain conditions, such as perfect information and a complete set of markets. With imperfect information and incomplete markets, the economy is constrained pareto-inefficient (Stiglitz, 1986). This implies opportunities almost always exist for interventions that can improve efficiency.

In general, institutions are defined as the rules of the game that constrain human interactions and provide incentives for individuals to engage in productive or unproductive (for that matter) economic, social or political interactions (North, 1990). North (1990) argues that institutions provide a stable structure for cooperative human interactions in the presence of incomplete information and a large number of players, especially from the perspective of increased transaction costs.

In addition to the transaction cost and imperfect information schools of economics, this dissertation draws on the theoretical framework developed by Binswanger and Rosenzweig (1986), which has been further developed in Binswanger et al. (1989) for semi-arid areas. The general assumptions are that (1) individual farm households face risk from production, market and health factors; (2) the acquisition of information has costs; (3) individuals are self-interested in their well-being and value their consumption; (4) there is a point for individuals beyond which they do not want to make additional effort, implying that (5) these individuals become risk-averse whenever their gains and losses exceed some level of income. The degree of risk aversion may differ between individuals, and even for the same individual at different levels of wealth (Binswanger et al., 1989). These assumptions have a wide range of implications in conceptualizing the relationship between risk, insurance against risk, information asymmetry, transaction costs and market imperfections (Binswanger and Rosenzweig, 1986). The basic contribution of Binswanger et al. (1989) to the transaction cost and imperfect information analyses is their application in a semi-arid tropical agriculture where the biophysical production relationships have substantial implications on risk, market characteristics (such as credit and insurance market imperfections) and human behavior.

2.2. Biophysical production relations

In less developed countries, agricultural land is an essential factor of production and is spatially dispersed. The immobility of land implies that other factors have to be brought to it, hence, agricultural production decisions involve travel and transport costs (Binswanger and Rosenzweig, 1986). The spatial nature of agricultural production creates a wide range of risks (Binswanger et al., 1989). For example, due to weather variability and other nature related factors, the yield and prices are unknown before production takes place. Similarly, the amount and timing of input use depends on the seasonal variation of weather conditions, which cannot be known in advance for certain. The duration of rainfall is very short, making agricultural production seasonal. Moreover, agricultural production takes place on small and fragmented (spatially dispersed) plots. In combination with the short duration and high variability of rainfall, this means that agriculture production consists of highly synchronous and overlapping activities. This implies that timing is critical for input application and agricultural production in general; therefore, if modern inputs (such as fertilizer) are not applied at the right time, they may not be as effective as expected or they even may have adverse consequences (Abdoulaye and Sanders, 2005). Thus, crop yields have a high positive and substantial covariate risk (Binswanger et al., 1989).

This PhD dissertation examines the effect of investment in irrigation on households' production behavior and well-being in a densely populated semi-arid environment. In Binswanger and Rosenzweig (1986) and Binswanger et al. (1989), low population density and abundant land availability were assumed to imply that there is no market for land, while in Tigray (the study area), the population density varies from 40 to 750 persons/Km^2 in the highlands (Hagos, 2003; Hagos *et al.*, 1999), and leading to small farm size and land scarcity. Land is a government ownership in the name of the public. Farmers are given user rights to land through their communities. Farmers have limited rights in the form of perpetual user rights, the right to bequeath, the right to obtain compensation for their investment in the land in case they lose the land, and the right to lease their land for a limited period. However, land sale is illegal and cannot be used as collateral for credit. With the exception of the scarcity of land and the presence of land rental markets, the premises for the Binswanger and Rosenzweig (1986) and Binswanger et al. (1989) analysis fits this study area well.

In general, farm households in Tigray face production (income) risk due to covariate risks such as rainfall failure (drought), rainfall variability (both in time and space), pests, floods and other natural calamities that affect whole communities or due to idiosyncratic risks that only affect individuals, such as illness. Moreover, transport and communication networks in the rural areas of Tigray are less developed where information is asymmetrically distributed and costly.

2.3. Risk in semi-arid areas and farm households' behavior

Much of the literature (Binswanger et al., 1989; Dercon, 2005; Udry, 1994) that explores the consequence of risk for individual behavior focuses on *ex-ante* strategies which risk-averse households might use to respond to risk. Risk-aversion implies that individuals are willing to pay some positive amount as an insurance premium against risks. However, the success of insurance may depend on the availability of information about the product and credit worthiness of the insured where collateral may be needed.

Moreover, the type of collateral also matters, because not all assets are suitable as collateral. For example, collateral should not be subject to risk because of damage or death of livestock, and must be payable to the lender in case of default (Binswanger et al., 1989). In this case, in areas where there is a legal constraint against using land as collateral and animals are subject to death due to drought, poor rural households are more likely to be screened out (Binswanger et al., 1989). As a response to the adverse selection, therefore, poor farmers may concentrate on less risky activities (Stiglitz and Weiss, 1981) or may use self-insurance strategies. For instance, farmers may diversify their income strategies by participating in different institutions, such as sharecropping, which may compromise allocative efficiency in order to reduce income fluctuations (Udry, 1994). In the case of *ex-ante* consumption pressure and economic hardship, poor farm households may sell land (or rent it in areas where land sale is legally prohibited) as a coping strategy where the non-farm economy is poorly developed and access to non-farm income is constrained (Holden, 2007; Masterson, 2007; Ruben and Masset, 2003).

Dercon (2005) argued that households' endowment, such as selling of animals and other assets, depleting past savings, off-farm employment, or consumption reduction might be used as self-insurance mechanisms. However, poor farm households that lack both *ex-ante* and *ex-post* consumption smoothing may not adopt profitable but risky technologies (such as fertilizer), and this may have negative consequences on their future income and food security (Udry, 1994). On the other hand, if the household has access to *ex-post* consumption smoothing (such as credit for consumption and crop insurance), incentive problems (moral hazards and adverse selection) may arise because those who are insured against *ex-post* income and consumption risk may lack incentive to work hard and to invest in purchased inputs (Binswanger and Rosenzweig, 1986).

The covariate risks usually affect whole communities and may affect both crop and livestock production. The implication is that it is difficult to cope with covariate risk within the community (Dercon, 2005), while insurance against idiosyncratic risks (such as transient illness) can be easily contained within the community (Dercon, 2005) because individuals may use social networks such as kinship contracts (Ghebru and Holden, 2008; Kassie and Holden, 2007). For example, Udry (1994) argued that farm households in Nigeria whose ancestors have lived in the same village for longer periods receive higher loans than those whose families have migrated recently.

2.4. Market imperfections and household behavior

When markets are characterized by high transaction costs due to asymmetric information and imperfect competition (WDR, 2008), production and consumption decisions cannot be separated (de Janvry and Sadoulet, 2006; Shiferaw et al., 2006). This implies that when market failure is prevalent and institutional support is absent, households' production decisions are affected by their consumption characteristics (de Janvry and Sadoulet, 2006). Under such conditions, initial labor and asset endowments affect households' resources use, production efficiency and well-being. Farm households' livelihood strategies are therefore conditioned by their endowments (both human capital and assets).

Credit market imperfections also affect households' production and consumption decisions. The household production levels that face credit constraints depend on their initial liquidity status (Feder *et al.*, 1990). The implication is that a household may respond to risk either through smoothing its consumption at a given level of income (Deaton, 1992) or reducing exposure to risk through adjustments in income generating strategies and other risk sharing mechanisms. The extent to which a farm household adjusts its investment decisions in response to *ex-post* risk exposure depends on its ability to smooth consumption (Rosenzweig and Binswanger, 1993), which in itself depends on savings and access to credit (Ghosh *et al.*, 2000; Lamberte *et al.*, 2006). This implies that if a household has access to credit for consumption smoothing, it may not need to save for insurance against *ex-post* production/consumption risk; therefore, resources are free for investment in the current period (Komicha, 2007; Lamberte et al., 2006). On the other hand, if farmers face or anticipate credit constraints, they may tend to limit their consumption and investment in the current period and save as an insurance against *ex-post* production and consumption risk

(Deaton, 1991, 1992; Komicha, 2007). This may include less use of purchased inputs (such as fertilizer).

3. Conceptual Framework

This section uses the foregoing theoretical basis of a farm household behavior and institutional theory. The framework (Figure 1) attempts to capture the relationship between production risk, technology adoption, imperfect markets and households' production, consumption, investment and coping behavior. To improve the food security status, the federal government in general and the regional government of Tigray in particular have formulated a poverty reduction strategy and a series of policy interventions. For example, substantial investment has been made in small-scale irrigation, soil and water conservation and safety-net programs. To implement these poverty reduction programs, different institutions have been constituted at different levels, including the Bureaus (Co-SARET, BoNAR), micro-finance (credit) institutions, tabia councils[3], farmer associations and water user associations. Of course, culture, norms, rules and regulations may have an impact during the implementation of the programs. However, this dissertation limits itself to investigate the effect of risks (both consumption and production risks) on household production decisions and the role of irrigation in households' technology adoption and efficiency on households' production behavior. The conceptual framework has been summarized in Figure 1.

The linkages between government policies (such as irrigation investment) and households' well-being are both direct and indirect. The direct linkages operate through households'

[3] Tabia is the lower level administration according to the Tigray Regional Government structure.

production and consumption behavior, while the indirect effect may cover different dimensions, both at household or higher levels (see Figure 1)[4].

Usually, off-farm employment and livestock selling are used as first candidate coping strategies before land sale/rent (Corbett, 1988; Dercon, 1999; Ruben and Masset, 2003). However, this may lead to an excess supply of labor and livestock in the market. Under such conditions, the poor are attacked from three sides (Holden and Shiferaw, 2004). First, agricultural production fails due to drought and bad weather conditions, which has negative implications on households' food stocks. Second, livestock prices and wage rates decrease, and third, food prices increase, thereby adversely affecting households' coping abilities. In the absence of buffer stocks, therefore, land rental may be used to meet immediate cash needs, probably with future negative consequences, because the poor are more vulnerable and may lose their land for an indefinite period of time (Basu, 1986; Holden, 2007; Masterson, 2007; Ruben and Masset, 2003) because they may not have the capacity to pay their debt and claim back their land. On the other hand, since irrigated agriculture is input intensive (both labor and other inputs), irrigation may aggravate the liquidity constraints of poor households, which in turn may affect their production and consumption behavior and may encourage them to rent out their land.

The impact of irrigation on household income and poverty reduction is captured through two major pathways (i.e., through land and labor productivity). Irrigation enhances the use of agricultural inputs, such as fertilizer, which in turn improves the productivity of land and agricultural labor, leading to high household income and food security. This may be caused either by the external shock minimizing effect of irrigation that leads to high fertilizer use or

[4] We emphasize the major linkages and pathways to demonstrate this relationship.

by the irrigated land and labor augmentation effect. Rainfall variability makes it risky for farmers to adopt fertilizer (Sushil, 2004). For example, FAO (1999) reported that higher productivity and production is associated with high input use. Furthermore, since crops may grow year round, irrigation may help poor households to spread production more evenly over the course of a year (Reardon and Taylor, 1996)

Although the technical efficiency effect of irrigation is subject to study, access to irrigation is assumed to shift the production frontier outwards. Unlike rain-fed agriculture, irrigation increases crop intensity, which can be a source of difference in production and productivity. Access to irrigation also helps to switch from low yielding, less profitable crops to high yielding cash crops. If all other variables remain constant, this implies switching from subsistence production to market-oriented production, which may lead to higher productivity and efficiency.

Another dimension in which irrigation can impact household income and food security is through its spillover effects. The economic integration (linkages) effect of irrigation is important, but in most cases remains masked. As discussed above, households with access to irrigation obtain a direct benefit through increased and more stable income or because of the higher value of irrigated land. On the other hand, even landless laborers and small farmers (net buyers of food) often benefit from irrigation through higher wages, lower food prices and a more balanced diet (FAO, 2003). However, the employment generation of small-scale irrigation could remain localized at the household level and could be closely tied to the ownership of irrigated land due to the low level of infrastructure and economic integration. Furthermore, due to the small size of irrigated plots, farmers may depend on their family's labor to cultivate their land. In general, the indirect effects of access to irrigation can be captured through intermediate pathways.

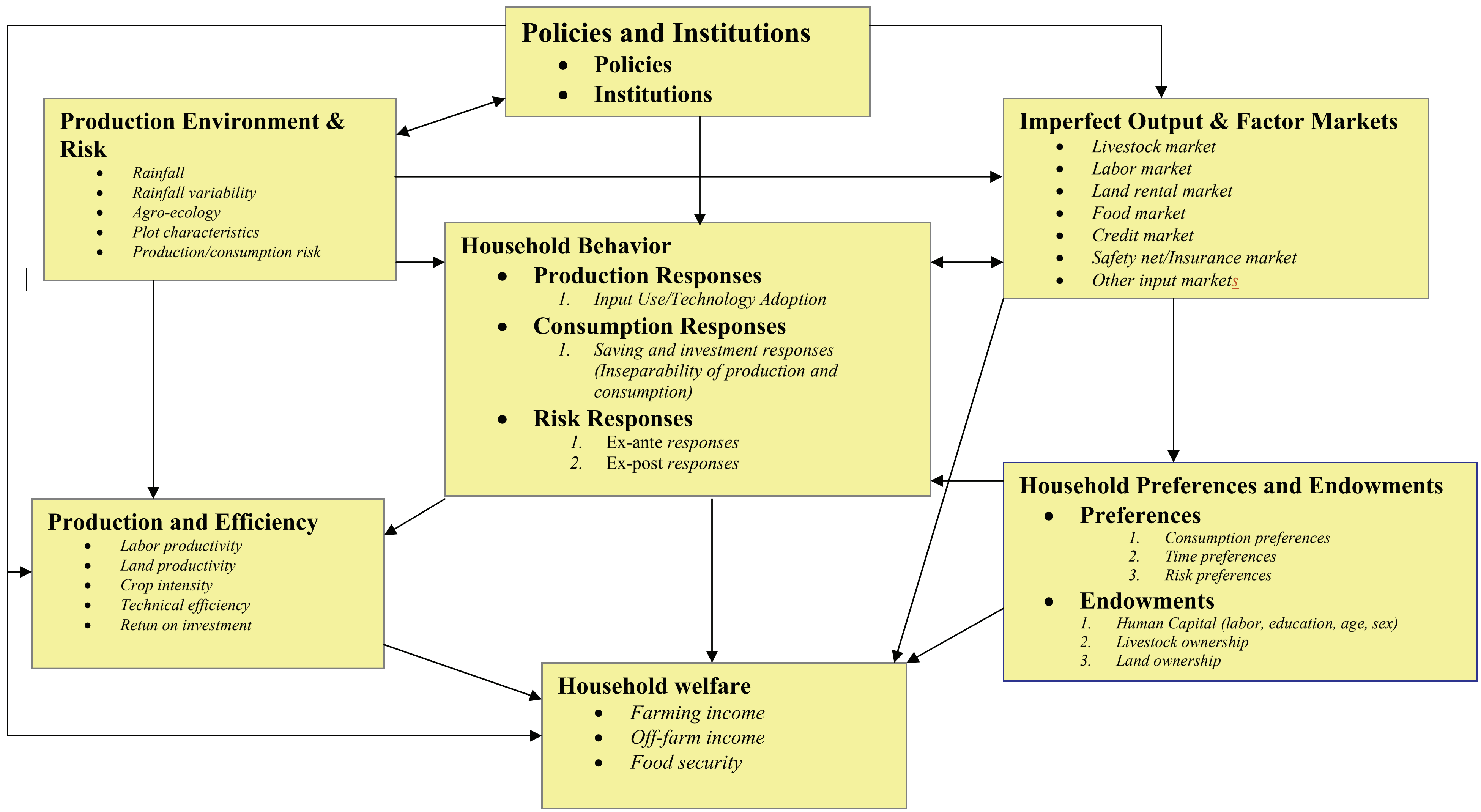

Figure 1: Production risk, technology adoption (irrigation, fertilizer), market imperfections, production and household welfare.

4. Study Area and Data

The data used in this dissertation are obtained from a survey conducted to study the impact of small-scale irrigation on a farm household's production activities, technical efficiency and income in the Tigray region. Tigray is located in the northern part of Ethiopia (see Figure 2). The total population of the region is estimated to be 4.17 million, of which 85% is engaged in agriculture (BoFED, 2006). The total area of the region is about 53000 Km^2, of which about 2 million hectares is cultivable land, of which about 300,000 hectares is irrigable (BoFED and Co-SAERT, 2001).

Data were collected from a sample of rural households using three-stage stratified random sampling. First, all *tabias* in the region with irrigation projects were stratified based on the irrigation technology, altitude, size of irrigable land, and experience. In the second stage, we stratified all farm households in each *tabia* based on their ownership of irrigated land. Finally, we randomly sampled 613 farm households (100 sample households from each of the five *tabias* and 113 households from tabia *Kara-Adi-Shawo*). Of the total of 613 sample households, 331 had access to irrigation, while the remaining 282 were purely rain-fed cultivators. In total, six sites were selected from four zones of Tigray (see Figure 2 and Table 1). Among the six sites, two of them use micro-dams, two use river diversions, and the other two use groundwater for irrigation (see Table 1).

Table 1
Sample households by zone, wereda and tabia

Location			Total households	Total households with access to irrigation	Number of sample households			Type of irrigation technology
Zone	Wereda	Tabia			With access to irrigation	Without access to irrigation	Total	
South	Saharti-Samre	Addi-Alem	1390	696	56	44	100	Micro-Dam
South	Raya-Azebo	Kara-Adishawo	1660	229	39	74	113	Ground water[a]
Eastern	Wekro	Laelay Agulae(Mesanu)	1213	857	76	24	100	River Diversion
Central	Kola Tembien	Adiha	1209	957	70	30	100	River Diversion
Western	Laelay Adiybo	Adigedena	1438	380	43	57	100	Micro-Dam
Western	Tahtay Koraro	Mai-Adrasha	736	474	47	53	100	Ground water[b]
Total			8646	3593	331	282	613	

[a] Kara-Adishawo uses pressurized tube irrigation, [b] Mai-Adrasha uses a shallow-well

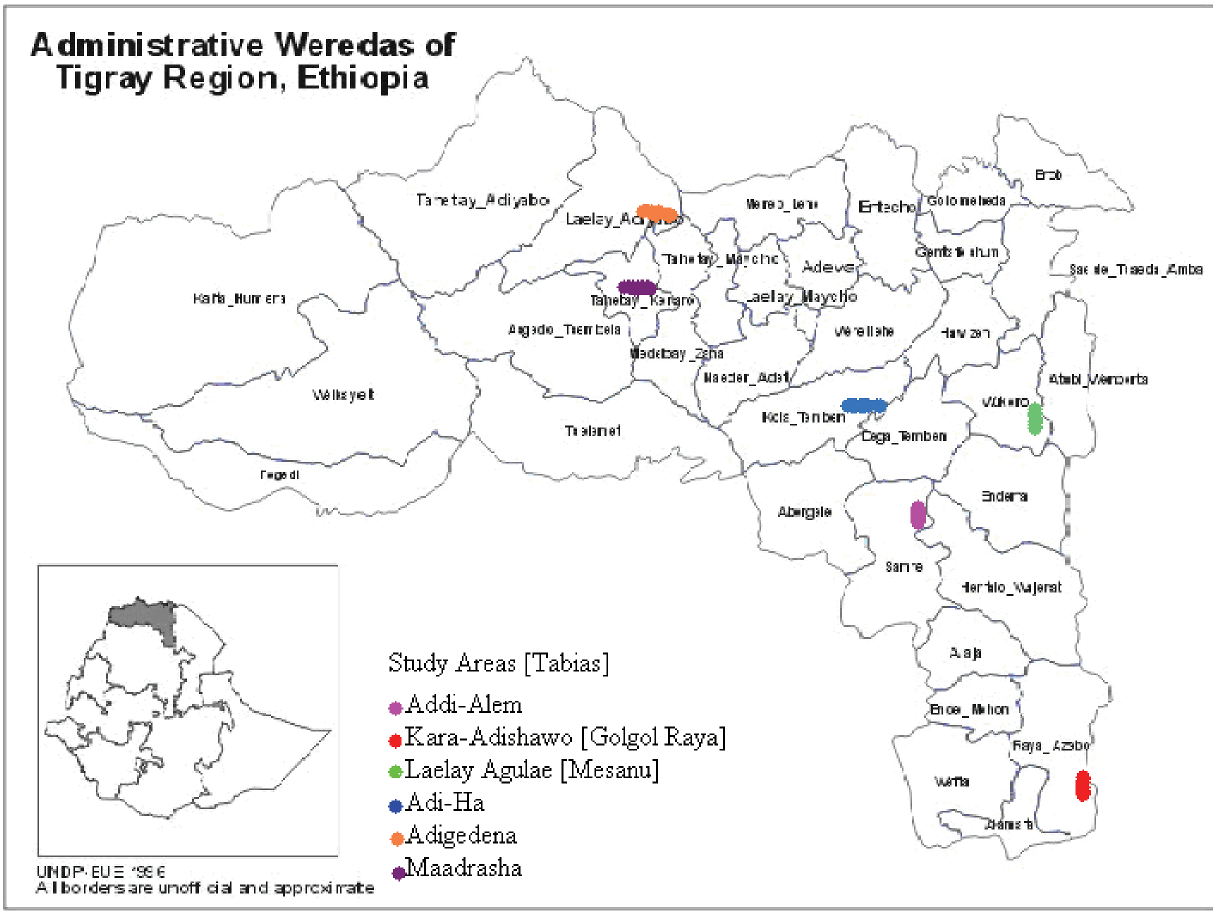

Figure 2: Map of Ethiopia and the Tigray Region .

5. Overall assessment of irrigation and agricultural production in Tigray

Ethiopia is one of the most abundant recipient countries of water in the east African region (Makombe *et al.*, 2007), which has about 12 river basins with an annual runoff of 122 billion m^3 and 2.6 billion m^3 ground water (Awulachew *et al.*, 2006). However, only about 5 to 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). Out of the 12 river basins, 3 of them are found in Tigray. The total annual runoff that can be used for irrigation is about 13.6 billion m^3. Until 2006, however, less than 1% of this potential has been developed to irrigate about 7% of the 300,000 ha of irrigable land (BoFED, 2006)[5]. Even with this large potential, the country in general and Tigray in particular fail to produce enough food to feed its population.

Based on secondary data from BoFED, the total cultivated area during the 2006 agricultural season was about 1.9 million hectares, of which only about 0.02 million hectares was irrigated (see Table 2). Using our sample data to estimate average production/ha, we calculate that the value of extra food (crop) production due to irrigation was about 49.73 million Birr per annum. This indicates that the regional food production may have increased by about 5.60 percent during 2006.

[5] BoFED= Bureau of Finance and Economic Development

Table 2
Summary of agricultural potential, estimated expected output and extra output (2006)

Land, Population and Production	Values
Total area (Km^2)	54548
Population (in million people)	4.17
Population density (people/Km^2)	76
Average annual rainfall (mm)	635
Cultivated Area (in million ha.)	
• Rain-fed	1.84
• Irrigated	0.02
• Total	1.86
Production per hectare*	
• Rain-fed	451
• Irrigation	3014
Agricultural Production (in million Birr)	
• Rain-fed	830.82
• Irrigation	58.48
• Total	889.29
Estimated value of extra production from irrigation (million Birr)	49.73
Estimated extra production from irrigation (in %)	5.6
Estimated reduction in food prices (in %)	3.9**

Source: (BoFED, 2006) and own calculation
* Values were estimated based on our survey data (see Paper 3), ** the demand elasticity for food was estimate to be about -0.7 (Regmi *et al.*, 2001)

According to Regmi *et al*. (2001) and Levinsohn and McMillan (2003), the demand elasticity of food (cereals) for low income countries was estimated at -0.7. Using this demand elasticity, the estimated extra production due to irrigation may have reduced output prices by about 4% and may have created indirect benefits to consumers, while the general equilibrium could have reduced the direct benefits to producers (farmers) who may have been net-sellers during the 2006 production year. Remember that these estimates are based on highly restrictive assumptions such as constant elasticity of demand for food, constant average productivity per hectare on irrigated and rain-fed farms at the same level of average productivity as in our sample data, and constant levels of technical efficiency.

6. Summary of papers

The four papers that addressed the research questions are summarized below.

Paper I

Distress Rentals and the Land Rental Market as a Safety Net: Evidence from Tigray, Ethiopia

Rural households in the semi-arid northern Ethiopian highlands are net buyers of food. Crop failure due to erratic and unpredictable rainfall occurs frequently and leads to food shortage and income shocks. These households may respond through *ex-post* coping responses in which asset selling (such as livestock) and off-farm labor employment come first. Such coping responses may then lead to an excess supply of livestock and labor in the local markets, causing a downward pressure on livestock prices and wage rates. Accordingly, poor households are affected by shocks due to their low food stocks and then due to reduced livestock prices and wage rates. This may further push food prices upward. In such circumstances, the least endowed farm households may fail to cope with such shocks, and are then forced to rent out their land due to immediate needs.

Although there is a growing literature on land rental contracts, there remains little understanding about the effect of capital constraints and temporary pre-harvest consumption shocks on land rental contract choices. Paper one develops a theoretical model for poor landlord rural households that face shocks (such as a short-term pre harvest liquidity constraint) and can choose between own cultivation of land or renting out through sharecropping or fixed rent when production is risky. We hypothesize that risk is an explanation for the choice of sharecropping, while distress rent is a response to random shocks to meet immediate cash needs. These hypotheses are tested using survey data from households with and without access to irrigation in a semi-arid area in northern Ethiopia. In order to get a better measure of the random shock portion of food stock, we estimated a probit model to predict the probability that a household has enough food stock in the previous year, from which we generated a residual where the negative part is used as a measure of food shock. This was used as an indicator of random shocks in the contract choice model. A Multinomial logit model was employed for the estimation of the land use and contract choice models.

The Multinomial logit model estimates indicate that poor households may prefer fixed rent contracts to owner cultivation. We also see that random food shortages push towards fixed rent contracts compared to sharecropping contracts. These results support the hypothesis that poor households use fixed rent contracts as a response to temporary food shortage. We further assessed the relationship between production risk, access to irrigation and contract choice. Fixed rent contracts are chosen over owner cultivation and sharecropping on irrigated plots and in areas where rainfall variability is lower. This indicates that fixed rent contracts are not necessarily distress contract choice responses, but may also be preferred when production risk is low.

We found that in areas with high rainfall variability, sharecropping was preferred over owner cultivation and fixed rent. This probably indicates that risk is an important reason for the emergence of sharecropping. Access to credit was also found to influence land rental contract choice, possibly indicating that if farm households are short of cash to buy inputs, access to credit may favor owner cultivation, while fixed rent may be preferred when credit is also needed to fill immediate consumption gaps. Finally, we examine the implication of coping strategies on contract choice. Selling of animals and other assets was found to be negatively related with fixed rent versus owner cultivation. This indicates that this coping strategy is more appropriate for wealthier households (i.e., livestock and labor rich households) who prefer to cultivate their land themselves, while the choice of fixed rent contracts as a coping strategy is more appropriate for the poor who face income shocks and who lack animals to sell.

This paper contributes methodologically and empirically to the body of literature on land rental markets and contract choice. First, the causal relationship between capital constraints/food shortages due to random shocks and land rental contract choice is new to this paper. Second, this paper captures random shocks in a novel way. Third, the nature of the problem, i.e., distress rental as a coping strategy, had not previously been carefully researched.

Paper II

Does Irrigation Enhance and Food Deficit Discourage Fertilizer Adoption in a Risky Environment? Evidence from Tigray, Ethiopia

Most households in Tigray are poor net buyers of food. On the other hand, the average land holding is small and there are limited possibilities for area expansion. This calls for agricultural intensification in order to produce enough food on the small farms. Input use (intensification), however, may depend on both production risk and consumption shocks. The literature on technology adoption (input use) and household behavior under production and consumption risks provide mixed arguments about producers' response. One element of the literature is based on the risk-averse profit maximizing firm model, and shows that under price risk, the firm will under-invest and under-produce to reduce its exposure to risk. On the other hand, restricting the analysis of risk only to pure producer firms may result in wrong conclusion when the producer consumes part of her/his product and faces multivariate risk from both price and income. Therefore, consumption risk is also relevant to the analysis. Accordingly, the literature shows that if people are poor and concerned about their survival, the solution might not be to under-invest and under-produce.

This paper assesses three issues: 1) The effect of production risk due to rainfall scarcity and rainfall variability on fertilizer adoption, 2) the role of irrigation to hedge against production risk and its role to stimulate fertilizer use, 3) the effect of food deficit (consumption shocks) on fertilizer adoption. In order to test the effects of households' food self-sufficiency and actual food deficits on households' fertilizer adoption, we run a probit model to predict the probability that households were food self-sufficient. We then use the residual of the predicted probability of food self-sufficiency to generate two dummy variables that capture food deficit households that were predicted to be food deficient and food deficient households that were predicted to be food self-sufficient.

Using a Cragg (Double Hurdle) model, it was found that households were significantly more likely to use fertilizer and used significantly higher amounts of fertilizer on irrigated plots than on rain-fed plots. Furthermore, households with access to irrigation were significantly more likely to use fertilizer, but those irrigating households using fertilizer did not use more of it than households without irrigation. The probability and intensity of fertilizer use were significantly higher in areas with higher average rainfall and in areas with lower rainfall variability. Irrigation was significantly more important for fertilizer adoption and fertilizer intensity in areas with lower rainfall. Irrigation had a stronger positive effect on the intensity of fertilizer use in areas with high rainfall variability. The probability of households being food self-sufficient was significantly negatively associated with the probability of fertilizer use. Food deficient households that were predicted to have food deficits were significantly less likely to use fertilizer; however, those households who decided to use fertilizer used significantly more fertilizer than households that did not have a food deficit.

Overall this paper concludes that the covariance between income and price risk may cause the risk premium to be negative for food deficit households and induce them to adopt and use more fertilizer to reduce their future food deficits. Furthermore, these results indicate that investment in irrigation can be an important policy instrument to enhance food security in semi-arid and drought prone areas where fertilizer can enhance food self-sufficiency.

Paper III

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

Technical efficiency is defined as the ability of a firm to produce the maximum output from a given set of inputs and technology. Unlike manufacturing and service firms, which have considerable control over their production environment, traditional agriculture relies heavily on environmental conditions. Despite this fact, most empirical studies on the technical efficiency of smallholder agriculture lack data to control for the effect of biophysical factors. Since biophysical factors are rarely symmetrically distributed, the omission of such factors may lead to an upward bias in the estimates of technical inefficiency.

This paper: 1) estimates the technical efficiency of irrigated and rain-fed agriculture, 2) identifies the sources of technical inefficiencies of small-scale irrigated and rain-fed agriculture, and 3) makes policy recommendations to enhance the technical efficiency of irrigated and rain-fed agriculture. We assumed that irrigated plots are more homogeneous in terms of soil type, soil quality, slope and agro-ecology, implying that stochastic frontier analysis may be better suited to capture inefficiency on irrigated land than on more heterogeneous rain-fed plots. This problem is tackled using a non-parametric matching method to identify those rain-fed plots that are relatively comparable to the irrigated plots based on their plot and environmental characteristics. The paper combines the non-parametric matching method with stochastic frontier analysis. This has the advantage that it allows us to create a more level playing field for comparison of technical efficiency in rain-fed and irrigated agricultural production.

The parameters of technical efficiency and inefficiency effects were estimated simultaneously using a maximum likelihood estimation method. Although we find that the average technical efficiency of irrigated agriculture is less than that of rain-fed agriculture, the production frontier of irrigated plots is higher than that of rain-fed plots. We found that the average technical efficiencies on irrigated and rain-fed plots are 45 and 82 percent, respectively. Therefore, the potential to increase agricultural production given current input use and technology is substantial on irrigated land, while rain-fed plots are producing close to their production frontier. This might be an indication that new investments in rain-fed agriculture are needed to uplift the production frontier, while efficiency improvements of irrigated agriculture could be an important strategy. In general, appropriate food security strategies could include efficiency improvement on irrigated land and making new investment in rain-fed agriculture.

This paper contributes to informed policymaking in the area of investments in irrigation and efficiency improvements of smallholder agriculture. It also contributes to the body of literature broadening our knowledge about smallholders' technical efficiency by providing insights from northern Ethiopia. This paper uses matched plots where potentially confounding factors can be controlled non-parametrically. We assume that in the pre-processed data, the variance of the estimated causal effects in rain-fed plots is reduced to the same level as that of irrigated plots, putting them at the same "benchmark" or "level of playing field". To the best of our knowledge, such a method of balancing heterogeneous characters of plots for technical efficiency analysis has not been used before.

Paper IV

Investment in Irrigation and its Impact on Household income: Empirical Evidence from Tigray, Ethiopia

This paper investigates the impact of access to irrigation on farm household income. To estimate the income effect of irrigation, we apply both propensity score matching and switching regression methods. Nearest neighbor, kernel and stratification matching methods were used to non-parametrically estimate the income effect of irrigation. Stochastic dominance analysis was also used to examine the incidence (head count ratio) and depth (gap) of poverty among farm households with and without access to irrigation. The combination of these methods allows the robustness of the results to be tested.

Households with access to irrigation were found to have more diversified income sources, of which farming income constitutes the most important. Consumption expenditure was also higher for irrigators than pure rain-fed cultivators. Furthermore, households with access to irrigation use more hired labor as compared to rain-fed cultivators, possibly indicating the labor absorption effect of irrigation. Estimation results indicate that the mean income of irrigating households was significantly higher than that of the non-irrigating households. According to the estimated results of the alternative matching methods, the average income gain due to access to irrigation ranges from 4090 to 4940 Birr per household per annum. However, differences were observed between the different types of irrigation technologies. The estimation result from the switching regression method also showed a significant gain from irrigation, where the estimated extra income was about 2363 Birr.

The observed income gain and consumption difference is also mirrored in the stochastic dominance analysis. This showed that the incidence (head count ratio) and depth (gap) of poverty are unambiguously lower for households with access to irrigation.

Despite the substantial investments that have been made in irrigation, no comprehensive analysis conducted to date. This paper makes an important empirical contribution. First, the propensity score matching, switching regression and stochastic dominance analyses results contribute to the existing but scant literature on irrigation-poverty linkages. It also makes an important contribution to enhance informed policymaking in relation to food security and investment in irrigation.

7. Overall conclusion

The empirical studies reviewed above lead to the following overall conclusions.

- Irrigation was found to significantly enhance fertilizer adoption and had a stronger positive effect on the intensity of fertilizer use in areas with low rainfall and high rainfall variability. This, therefore, may give an indication of where to locate irrigation investment. However, this need to be supported with overall cost-benefit analysis means that it may also be more costly to invest in irrigation in dryer areas.
- The findings in Tigray show that investment in irrigation has increased the production frontier in smallholder agriculture. The amount of production per hectare is

substantially higher on irrigated farms than on rain-fed farms. The average and marginal product of input use is also significantly higher in irrigated agriculture than in rain-fed agriculture. Moreover, the average income of households that have access to irrigation is significantly higher than the average income of households that have no access to irrigation. The head count ratio and poverty gap estimates also indicate that the well-being of households with access to irrigation have improved.

- The rough regional level (macro) estimates indicate that food production in the region has so far been increased by 5-6% because of irrigation investments, and this may have contributed to reducing the food prices by about 4% as an extra benefit to the net buyers of food. Simply scaling up the figures, assuming that the same productivity could be achieved on all potentially irrigable land in Tigray, it is estimated that food production can be increased by about 80%.
- However, the technical efficiency of irrigated agriculture is still low so that the potential of the investments discussed above has not yet been fully utilized. This may indicate that side by side with new investments, improving the efficiency of irrigated agriculture could be an important policy option to enhance food production. Further research is required to better understand the reasons for low technical efficiency on irrigated land and how best to enhance this efficiency.

References

Abraha, Z., 2003. Business Plan: First Draft, Executive Summary. Tigray Regional National State, Bureau of Water Resource Development (Irrigation Construction enterprise), Mekelle.

Abdoulaye, T., Sanders, J. H., 2005. Stages and determinants of fertilizer use in semiarid African agriculture: the Niger experience Agricultural Economics. 32 (2), 167–179.

Akerlof, G. A., 1970. The Market for "Lemons": Quality Uncertainty and the Market Mechanism. The Quarterly Journal of Economics. 84(3), 488-500.

Awulachew, S. B., Menker, M., Abesha, D., Atnafe, T., Wondimkun, Y., 2006. Background: About the Symposium and Exhibition. Best practices and technologies for small scale agricultural water management in Ethiopia: MoARD/MoWR/USAID/IWMI symposium and exhibition, held at Ghion Hotel, Addis Ababa 7-9 March. International Water Management Institute (IWMI).

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T., 2007. Water Resources and Irrigation Development in Ethiopia. Working Paper 123. International Water Management Institute.

Bardhan, P., 1989. The New Institutional Economics and Development Theory: A Brief Critical Assessment. World Development. 17(9), 1389-1395.

Basu, K., 1986. The Market for Land: An Analysis of Interim Transactions. Journal of Development Economics 20 163-177.

Berg, M. V. D., Ruben, R., 2006. Small-Scale Irrigation and Income Distribution in Ethiopia. Journal of Development Studies. 42(5), 868–880.

Binswanger, H., McIntire, J., Udry, C., 1989. Production Relations in Semi-arid African Agriculture. In: Bardhan, P. (Ed.), The Economic Theory of Agrarian Institutions. Oxford University Press, New York.

Binswanger, H. P., Rosenzweig, M. R., 1986. Behavioral and material Determinants of Production Relations in Agriculture Journal of Development Studies 22 503-539.

BoFED, 2006. Five year Strategic plan of the Regional Government of Tigray (Tigrgna version). Mekelle, Ethiopia.

BoFED, Co-SAERT, 2001. Preliminary Assessment on Socio-economic and Environmental Impacts of Dams (First Draft). Bureau of Finance and Economic Development and Co-SAERT.

BoNAR, 2006. cultivated land and production by irrigation & number of beneficieries- 1998 EFY. Bureau of Natural and Agricultural Resources, Mekelle.

Cheung, S. N. S., 1969. Theory of Share Tenancy Chicago, III: . University of Chicago Press.

Corbett, J., 1988. Famine and Household Coping Strategies. World Development. 16(9), 1099-1112.

de Janvry, A., Sadoulet, E., 2006. Progress in the Modeling of Rural Households' Behavior Under Market Failures. In: de-Janvry, A., Kanbur, R. (Eds.), Poverty, Inequality and Development, Essays in Honor of Erik Thorbecke. Kluwer publishing, USA.

Deaton, A., 1991. Saving and Liquidity Constraints. Econometrica. 59(5), 1221-1248

Deaton, A., 1992. Household Saving in LDCs: Credit Markets, Insurance and Welfare. The Scandinavian Journal of Economics 94(2), 253-273

Dercon, S., 1999. Ethiopia: Poverty Assessment Study, Revised version of report for IFAD

Dercon, S., 2005. Risk, Insurance, and Poverty: A Review. In: Dercon, S. (Ed.), Insurance Against Poverty. Oxford University Press, New York.

FAO, 1999. Poverty Reduction and Irrigated Agriculture. International Program for Technology and Research in Irrigation and Drainage,Issues paper No. 1, January, Rome.

FAO, 2003. Water and food Security. The State of Food Insecurity in the World: Monitoring progress towards the World Food Summit and Millennium Development Goals, Italy.
Feder, G., Lau, L. J., Lin, J. Y., Luo, X., 1990. The Relationship between Credit and Productivity in Chinese Agriculture: A Microeconomic Model of Disequilibrium. American Journal of Agricultural Economics. 72(5), 1151-1157
Ghebru, H., Holden, S., 2008. Factor Market Imperfections and Rural Land Rental Markets in Northern Ethiopian Highlands. In: Holden, S., Otsuka, K., Place, F. (Eds.), The Emergence of Land Markets in Africa: Assessing the Impacts on Poverty, Equity and Efficiency. Resources For the Future Press, New York.
Ghosh, P., Mookherjee, D., Ray, D., 2000. Credit Rationing in Developing Countries: An Overview of the Theory. In: Mookherjee, D., Ray, D. (Eds.), A Reader in Development Economics. Blackwell, London.
Hagos, F., 2003. Poverty, Institutions, Peasant Behavior and Conservation Investment in Northern Ethiopia. PhD Thesis. Agricultural University of Norway, Department of Economics and Resource Management, Ås, Norway.
Hagos, F., Pender, J., Gebreselassie, N., 1999. 'Land Degradation in the Highlands of Tigray and Strategies for Sustainable Land Management', Socioeconomic and Policy Research Working Paper No. 25. International Livestock Research Institute, Ethiopia.
Hoff, K., Braverman, A., Stiglitz, J. E., 1993. Introduction. In: Hoff, K., Braverman, A., Stiglitz, J. E. (Eds.), The economics of rural organization: Theory, practice, and policy. Oxford University Press, New York.
Holden, S., 2007. Growing Importance of Land Tenancy and its Implications for Efficiency and Equity in Africa. Department of Economics and Resource Management, Norwegian University of Life Sciences
Holden, S., Shiferaw, B., 2004. Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: a bio-economic model with market imperfections. Agricultural Economics 30, 31-49.
Kassie, M., Holden, S., 2007. Sharecropping efficiency in Ethiopia: threats of eviction and kinship. Agricultural Economics. 37, 179–188.
Komicha, H. H., 2007. Farm Household Economic Behaviour in Imperfect Financial Markets: Empirical Evidence and Policy Implications on Saving, Credit and Production Efficiency in Southeastern Ethiopia. Doctoral Thesis. Swedish University of Agricultural Sciences, Department of Economics, Uppsala.
Lamberte, M. B., Vogel, R. C., Moyes, R. T., Fernando, N. A. (Eds.), 2006. Beyond Microfinance: Building Inclusive Rural Financial Markets in Central Asia. Asian Development Bank, Philippines.
Levinsohn, J., McMillan, M., 2003. Does Food Aid Harm the Poor? Household Evidence from Ethiopia. (accessed 25,09,08 http://www-personal.umich.edu/~jamesl/food.pdf).
Makombe, G., Kelemework, D., Aredo, D., 2007. A comparative analysis of rainfed and irrigated agriculture production in Ethiopia. Irrigation and Drainage Systems: Published online. 21, 31-44.
Masterson, T., 2007. Land Rental and Sales Markets in Paraguay. Working Paper No. 491, Working Paper No. 491. The Levy Economics Institute of Bard College.
MoFED, 2007. Ethiopia: Building on Progress: A Plan for Accelerated and Sustained Development to End Poverty (PASDEP) Annual Progress Report 2005/06. Ministry of Finance and Economic Development (MoFED).
North, D. C., 1990. Institutions, Institutional Change and Economic Performance. Political Economy of Institutions and Decisions. Cambridge University Press, USA.

Pender, J., Gebremedhin, B., 2004. Impacts of Policies and Technologies in Dryland Agriculture: Evidence from Northern Ethiopia. In: Challenges and Strategies for Dryland Agriculture. CSSA Special Publication no. 32.

Pender, J., Gebremedhin, B., 2007. Determinants of Agricultural and Land Management Practices and Impacts on Crop Production and Household Income in the Highlands of Tigray, Ethiopia. JOURNAL OF AFRICAN ECONOMIES.

Pender, J., P.Jagger, Gebremedhin, B., Haile, M., 2002. Agricultural Change and Land Management in the Highlands of Tigray: Causes and Implications. Policies for Sustainable Land Management in the Highlands of Tigray, Northern Ethiopia:Summary of Papers and Proceedings of Workshop held at Axum Hotel, Mekelle, Etiopia, 28-29 March 2002. Socio-economic and Policy Research Working Paper 54. ILRI (Internationa Livestock Research Institute), Nairobi. 75 pp.

Ray, D., 1998. Development Economics. Princeton University Press, Princeton, New Jersey.

Reardon, T., Taylor, J. E., 1996. Agroclimatic Shock, Income Inequality, and Poverty: Evidence from Burkina Faso. World Development. 24(5), 901-914.

Regmi, A., Deepak, M. S., Jr., J. L. S., Bernstein, J., 2001. Cross-Country Analysis of Food Consumption Patterns. Changing Structure of Global Food Consumption and Trade / WRS-01-1. Economic Research Service/USDA

Rosenzweig, M. R., Binswanger, H. P., 1993. Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments. The Economic Journal. 103(416), 56-78

Ruben, R., Masset, E., 2003. Land Markets, Risk and Distress Sales in Nicaragua: The Impact of Income Shocks on Rural Differentiation. Journal of Agrarian Change. 3(4), 481-499.

Shiferaw, B., Obare, G., Muricho, G., 2006. Rural Institutions and Producer Organizations in Imperfect Markets: Experiences from Producer Marketing Groups in Semi-Arid Eastern Kenya. CAPRi Working Paper No. 60 International Crops Research Institute for the Semi Arid Tropics, Cali, Colombia.

Stiglitz, J. E., 1974. Incentives and Risk Sharing in Sharecropping. The Review of Economic Studies. 41(2), 219-255.

Stiglitz, J. E., 1986. The New Development Economics. World Development. 14(2), 257-265.

Stiglitz, J. E., Weiss, A., 1981. Credit Rationing in Markets with Imperfect Information. The American Economic Review. 71(3), 393-410.

Sushil, P., 2004. Risk and Fertilizer Use in the Rainfed Rice Ecosystem of Tarlac, Philippines. Journal of Agricultural and Applied Economics. 36(1), 241-250.

Teshome, W., 2003. Irrigation Practices, State Intervention and Farmers' Life-Worlds in Drought-Prone Tigray, Ethiopia. PhD Thesis. Wageningen the Netherlands

Udry, C., 1994. Risk and Insurance in a Rural Credit Market: An Empirical Investigation in Northern Nigeria. The Review of Economic Studies. 61(3), 495-526.

WDR, 2008. World Development Indicator 2008: Agriculture for Development. World Bank, Washington, D.C.

World-Bank, 2005. Ethiopia: Well-Being and Poverty in Ethiopia: The role of agriculture and agency. Report No. 29468-ET (http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2005/09/20/000160016_20050920094758/Rendered/PDF/294680ET.pdf)

Paper I

Distress Rentals and the Land Rental Market as a Safety Net: Evidence from Tigray, Ethiopia

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Abstract

Rural households in the semi-arid Northern Ethiopian highlands are net buyers of food. Crop failure due to erratic and unpredictable rainfall occurs frequently and leads to food shortages and income shocks. The renting out of land may be one of the coping responses of households exposed to shocks. We developed a theoretical household model for poor landlord households capturing their contract choice response to downside production shocks. We tested econometrically whether contract choice may depend on poverty, capital constraints, production risk and random shocks. The multinomial logit model estimates show that poor households experiencing random shocks are more likely to choose fixed rent contracts as a distress response to shocks, suggesting that fixed rent contracts may be used to meet immediate needs, but at the expense of future incomes. We also found that fixed rent contracts are preferred by both landlords and tenants when production risk is low, while sharecropping is more likely where production risk is high. Finally, we found an indication that the choice of a fixed rent contract as a coping response comes as a last resort after all other means are exhausted.

Keywords: Land contract choice, sharecropping, fixed rent, random shocks, risk, distress rental, other coping responses, Ethiopia.

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1. Introduction

There is a growing theoretical and empirical literature on land rental contracts (Adams and Rask, 1968; Bardhan and Singh, 1987; Heady, 1947; Morooka and Hayami, 1989; Otsuka *et al.*, 1992), including new studies on the emergence of land markets in Africa (Holden *et al.*, 2008). There is a broad theoretical literature on contract choice in relation to land and labor contracts with alternative hypotheses about risk, risk preferences, credit constraints and moral hazard as explanations for contract choice (Bardhan, 1989; Cheung, 1969; Stiglitz, 1974). More recently, literature has emerged that has gone into the empirical testing of alternative theories (Ackerberg and Botticini, 2000, 2002; Aggarwal, 2007; Allen and Lueck, 1999; Bellemare, 2008; Dubois, 2002; Laffont and Matoussi, 1995). These studies find limited support for the risk hypothesis as an explanation for sharecropping. The seminal contributions to land contract theory, Cheung (1969) and Stiglitz (1974), emphasized that risk and risk aversion play important roles in explaining the persistence and high frequency of sharecropping in land contracting, while the hiring of labor was constrained by moral hazard and high costs of monitoring hired labor and has lead to the principal-agent model with risk neutral landlords and risk averse tenants. However, the model fails to explain why sharecropping is common when landlords are poorer than tenants (“reverse share tenancy”). Furthermore, the theoretical literature has not developed models that capture land contract choice as a response to shocks, and there are hardly any rigorous empirical studies examining land contract choice as a response to shocks.

In this paper we aim to fill some of these gaps. We develop a theoretical model for poor landlord households that face shocks such as a short-term pre-harvest liquidity constraint and can choose between operating their land themselves or renting out land through sharecropping or through fixed rent contracts when production is risky. We test the hypothesis that risk is an explanation for preference of sharecropping while random shocks lead to distress fixed rent contracts using data from a risky (semi-arid) environment (Tigray region) in the northern Ethiopian highlands.

Given that the majority of farm households in Tigray, Ethiopia, are subsistence producers and net buyers of food and subject to shocks due to unreliable weather conditions, it is likely that poorer households are more vulnerable to such shocks. Land rental contracts (as a close substitute to land sales[6]) may be used as a safety net to ease short-term consumption pressures. Households may respond to their constraints through non-land coping mechanisms, such as off-farm employment and livestock sales. However, off-farm employment opportunities are usually poorly paid, unskilled and physically weak labor (Dercon, 1999), and getting such employment during a crisis period is difficult due to excess supply of labor. Furthermore, during drought periods, crop prices increase while livestock prices fall dramatically due to distress sales of livestock (Holden and Shiferawl, 2004). Credit can be another coping mechanism, although formal credit for consumption is usually non-existent. Therefore, reduction in consumption is a common strategy that poor households use to cope with consumption pressure (Dercon, 1999), though this may come with severe long-term consequences for the households' human capital. In general, poor households' coping strategies differ based on their resource base, which may have implications on the use of land renting as a safety net.

The outline of the paper is as follows. In the next section, we provide a brief review of theoretical models and empirical evidence on land contract choice. Section 3 describes the study area and data. In section 4, we put forth an analytical household model of contract

[6] In Ethiopia, land sales are prohibited by law.

choice with poor landlord households and random shocks that may lead to distress rental. Section 5 describes the estimation method while section 6 presents results and discussion before we conclude in section 7.

2. Theoretical Models and Empirical Evidence

2.1. Theoretical Models

The seminal contributions by Cheung (1969) and Stiglitz (1974) triggered a rapid development of theoretical contributions to explain sharecropping and its efficiency implications in ways that were quite different from the classical views of Adam Smith and Alfred Marshall, who emphasized that sharecropping resulted in inefficiency because the tenant did not get the full marginal return to her/his effort. Cheung (1969) brought the perspective that sharecropping has the advantage that risk is shared between the landlord and the tenant. Stiglitz (1974) developed a model that showed that sharecropping could emerge as a trade-off between risk and moral hazard. This provided the basis for the standard static principal-agent model with a risk-neutral landlord and risk-averse tenant, where the landlord was typically wealthy and the tenant poor.

Laffont and Matoussi (1995) developed a theoretical model where moral hazard and the capital constraints of the tenant could explain the adoption of sharecropping while the capital constraints of the landlord favored fixed rent contracts. On the other hand, Tikabo and Holden (2003) developed a model that can explain the coexistence of fixed rent, pure sharecropping (output sharing) and cost-sharing (input and output sharing) contracts based on variation in risk aversion and capital constraints of landlords and tenants in an environment with reverse tenancy (poor landlords and wealthier tenants). Relatively wealthier landlords and poor tenants are attracted to each other in cost-sharing contracts;

relatively poorer landlords and wealthier tenants are attracted to each other in fixed rent contracts, and equally poor landlords and tenants are attracted to each other with sharecropping contracts.

Dubois (2002) developed a dynamic model capturing land fertility with a trade-off between future land quality and short-term productivity. The model demonstrates that landlords may prefer sharecropping contracts to reduce incentives of the tenants to over-exploit the land. Bellemare (2008) developed a dynamic theoretical model where asset risk (tenure insecurity) is correlated with who carries the risk in land rental contracts, such that sharecropping contracts give higher tenure security to landlords than do fixed rent contracts.

Another theory from Rao (1971) and Prendergast (2002) emphasizes that managerial effort and entrepreneurial activities are more valuable in risky environments, giving more reason to delegate responsibility to the tenant in such environments and leaving him a higher share. The implication is the opposite of that from the principal-agent model: risky environments and activities should favor fixed-rent contracts.

2.2. Empirical Evidence

More rigorous work to test the various theoretical models on contract choice and the efficiency implications started quite a bit after many of the theoretical contributions (Otsuka et al., 1992). Most of the empirical literature also focused primarily on the efficiency implications and less on the determinants of contract choice. Only very recently have a number of studies focused on testing the importance of sharing of risk and risk aversion vs. alternative explanations for sharecropping. We will briefly summarize key findings from these studies below.

Laffont and Matoussi (1995) tested the capital constraint hypothesis versus the risk sharing hypothesis with data from Tunisia, where tenants' working capital captured the capital constraint and tenants' wealth captured risk aversion. Only the working capital variable was significant in their model, so they concluded that capital constraints, rather than risk sharing, explained contract choice (sharecropping) in their study area. However, they caution that working capital and wealth can be quite closely related, so their conclusion is not very strong on this. One study that detected that risk is correlated with sharecropping is by Boadu (1992) in Ghana, which found a higher frequency of sharecropping in areas with higher variability in cocoa yields.

Allen and Lueck (1999) analyzed 4000 individual contracts from North American agriculture and reject the principal-agent model, which emphasizes the risk sharing and risk aversion explanation for sharecropping contracts.

Tikabo and Holden (2003) found evidence of wealth affecting the contract choice of landlords and tenants in Eritrea, where landlords are typically poorer than tenants. Relatively poor landlords and wealthier tenants are attracted to each other by forming fixed rent contracts, relatively wealthier landlords and poorer tenants form cost-sharing contracts, and equally poor landlords and tenants form pure sharecropping contracts (output sharing only). They did not have data enabling them to distinguish whether this pattern of endogenous matching was caused by risk sharing or capital constraints.

Ackerberg and Botticini (2000) analyzed data from medieval Italy and found support for the capital constraint and moral hazard hypotheses as an explanation for sharecropping there, but they did not find support for the risk sharing hypothesis. However, they did not control for the endogenous matching of landlords and tenants in this paper, though they did so in Ackerberg and Botticini (2002). After testing and controlling for endogenous matching, they found a stronger and significant effect of tenants' wealth. Given that wealth is a proxy for risk aversion, this led to a reversal of the conclusion from the previous paper, and risk sharing has become an important explanation for the choice of sharecropping.

Dubois(2002) used data from the Philippines and concluded that landlords use sharecropping contracts with less incentive when there is a danger of over-exploitation of the land, while fixed rent contracts are preferred on land that is less susceptible to over-use. The risk sharing hypothesis is rejected in his empirical analysis.

Aggarwal (2007) analyzed sharecropping and groundwater contracts in a semi-arid area in India and rejected the risk sharing explanation for share contracts. His data are more consistent with a double-sided incentive model.

Finally, Bellemare (2008) analyzed data from rice farmers in Madagascar with reverse tenancy and found support for the tenure insecurity hypothesis. However, the data lend little support for the risk sharing hypothesis.

To sum up, the empirical literature lends little support for risk sharing as the explanation for sharecropping contracts, contrary to the emphasis on this in the dominant principal-agent model. However, there are methodological weaknesses in many of the empirical studies since variables capturing risk and risk aversion may be contaminated by endogenous matching bias. It is thus interesting that Ackerberg and Botticini (2002) found support for the risk sharing hypothesis after having controlled for endogenous matching, while the hypothesis was rejected before this was controlled for (Ackerberg and Botticini, 2000). Still, even after controlling for endogenous matching, Aggarwal (2007) and Bellemare (2008) did not find support for the risk-sharing hypothesis in their studies in India and Madagascar.

Based on this literature review, we develop a theoretical model (presented in section 4 below) of reverse tenancy with poor landlord households where the contract choice may depend not only on risk based on the risk-sharing motive but also based on capital constraints and downside random shocks. We are not aware of anybody else who has made contract choice dependent on shocks in this way. In our setup, risk in general will favor risk-sharing, but downside shocks will favor fixed rent contracts due to the immediate need for cash.

3. The Study Area, Data and Descriptive Statistics

3.1. The Study Area

Because of the scarcity and erratic nature of rainfall, cereal production in the Tigray region remains at less than one ton per hectare (Pender and Gebremedhin, 2004). The region is densely populated and exposed to severe drought risks that represent threats to households' food security. Investment in irrigation has been used as a strategy to cope with such environmental shocks. Safety net programs include food-for-work, cash-for-work and free food distributions.

Our study area covers six communities/tabias[7]. These sites were selected to represent different agro-ecological settings, but all have irrigated land because the survey was

[7] *Tabia* is an administrative unit at the lower level equivalent to a municipality. It may consist of three to four *kushets* (villages).

designed to measure the impacts of irrigation. Of the six sites, two each are in the Southern and North-west zones of the Tigray region, while the other two are one each in the Eastern and Central zones of the region. A multi-stage stratified random sampling was used to identify sample households. First, all *tabias* in the region that have irrigation projects were stratified based on the type of irrigation. Six sites were selected, among which two use micro-dam irrigation, two use river diversions and the remaining two use ground water as a source of irrigation water.

Data collection was carried out in October-December 2005 for the 2004/2005 production year and included household specific characteristics, plot level data on inputs and outputs, land characteristics, land rental arrangement and access to irrigation. Plot sizes were not physically measured, but the respondents were asked to tell the size in the local measurement unit, tsimdi[8], which was easy for them. We then converted tsimdi into hectares. We define a plot as a distinct management unit based on the crop type produced during the season.

We used farm plot level data from 378 of the households in a sample of 613. Among these households, 136 rented/sharecropped out part of their land, while the remaining 242 households were owner operators.

3.2. Descriptive Statistics

Table 1 presents data on land contract arrangements for all rain-fed and irrigated plots of landlord- and owner-operated households. We see that 25% of the rain-fed plots and 31.5% of the irrigated plots were rented out. Only 2.8% of the rain-fed plots were rented out with

[8] Four tsimdi is approximately equal to one hectare.

fixed rent contracts whereas 7.6% of the irrigated plots were rented out with fixed rent contracts. Overall, we see a strong dominance of sharecropping as the most common contract on rented out land.

Table 2 presents descriptive statistics of variables used in this analysis. Out of the 378 households considered in this paper, 136 (36%) are landlord households. About 68% of the landlord and 16% of owner cultivator households are female-headed. Table 2 also shows that landlord households are significantly poorer than non-participants in the land rental market. We see that landlord households have significantly less male labor, oxen, other livestock, and off-farm income and are significantly less well educated. They have significantly poorer access to credit and are significantly less likely to have sufficient food in June (early rainy season). They were significantly less likely to use migration as a coping strategy, perhaps indicating that this strategy is also capital-demanding. They were also significantly less likely to sell animals as a coping strategy because of their low stock of animals, while they were significantly more likely to sell other assets as a coping response. All these findings point in the direction that renting out land may be a coping response by these poor landlord households.

Table 3 compares the characteristics of households choosing fixed rent contracts with the characteristics of households choosing sharecropping contracts. We see that households choosing sharecropping had significantly more land per adult (5%), older household head (10%), less adult female labor (1%), and less negative food deficit shock residual (10%). The first and the last of these results are weak indications of fixed rent contracts being positively associated with poverty in land and adverse shocks. More rigorous analysis follows below.

4. Analytical Framework: Household Model with Distress Land Rental

We may define distress sale or rental as a situation where a property is sold or rented due to an urgent need (e.g., need for cash to buy food or to cover medical expenses), and often this sale or rental happens at a reduced price due to the weak bargaining power of the person selling or renting out.

We develop a household model that captures the decision-situation of a poor rural household that may be forced to go into distress sale or rental of its assets to meet its urgent needs. We assume that the household lives in a land scarce, risky environment due to unreliable rainfall that affects its agricultural production and also creates seasonal variation in access to food. There is a time lag from when inputs are purchased and used in production until the harvest of food. Households have three endowments: land (*K*), livestock (A_0) and human capital (*L*). There is only a rental market for land, while there is a sales market for livestock. Households have only seasonal (constrained) access to the labor market due to limited employment opportunities. Land may be rented out or rented in using cash (rK_1^r) or sharecropping (K_1^s). With cash rental, payment is made up-front, while with sharecropping, payment is made after the harvest (implying that the landlord provides credit in the case of sharecropping).

For simplicity, we divide the year in two periods. The first season is from the time of land preparation for the next production until the time of harvest. At the beginning of this season, the household has to decide whether to produce on the land itself, whether to rent out part of the land, and, in the case of rental, what contract to choose. This decision is made on the basis of the initial (non-negative) endowment and asset stocks of the household. In addition to the three endowments, we also assume that the household has a stock of food (C_0^S) to meet its food requirements up to the next harvest ($C_1^{Min}(L)$) or an amount of cash that can be used to meet this demand (R_0). We may formulate this as a two-period utility-maximization problem using a time-separable utility function with the normal properties:

$$U = U(C_1, C_2) = u_1(C_1) + \rho u_2(C_2) \tag{1}$$

where $\rho = \dfrac{1}{1+\delta}$ is the usual discount factor and C_1, C_2 capture consumption in seasons one and two, respectively. This utility-maximization problem can be nested in a dynamic investment problem that can be captured by a Bellman equation:

$$V\left(K, L, A_0, C_0^s, R_0\right) = Max\left\{U + \rho^T V\left(K, L, A_T, C_T^s, R_T\right)\right\} \tag{2}$$

where K is the land capital, L is the human capital, A_0 is the initial livestock endowment, and T indicates next period stocks. Scarcity of cash and food may create a distress situation for the household. Drought in the previous year may have caused a low level of food stock and cash availability. Health problems and a need for medical treatment may also cause a distress situation. Household responses to a situation with insufficient food or cash until the next harvest may then be to sell some of the livestock ($p_a(A_0 - A_1) > 0$) or to rent out land for cash. If limited (low-paying) employment opportunities are available, the members of the household may also be willing to work for low pay to meet their urgent needs (wL_1^O). If the household is forced to rent out part of its land at a low (cash) price, it is also able to use less of its land for its own food production for the next period, $K_1^r + K_1^s + K^q = K$. If the household rents out land through sharecropping, it gets only a share, α, of the output, but the advantage is that it does not have to provide other inputs in production, like labor and purchased inputs ($p_x X_1^q$). Own production and the share of output from sharecropping contribute to consumption utility in period 2:

$$C_2 = p_q \alpha \theta^s Q_2^s \left(K_1^s \right) + p_q \theta^q Q_2^q \left(K_1^q, L_1^q, X_1^q \right) + wL_2^O + p_a (A_1 - A_2) \tag{3}$$

The household provides only land and no other inputs for sharecropping and shares the risk with the tenant. This production risk is captured by the stochastic term θ^s that has a value between 0 and 1 such that Q_2^s is the potential output under perfect conditions. Bad weather, pests and diseases and poor performance of the tenant may cause yields to be lower. In own agricultural production, the household contributes and controls more of the inputs, carries all the risk and gets all the output. It faces risk in relation to weather, pests and diseases, and this is assumed to be captured by θ^q, but production may also be negatively affected by suboptimal input application (e.g., due to labor and cash constraints). This formulation of the production functions has the advantage of capturing the fact that risk in production is primarily a downside risk phenomenon.

The cash constraint the household faces in period 1 may be formulated as follows:

$$p_1^q \left(C_1^{Min} - C_0^s \right) + p_1^x X_1^q = rK_1^r + wL_1^O + p_1^a \left(A_0 - A_1 \right) + R_0 \tag{4}$$

where the subscript 0 represents the beginning of season one and the subscript 1 represents season one or the end of season one for animal stocks. From this equation, it is easy to see that cash and food scarcity may force households to sell animals or to rent out their land for cash in order to meet their urgent consumption needs. Sharecropping does not meet their immediate cash and food needs. However, it may still relieve their labor and cash constraints in relation to the purchase of cash inputs that may be important in enhancing their production if they cultivate the land themselves. Low initial endowments of livestock, labor and cash also limit the ability of households to absorb shocks through the mobilization of these endowments.

If we assume that the household has no access to credit for consumption smoothing, it can only use its own resources for that purpose. This, however, may also affect the discount rate of the household, which no longer is exogenous but subjective and varying across households and over time (Holden *et al.*, 1998). This shadow discount rate may also become very high for very poor households that are in a desperate situation. They may become willing to rent out their land or sell their labor or animals at very low prices in order to meet urgent consumption needs.

A random shock that happens in one year, like a drought that affects a whole community, causes low agricultural production and also causes the stock of food to be small. This will cause a larger share of households to face food and liquidity constraints. Households that are relatively well endowed initially may be able to cope with the shock based on their resource endowments. Households that are "medium" endowed may have to resort to sharecropping or selling animals to meet their short-term needs. The least well endowed households may be unable to cope with the shock by selling animals due to a low stock of animals and by selling their labor due to limited labor power and/or limited labor market access. These households may be forced to rent out their land through fixed rent contracts to meet their immediate cash needs.

Based on what we have outlined above, the simple maximization problem from equation (1) may be expressed as:

$$\max_{K_1^s, K_1^q, L_1^q, X_1^q, A_1} U = \left\{ \begin{array}{l} U_1\left(\begin{array}{l} p_1^q C_0^s + r\left(K - K_1^s - K_1^q\right) + w\left(L - L_1^q\right) \\ + p_1^a\left(A_0 - A_1\right) + R_0 - p_1^x X_1^q \end{array} \right) \\ + \rho U_2 \left[\begin{array}{l} p_2^q \alpha \theta^s Q_2^s\left(K_1^s\right) + p_2^q \theta^q Q_2^q\left(K_1^q, L_1^q, A_1, X_1^q\right) \\ + p_2^a A_1 \end{array} \right] \end{array} \right\} \tag{5}$$

subject to the cash constraint (4) above and the usual non-negativity constraints for all assets and inputs. The FOCs for the land variables are as follows if the cash constraint is not binding:

$$K_1^s : \frac{\partial U_1}{\partial C_1}(-r) + \rho\left(\frac{\partial U_2}{\partial C_2} p_q \alpha \theta^s \frac{\partial Q_2^s}{\partial K_1^s}\right)\begin{Bmatrix} = 0 \text{ if } K_1^s, K_1^r > 0 \\ < 0 \text{ if } K_1^s = 0, K_1^r > 0 \\ > 0 \text{ if } K_1^s > 0, K_1^r = 0 \end{Bmatrix} \tag{6}$$

This implies that the marginal utility of renting out land (fixed rent) is equal to the discounted marginal (expected) utility of sharecropping out land if the household uses both types of contracts; otherwise, it will choose the one that gives higher utility (taking discounting and disutility of risk in sharecropping into account).

$$K_1^q : \frac{\partial U_1}{\partial C_1}(-r) + \rho\left(\frac{\partial U_2}{\partial C_2} p_q \theta^q \frac{\partial Q_2^q}{\partial K_1^q}\right)\begin{Bmatrix} = 0 \text{ if } K_1^q, K_1^r > 0 \\ < 0 \text{ if } K_1^q = 0, K_1^r > 0 \\ > 0 \text{ if } K_1^q > 0, K_1^r = 0 \end{Bmatrix} \tag{7}$$

This implies that the marginal utility of renting out land (fixed rent) is equal to the discounted marginal (expected) utility of owner-cultivation of the land. At the optimum, either fixed rent or owner-cultivation gives higher utility and is chosen while the other is zero.

$$L_1^q : \frac{\partial U_1}{\partial C_1}(-w) + \rho\left(\frac{\partial U_2}{\partial C_2} p_q \theta^q \frac{\partial Q_2^q}{\partial L_1^q}\right) = 0 \tag{8}$$

Labor is applied in own production until the marginal disutility (cost) is equal to the (discounted) marginal expected utility.

$$X_1^q : \frac{\partial U_1}{\partial C_1}(-p_x) + \rho\left(\frac{\partial U_2}{\partial C_2} p_q \theta^q \frac{\partial Q_2^q}{\partial X_1^q}\right) = 0 \tag{9}$$

Purchased inputs are applied up to the point at which marginal disutility (cost) is equal to the discounted marginal expected utility of the inputs' return in production.

$$A_1 : \frac{\partial U_1}{\partial C_1}\left(-p_1^a\right) + \rho\left(\frac{\partial U_2}{\partial C_2} p_q \theta^q \frac{\partial Q_2^q}{\partial A_1} + \frac{\partial U_2}{\partial C_2} p_2^a\right) = 0 \qquad (10)$$

Animals are retained for the second period up to the point at which the marginal cost of keeping them is equal to the discounted marginal benefit of having them in the next period, taking into account both their production benefit and asset value when prices may change.

Another factor that plays an important role in the rental market is the production risk, which is captured by the distribution of $\left(1-\theta\right)$, related to environmental shocks that cause output to be less than the maximum (without shock). In Eqn. (6), the landlord household's risk in sharecropping contracts is proportional to her/his output share$\left(\alpha\right)$, while in the case of own production (Eqn.7), the landlord household will assume the entire risk. If the expected downside risk $\left(1-\theta_\mu^q\right)$ is high, the expected output in period 2, $\theta_\mu^q Q_2^q$, is low; hence, the farmer may prefer to rent out his land in order to collect up-front rental payments. However, it is also likely that the equilibrium fixed rent is lower in a risky environment. Moreover, it is likely to be lower the more risk averse both parties are, because that will drive up the supply of land and drive down the demand at a given level of risk. Finally, the fixed rent is likely to be lower the higher the discount rates of both of the negotiating parties.

One can argue that the decision of such a farm household to rent out can be a temporary adjustment of factors of production as a response to shocks; however, poor households may use it regularly or because they have agreed on a long-term contract. This may also lead to a poverty trap, because when more land is rented out for fixed rent, it becomes more difficult to build the food stock in the next period. This process can become a vicious spiral.

To illustrate the implications of contract choice more clearly, the utility of the three alternative contracts, $m \in \{r, s, q\}$, including owner-cultivation, may be formulated as follows with explicit risk premiums and transaction costs:

$$u\left(\mathbb{C}^m\right) = \begin{Bmatrix} u\left(\mathbb{C}^r\right) = rK_1^r - T^r\left(K_1^r\right) \\ u\left(\mathbb{C}^s\right) = \rho\left(p_q \alpha \theta^s Q_2^s\left(K_1^s\right)\left(1-\psi\left(R, \theta_{\text{var}}^s\right)\right)\right) - T^s\left(K_1^s\right) \\ u\left(\mathbb{C}^q\right) = \rho\left(p_q \theta^q Q_2^q\left(K_1^q, L_1^q, X_1^q\right)\left(1-\psi\left(R, \theta_{\text{var}}^q\right)\right)\right) - wL_1^q - p_1^x X_1^q \end{Bmatrix} \tag{11}$$

The risk premium, $\psi\left(R, \theta_{\text{var}}^s\right)$, is an increasing function of the relative risk aversion (R) and the variance of θ, which we state as θ_{Var}. Transaction costs in the land rental market are a non-decreasing function of the area rented out. We assume that landlord households will choose the type of contract that maximizes their utility: $u\left(\mathbb{C}^*\right) = \arg\max u\left(\mathbb{C}^m\right)$. We can easily see that owner-cultivation carries more risk and up-front production costs but no transaction costs; fixed-rent provides immediate cash income and no risk but some transaction costs to find a partner, and sharecropping carries no up-front production costs and less risk than owner-cultivation but involves transaction costs in relation to search, negotiation, monitoring and enforcement of the contract. In addition, with sharecropping the expected income is discounted with the subjective discount rate.

If the household has some irrigated land, such land is likely to give higher expected output, have less production risk, require more labor and cash inputs, and have a higher land value (rental price). Examining the alternative contracts above, we propose that: a) irrigated land is more likely to be rented with fixed-rent contracts (because of lower production risk, lower risk premium and higher rental price), and b) landlords who have cash and labor resources/skills farm irrigated land themselves, while landlords who lack cash and labor resources are more likely to rent out their irrigated land with a fixed-rent contract because of the more attractive rental price.

We derive the comparative statics results for a simplified version of the landlord model with choice between fixed-rent and owner-cultivation only for the share of land rented out to the total land holding, and we obtain the following expected signs:

$$\frac{K_1^r}{K} = \frac{K_1^r}{K}\left(\overset{(+)}{r}, \overset{(+)}{p_1^x}, \overset{(+/-)}{K}, \overset{(-)}{p_2^q}, \overset{(-)}{\theta^q}, \overset{(+)}{C^{MIN}}, \overset{(-)}{\rho} \right) \tag{12}$$

Based on the theoretical model, we summarize the key hypotheses we want to test empirically:

H1: *Poor households are more likely to respond to shocks by choosing fixed-rent contracts in order to meet their immediate consumption needs*. The implication is that households with more food stock, livestock, off-farm income and labor endowment are less likely to rent out their land through fixed-rent contracts, while households exposed to shocks are more likely to do so the larger the shock is. The alternative coping strategies of selling livestock and working off-farm may be preferred by wealthier households.

H2: *Households respond to risk by sharing risk in sharecropping contracts.* More specifically, we test this hypothesis with the following derived hypotheses:

H2a. *Fixed rent contracts are more likely to be chosen where risk is low.* Irrigated land is more likely to be rented out with fixed-rent contracts by households that do not have the capacity to farm themselves. Production risk is likely to be lower for irrigated land and higher for areas with larger variation in rainfall. We consider these variables as good exogenous variables that are not contaminated by unobserved household heterogeneity and endogenous matching.

H2b. *Sharecropping contracts are more likely to be preferred where risk is high*. This may be the case on rain-fed plots and in areas with more rainfall variability. This is also an implicit test of the risk explanation for sharecropping as discussed in the literature review.

5. Estimation Methods

We have data on whether households had sufficient food at the beginning of the rainy season (June). This variable is likely to be endogenous and depend on structural characteristics (household wealth, composition, farm size, and general agro-climatic conditions) but may also be affected by shocks that possibly could hit whole communities (like droughts) or individual households (like health problems affecting the labor force during the production season). Due to the lack of good instruments to predict this variable, the following estimation strategy was used to extract the random shock component as much as possible from the food availability variable: 1) we ran a probit model with food availability in June as the dependent variable (1=enough food, 0=insufficient food), using observable household, farm and agro-ecological characteristics as explanatory variables (results are presented in Table 4), 2) we used the probit results to predict the probability that households have sufficient food in June, and 3) we generated the residual = actual food availability – predicted availability. A kdensity graph of the distribution of the residual is presented in Figure 1. Then we trimmed the residual by setting all values above zero equal to zero. The argument for this is that positive values of the residual capture households with sufficient food, while negative values capture households that have less food than predicted, thus indicating that they have been exposed to a more or less significant downside risk shock. Finally, we use the trimmed residual in the contract choice models as an indicator variable for random negative shocks, and we expect contract choice to have been affected by such shocks. We test whether such shocks may have increased the probability of distress rentals in the form of fixed rent contracts.

The choice of tenancy involves three discrete choices: 1=Owner cultivation, 2=Sharecropping, and 3=Fixed rent. We assume that the tenancy choice is made simultaneously for each plot of landlord households, where the household is simultaneously deciding which plots to rent out and the type of contract for plots rented out. We use a multinomial logit model (MNLM) to capture this. The advantage of MNLM is that the effects of independent variables are allowed to differ for each outcome in contrast to ordered logit models (Long, 1997). Long (1997) argues that even if confusion arises whether the choice is ordinal or nominal, the potential loss in efficiency due to using MNLM is compensated by avoiding a potential bias that could have been caused by using ordinal models. By using MNLM, the potential selection bias on observed contracts can be controlled by estimating the simultaneous choice of contracts (Dubois, 2002). In the MNLM, all of the binary logits are estimated simultaneously, which enforces the logical relationship among the parameters and uses data more efficiently. The odds of fixed rent versus owner cultivation can be specified as follows.

$$Odds_{fixed/owner}\left(x_i\right)=\left(\frac{\Pr\left(fixed\,|x_i\right)}{\Pr\left(owner|x_i\right)}\right)=\left\{\frac{\left(\dfrac{\exp\left(x_i\beta_{fixed}\right)}{\sum_{j=1}^{3}\exp\left(x_i\beta_j\right)}\right)}{\left(\dfrac{\exp\left(x_i\beta_{owner}\right)}{\sum_{j=1}^{3}\exp\left(x_i\beta_j\right)}\right)}\right\}=\frac{\exp\left(x_i\beta_{fixed}\right)}{\exp\left(x_i\beta_{owner}\right)}\quad(13)$$

where the subscripts *fixed* and *owner* represent fixed rent and owner cultivation, respectively. Combining the exponents, Equation (13) can be formulated into an equation giving the odds as:

$$Odds_{fixed/owner}(x_i) = \exp\left(x_i\left(\beta_{fixed} - \beta_{owner}\right)\right)$$

(14)

Equation (13) shows the probability of choosing fixed rent versus owner cultivation, which can be interpreted as the odds of fixed rent versus owner cultivation given the independent variable$\left(x_i\right)$. If the coefficient is positive, the odds imply that fixed rent is chosen given the independent variable$\left(x_i\right)$; however, identification is a main concern. Moreover, its nonlinearity makes interpretation cumbersome; therefore, to estimate a linear relationship between the explanatory variables and tenancy choice, Equation (14) needs to be transformed into log form as follows:

$$\ln Odds_{fixed/owner}(x_i) = x_i\left(\beta_{fixed} - \beta_{owner}\right) \tag{15}$$

Since we imposed a constraint on the base category (owner cultivation in this case) as $\beta_{owner} = 0$ to solve the identification problem, Equation (15) simplifies to $\ln Odds_{fixed/owner}(x_i) = x_i\beta_{fixed}$. But, since this is in log form, interpretation is still difficult; hence, we consider the antilog value of the coefficient, i.e., $\exp\left(\beta_{fixed}\right)$, to obtain the relative risk. Sometimes called "risk ratio" (Agrawal, 2005; Long and Freese, 2006), it is interpreted as a likelihood of fixed rent versus owner cultivation. If $\exp\left(\beta_{fixed}\right) > 1$, the likelihood of fixed rent as compared to owner cultivation is higher, which can be interpreted as the fixed rent being $\exp\left(\beta_{fixed}\right)$ times more likely than owner cultivation (Agrawal, 2005). On the other hand, if $\exp\left(\beta_{fixed}\right) = 1$, both fixed rent and owner cultivation are equally likely. A similar procedure can be used to estimate the relative risk of fixed rent versus sharecropping and sharecropping versus owner cultivation by replacing the base category.

6. Results and Discussion

In order to assess the link between immediate needs and contract choice (distress rental), we first look at the determinants of food shortage in the beginning of the rainy season, because at this time, limited cash may be available and may either be used for buying farm inputs or food, the largest expenditure item for poor households that do not have any food store left. We see from Table 4 that households with oxen are less likely to face food shortages. We also saw in Table 2 that landlord households have significantly less oxen than non-participants in the land rental market. Ghebru and Holden (2008) have shown that tenants typically have more oxen and rent land from households without oxen in Tigray. Landlord households without oxen are therefore more likely to face food shortages. Furthermore, we see from Table 4 that food shortages are positively and significantly associated with using coping strategies to search for casual off-farm employment, migrate, sell animals and look for aid, while households without a food shortage are willing to reduce consumption as a response to shocks, indicating their better-off position. We did not have any good instruments to predict food shortage but used an alternative innovative approach (explained in the methods part) to extract a measure of the random shock part of this variable and included this trimmed residual variable (the negative part in Figure 1) in the following contract choice models.

The multinomial logit estimation results are presented in Tables 5 and 6, where Table 5 shows the likelihood of fixed rent versus owner cultivation and fixed rent versus sharecropping, and Table 6 shows the likelihood for the choice between sharecropping versus owner cultivation.

Our first hypothesis stated that poor households and households exposed to shocks are more likely to choose fixed-rent contracts in order to meet their immediate consumption needs. We see from Table 5 that female-headed households (significant at the 1% level in all three models) and households with less education (significant at the 5, 5 and 1% levels) were more likely to choose fixed rent contracts over owner-cultivation, and these households are typically among the poorest. Their poverty may cause them to be more risk averse as well as more cash constrained and thus to have higher discount rates.

We also see that households that experienced a random food shortage shock were significantly (at the 1% level in all three models) more likely to choose fixed rent over owner cultivation. Fixed rent contracts may help to meet this immediate need but at the expense of food availability next year, which could have been improved with a sharecropping contract. A bit surprisingly, we also found a strong positive and significant effect (at the 1% level in all three models) of the female labor force that pushed in the direction of fixed-rent contracts over owner-cultivation. This could be because female labor, due to cultural norms, cannot be used for land cultivation with oxen. Thus if land has to be rented out, these female household members may add more to the food needs of the household than to household income because of their limited access to off-farm income, which also is related to their low level of education.

The effect on choice of fixed rent versus sharecropping contracts in Table 5 were less clear and significant, with the exception of the random food shortage variable, which was significant at the 5% level in two of the models and at the 1% level in one model. This shows that such shocks were likely to lead to the choice of fixed rent instead of sharecropping contracts. Female labor was still positively and significantly (at the 5% level in two and at the 1% level in one of the models) related to the choice of fixed rent contracts over sharecropping. This may indicate surplus unproductive labor, possibly due to a lack of complementary inputs that are needed for farming, and labor market imperfections. Two of the models also had a significant (at the 10% level) negative relation between the age of the household head and the choice of fixed rent contracts. This could possibly be because older household heads have a stronger preference for sharecropping contracts. These results support our hypothesis that fixed-rent contracts may be used as a distress response to shocks that have caused food shortage.

Our second hypothesis stated that fixed-rent contracts are more likely when production risk is low. We found evidence in Table 5 that fixed rent contracts were more likely to be chosen over owner-cultivation on irrigated land (significant at the 5 and 10% levels) in two of the three models and fixed rent contracts were significantly more (at the 5% level in one model) likely to be chosen over sharecropping on irrigated land. Fixed-rent contracts are not necessarily a sign of distress but may indicate that when production risk is low, fixed rent contracts are preferred by both landlords and tenants. We also found that fixed rent contracts were less likely to be chosen over owner-cultivation and over sharecropping in areas where rainfall variability is high (both significant at the 1% level). This also implies that fixed rent contracts are more likely to be chosen where risk is low, while sharecropping is associated with high rainfall variability in this semi-arid area. This result appears very robust and our measure of risk (rainfall variability) is clearly exogenous and not contaminated by endogenous crop choice like yield variability would be. We also see that sharecropping is preferred over owner-cultivation where rainfall variability is high (significant at the 5% level in Table 6). These findings are in line with the theories of Cheung (1969), Stiglitz (1974) and Otsuka and Hayami (1988) that risk is an important reason for the preference for sharecropping contracts. Like we saw in the literature review, few empirical studies have been able to detect such a relationship between contract choice and risk.

One additional puzzling result was found in Table 5. Fixed rent contracts were less likely to be chosen where rainfall is higher, while higher rainfall should be associated with lower risk. Since the rainfall risk has already been controlled for, there must be a different reason for this result for which we do not have a good explanation. It was also found that fixed rent contracts were more likely to be chosen where the population is high. Higher population could be associated with more market development, which could lead to a preference for more fixed rent contracts due to better off-farm opportunities.

Our findings also lend support to the credit constraint hypothesis, as households with access to credit were significantly (at the 10% level in one of three models) less likely to choose sharecropping rather than owner-cultivation. Such households with access to credit may be more able to purchase inputs and farm their land themselves. This indicates that "mild credit constraints" (to buy farm inputs) lead to a preference for sharecropping while "severe credit constraints" (to meet immediate consumption needs when there is food shortage) lead to a preference for fixed-rent contracts among landlords. This also makes sense because formal credit is only available for the purchase of farm inputs and not for consumption purposes. Other wealth- and capacity-related variables that favored owner-operation over sharecropping include oxen, male labor force, education, and young household heads.

When we look at the models where the preferences for alternative coping strategies were included in Tables 5 and 6, we find that the selling of animals and other assets was significantly (at the 1 and 5% levels) and negatively correlated with choosing a fixed rent contract over owner-cultivation, while the choice of fixed rent contracts was significantly positively (at the 1% level) related to the harvesting of firewood as a coping strategy. This may indicate that fixed-rent contracts are chosen only after considerable depletion of other household assets. The harvesting of firewood may therefore be another desperate strategy that may even deplete the environmental resource base. Households choosing fixed rent contracts were significantly less likely (at the 5% level) to sell animals and look for aid as coping strategies than households choosing sharecropping.

Households that chose sharecropping over owner-cultivation were also less likely to migrate and sell animals as coping strategies than households choosing owner-cultivation. The monitoring of sharecropping tenants is not easy to combine with migration. Finally, sharecropping was positively associated with looking for aid as a coping strategy (significant at the 10% level only).

7. Conclusion

The standard principal-agent model with risk neutral landlords and risk averse tenants does not fit well in Northern Ethiopia where landlords are typically poorer than tenants. It may thus appear as a puzzle that sharecropping is so dominant in this area since the poverty of landlords, if correlated with risk aversion and high discount rates, does not result in a strong preference for fixed rent contracts. Likewise, most of the empirical tests of risk and risk aversion as explanations for sharecropping have rejected the risk hypothesis (Aggarwal, 2007; Allen and Lueck, 1999; Dubois, 2002; Laffont and Matoussi, 1995) and new theories forwarded by Prendergast (2002), emphasizing the importance of managerial skills in risky environments, also favor fixed rent contracts. However, our findings support the risk hypothesis as an explanation for sharecropping in this risky environment even under reverse tenancy. This could be consistent with both landlords and tenants being risk averse (Hagos and Holden, 2006). Rainfall variability was highly significant and positively correlated with a preference for sharecropping in our study, while fixed rent contracts were significantly more common on irrigated land where risk is lower.

Furthermore, we found that shocks leading to food shortages increased the probability of the choice of fixed rent contracts as a form of distress rental. Likewise, we found evidence that very poor landlord households may go for fixed-rent contracts, and this may be due to their high level of risk aversion and high discount rates. Safety net programs, like food-for-work and cash-for-work, and alternative coping strategies, like the selling of animals and other assets, search for off-farm employment, etc., are preferred by the less poor households, while distress land rental with fixed rent contracts is one of the last options that households go for only after they have depleted their other assets due to the low price they then get for their land. An exception may be irrigated land, for which they may get a better price. Overall, sharecropping appears to be the best alternative contract form for poor female landlord households who lack the resources to farm the land efficiently themselves. Sharecropping contracts provide them with an important source of food and cause the land rental market to represent an important safety net. The recently introduced restriction that only 50% of the land should be rented out may thus represent a threat to the food security of poor female-headed households who typically rent out more than 50% of their land.

References

Ackerberg, D. A., Botticini, M., 2000. The Choice of Agrarian Contracts in Early Renaissance Tuscany: Risk Sharing, Moral Hazard, or Capital Market Imperfections? Explorations in Economic History. 37, 241–257.

Ackerberg, D. A., Botticini, M., 2002. Endogenous Matching and the Empirical Determinants of Contract Form. Journal of Political Economy. 110(3), 564-591.

Adams, D. W., Rask, N., 1968. Economics of Cost-Share Leases in Less-Developed Countries

American Journal of Agricultural Economics. 50(4), 935-942.

Aggarwal, R. M., 2007. Role of risk sharing and transaction costs in contract choice: Theory and evidence from groundwater contracts. Journal of Economic Behavior & Organization. 63, 475–496.

Agrawal, D., 2005. Inappropriate Interpretation of the Odds Ratio: Oddly Not That Uncommon PEDIATRICS 116 (6), 1612-1613.

Allen, D. W., Lueck, D., 1999. The Role of Risk in Contract Choice. The Journal of Law, Economics and Organization. 15(3), 704-736.

Bardhan, P., 1989. A Note on Interlinked Rural Economic Arrangements. In: Bardhan, P. (Ed.), The Economic Theory of Agrarian Institutions. Clarendon Press, Oxford.

Bardhan, P., Singh, N., 1987. On Moral Hazard and Cost Sharing under Sharecropping

American Journal of Agricultural Economics. 69(2), 382-383.

Bellemare, M. F., 2008. Insecure Land Rights and Reverse Share Tenancy in Madagascar. Duke University - Terry Sanford Institute of Public Policy; Trinity College of Arts & Sciences - Department of Economics

Boadu, F., 1992. The efficiency of share contracts in Ghana's cocoa industry. Journal of Development Studies. 29 (October), 108-120.

Cheung, S. N. S., 1969. Theory of Share Tenancy. Chicago: University of Chicago Press.

Dercon, S., 1999. ETHIOPIA: Poverty Assessment Study, Revised version of report for IFAD

Dubois, P., 2002. Moral hazard, land fertility and sharecropping in a rural area of the Philippines. Journal of Development Economics. 68 35–64.

Ghebru, H., Holden, S., 2008. Factor Market Imperfections and Rural Land Rental Markets in Northern Ethiopian Highlands. In: Holden, S., Otsuka, K., Place, F. (Eds.), The Emergence of Land Markets in Africa: Assessing the Impacts on Poverty, Equity and Efficiency. Resources For the Future Press, New York.

Hagos, F., Holden, S., 2006. Tenure security, resource poverty, public programs, and household plot-level conservation investments in the highlands of northern Ethiopia. Agricultural Economics 34 183–196.

Heady, E. O., 1947. Economics of Farm Leasing Systems. Journal of Farm Economics. 29(3), 659-678.

Holden, S., Otsuka, K., Place, F. (Eds.), 2008. The Emergence of Land Markets in Africa: Assessing the Impacts on Poverty, Equity and Efficiency. Resources For the Future Press, New York.

Holden, S., Shiferaw, B., Wik, M., 1998. Poverty, market imperfections and time preferences: of relevance for environmental policy? Environment and Development Economics 3 105–130.

Holden, S., Shiferawl, B., 2004. Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: a bio-economic model with market imperfections. Agricultural Economics 30, 31-49.

Laffont, J.-J., Matoussi, M. S., 1995. Moral azard Financia Constraints and Sharecropping in El Oulja Review of Economic Studies 62, 381-399.
Long, J. S., 1997. Regression Models for Categorical and Limited Dependent Variables Advanced Quantitative Techniques in the Social Sciences Series, vol. 7. Sage Publications, Inc, USA.
Long, J. S., Freese, J., 2006. Regression Models for Categorical and Dependent Variables Using STATA, Second Edition. A Stata Press Publication, Stata Corp LP Texas.
Morooka, Y., Hayami, Y., 1989. Contract Choice and Enforcement in an Agrarian Community: Agricultural Tenancy in Upland Java. The Journal of Development Studies. 26, 28-42.
Otsuka, K., Chuma, H., Hayami, Y., 1992. Land and Labor Contracts in Agrarian Economies: Theories and Facts. Journal of Economic Literature. 30(4), 1965-2018.
Otsuka, K., Hayami, Y., 1988. Theories of Share Tenancy: A Critical Survey. Economic Development and Cultural Change. 37(1), 31-68.
Pender, J., Gebremedhin, B., 2004. Impacts of Policies and Technologies in Dryland Agriculture: Evidence from Northern Ethiopia. In: Challenges and Strategies for Dryland Agriculture. CSSA Special Publication no. 32.
Prendergast, C., 2002. The Tenuous Trade-off between Risk and Incentives. Journal of Political Economy. 110(5), 1071-1101.
Rao, C. H. H., 1971. Uncertainty, Entrepreneurship, and Sharecropping in India. The Journal of Political Economy. 79(3), 578-595.
Stiglitz, J. E., 1974. Incentives and Risk Sharing in Sharecropping. The Review of Economic Studies. 41(2), 219-255.
Tikabo, M. O., Holden, S. T., 2003. Land Contract Choice: Poor Landlords and Rich Tenants-Evidence fron the Highlands of Eritrea. Norwegian University of Life Sciences, Department of Economics and Resource Management, Ås.

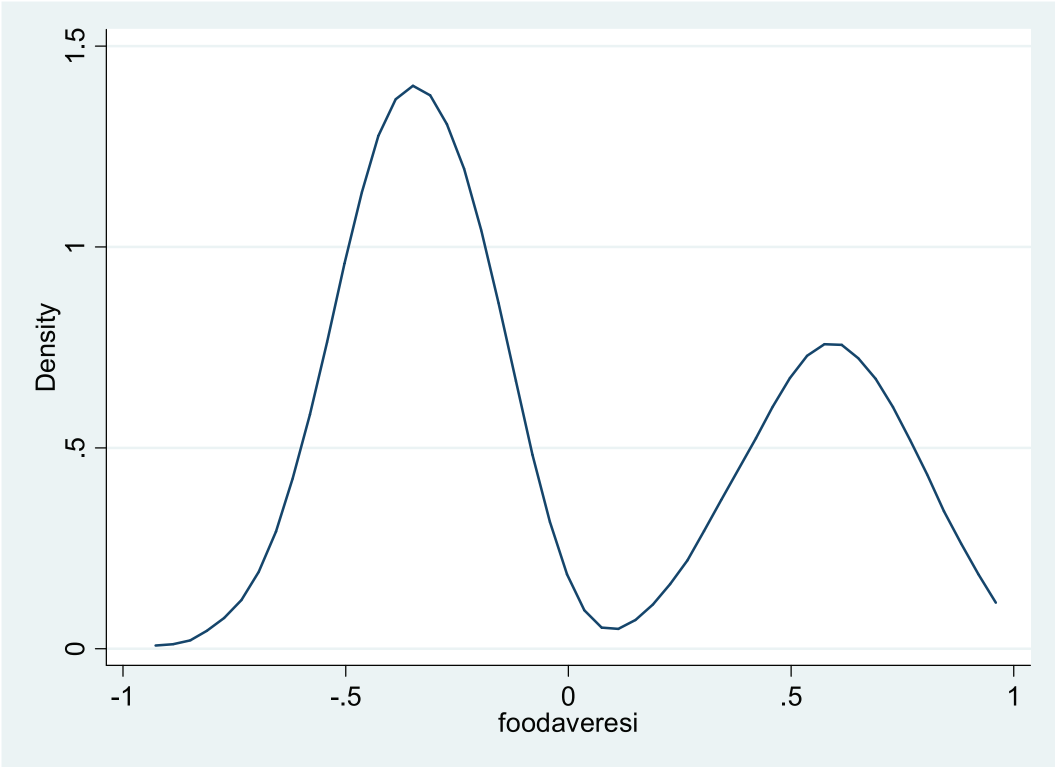

Figure 1: A kdensity graph of predicted food deficit at the beginning of the rainy season (June 2005) (Actual food availability minus predicted availability)

Table 1
Farm plots of landlords and pure owner-operators by irrigation access and land contract arrangement

	Type of plot				Total	
	Rain-fed		Irrigated			
Land contract type	Number of plots	Percent	Number of plots	Percent	Number of plots	Percent
Owner cultivation	768	75.0	189	68.5	957	73.6
Sharecropping	227	22.2	66	23.9	293	22.5
Fixed rent	29	2.8	21	7.6	50	3.9
Total	1,024	100	276	100	1,300	100

Table 2
Descriptive statistics of variables used in regression

Variable description	Landlord Household[a]	Owner cultivator Household[a]	Significance test of difference[b]
Household level variables			
Household head's sex (1=male)	.316(.040)	.839(.024)	0.000***(11.999)
Household head's age	50(1.619)	48.521(.943)	0.307(-1.023)
Female adult labor	1.654(.080)	1.632(.062)	0.828(-0.217)
Male adult labor	1.037(.093)	1.545(.065)	0.000***(4.552)
Education (literate) household members	.787(.081)	1.554(.101)	0.000***(5.206)
Farm size per adult (ha.)	3.689(.179)	3.819(.128)	0.183(-1.335)
Type of plot (1=irrigated, 0=rainfed)	.544(.043)	.525(.032)	0.719(-0.361)
Oxen ownership (tlu)	.241(.047)	.790(.054)	0.000***(6.859)
Livestock ownership (tlu)	.635(.113)	1.688(.152)	0.000***(4.785)
Off-farm income (previous year)	421(67)	873(82)	0.000***(3.729)
Household's access to credit (1=yes)	.566(.043)	.686(.030)	0.020**(2.343)
Household's food stock in June 2005 (1=enough stock, 0=not enough stock)	.265(.038)	.438(.032)	0.001***(3.381)
Household's food deficit in June 2005	-.230(.014)	-.212(.013)	0.363(0.911)
Coping strategies			
Daily labor as a coping strategy (1=yes)	.456(.043)	.496(.032)	0.457(0.745)
Migration as coping strategy (1=yes)	.125(.028)	.215(.026)	0.030**(2.179)
Selling animals as a coping strategy (1=yes)	.412(.042)	.620(.031)	0.000***(3.969)
Selling firewood as a coping strategy (1=yes)	.272(.038)	.248(.028)	0.607(-0.514)
Selling assets as a coping strategy (1=yes)	.228(.036)	.140(.022)	0.031**(-2.170)
Looking for aid as a coping strategy (1=yes)	.551(.043)	.492(.032)	0.266(-1.114)
Reducing consumption as a coping strategy (1=yes)	.728(.038)	.690(.030)	0.441(-0.772)
Number of observations	136	242	
Village level variables[c]			
Mean annual rainfall (mm)	705(12)		
Coefficient of rainfall variability	.340(.011)		
Altitude of the tabia (meters above sea level)	1956(7)		
Total population in the tabia	5062(52)		
Number of observations	6		

*, **, ** are level of significance at 10%, 5%, and 1%, respectively. [a] Figures in parentheses are standard errors. [b] Figures in parentheses are *t-values*. [c]Mean values of village level variables are the same for landlord and owner cultivator households.

Table 3

Means and significance test for household level variables by contract choice of landlord households

Variable description	Sharecropper Household[a]	Fixed renting Household[a]	Significance test of difference[b]
Household head's sex (1=male)	.289(0.043)	.455(0.109)	0.129(1.526)
Household head's age	52(1.759)	44(3.938)	0.074*(-1.800)
Female adult labor	1.544(0.080)	2.227(0.237)	0.001***(3.267)
Male adult labor	1.009(0.104)	1.182(0.204)	0.495(0.684)
Education (literate) household members	.772(0.088)	.864(0.211)	0.679(0.415)
Farm size per adult (ha.)	1.825(0.190)	.939(0.127)	0.045**(-2.027)
Type of plot (1=irrigated, 0=rainfed)	.176(0.036)	.318(0.102)	0.159(1.417)
Oxen ownership (tlu)	.225(0.048)	.327(0.146)	0.420(0.808)
Livestock ownership (tlu)	.581(0.110)	.914(0.407)	0.280(1.084)
Off-farm income (previous year)	385(74)	603(156)	0.234(1.197)
Household's access to credit (1=yes)	.553(0.047)	.636(0.105)	0.472(0.722)
Household's food stock in June 2005 (1=enough stock, 0=not enough stock)	.272(0.042)	.227(0.091)	0.667(-0.432)
Truncated residual shock variable for food shortage in June 2005	-.218(0.015)	-.292(0.044)	0.055*(-1.932)

*, **, ** are level of significance at 10%, 5%, and 1%, respectively. [a] Figures in parentheses are standard errors. [b] Figures in parentheses are *t-values*.

Table 4
Probit model estimates of factors explaining a household's food stock in June (Household level Analysis)

Variable description	With village level variables	With village fixed effects	With village fixed effects and coping mechanisms
Dependent variable: Household's food stock in June 2005 (1=enough stock, 0=not enough stock)			
Household head's sex (1=male)	0.173(0.158)	0.159(0.159)	0.228(0.178)
Household head's age	-0.005(0.005)	-0.004(0.005)	-0.008(0.005)
Female adult labor	0.057(0.075)	0.056(0.075)	0.077(0.081)
Male adult labor	0.083(0.068)	0.078(0.068)	0.044(0.074)
Education (literate) household members	-0.081(0.055)	-0.092*(0.055)	-0.020(0.062)
Type of plot (1=irrigated, 0=rainfed)	0.138(0.167)	0.139(0.167)	0.258(0.178)
Farm size per adult (ha.)	0.047(0.082)	0.040(0.082)	0.002(0.088)
Oxen ownership (tlu)	0.244**(0.121)	0.249**(0.120)	0.303**(0.132)
Livestock ownership (tlu)	0.010(0.043)	0.011(0.043)	-0.003(0.046)
Off-farm income (previous year)	0.000(0.000)	0.000(0.000)	0.000(0.000)
Household's access to credit (1=yes)	-0.082(0.149)	-0.086(0.149)	-0.205(0.169)
Tabia fixed effects	No	Yes	Yes
Daily labor as a coping strategy (1=yes)			-0.624***(0.183)
Migration as coping strategy (1=yes)			-0.470**(0.221)
Selling animals as a coping strategy (1=yes)			-0.323*(0.180)
Selling firewood as a coping strategy (1=yes)			0.143(0.231)
Selling household assets as a coping strategy (1=yes)			0.073(0.269)
Looking for aid as a coping strategy (1=yes)			-0.600***(0.161)
Reducing consumption as a coping strategy (1=yes)			0.518***(0.195)
Mean annual rainfall (mm)	0.001(0.001)		
Coefficient of rainfall variability	-0.076(0.733)		
Total population in the tabia	-0.000(0.000)		
Altitude of the tabia (meters above sea level)	-0.000(0.000)		
Constant	-0.234(1.184)	-0.491(0.319)	0.082(0.379)
pseudo R2	0.054	0.057	0.168
Prob > chi2	.045	.038	0.000
Wald chi2(15)	25.385	27.370	68.060
Log likelihood	-236.806	-236.001	-197.427
Number of observations	378	378	359

*, **, ** are level of significance at 10%, 5%, and 1%, respectively. Figures in parentheses are robust standard errors.

Table 5
Multinomial logit estimates of relative risk of fixed rent versus owner cultivation and sharecropping

Variable description	Fixed rent Versus Owner cultivation			Fixed rent Versus Sharecropping		
	With village level variables	With village fixed effect	With village fixed effects and coping mechanisms	With village level variables	With village fixed effect	With village fixed effects and coping mechanisms
Household head's sex (1=male)	.078***(.043)	.0714***(.040)	.041***(.028)	.934(.508)	.890(.499)	.477(.337)
Household head's age	1.004(.016)	1.005(.015)	1.021(.022)	.971*(.015)	.971*(.015)	.985(.021)
Female adult labor	2.835***(.908)	2.820***(.899)	2.786***(.787)	2.439**(.878)	2.414**(.844)	2.263***(.664)
Male adult labor	.638(.208)	.668(.210)	.856(.252)	.964(.336)	1.001(.335)	1.402(.441)
Literate household members	.394***(.137)	.403**(.144)	.459**(.145)	.673(.236)	.673(.239)	.731(.231)
Type of plot (1=irrigated)	1.916*(.686)	1.649(.618)	2.422**(.970)	1.699(.579)	1.583(.559)	2.148**(.809)
Farm size per adult (ha.)	.644*(.156)	.679(.166)	.789(.226)	.644*(.156)	.6793(.166)	.790(.226)
Oxen ownership (tlu)	.709(.389)	.674(.367)	1.024(.578)	1.679(.934)	1.650(.910)	2.403(1.415)
Livestock ownership (tlu)	.947(.197)	.950(.200)	.823(.188)	1.038(.232)	1.024(.230)	.936(.234)
Off-farm income	.999(.000)	.999(.000)	1.000(.000)	1.000(.000)	1.000(.000)	1.000(.000)
Access to credit (1=yes)	.843(.446)	.917(.487)	.671(.395)	1.37(.755)	1.473(.812)	1.035(.641)
Random food deficit in June	.013***(.018)	.015***(.019)	.000***(.001)	.027**(.041)	.034**(.049)	.001***(.002)
Mean annual rainfall (mm)	.991***(.003)			.990***(.003)		
Rainfall variability	.001**(.003)			.000***(.000)		
Altitude (meters above sea level)	.998(.002)			.999(.002)		
Total population in the tabia	1.001***(.000)			1.001***(.000)		
Daily labor as a coping strategy			3.645(2.992)			3.665(3.051)
Migration as coping strategy			.608(.396)			2.275(1.683)
Selling animals coping strategy			.066***(.063)			.140**(.134)
Selling firewood coping strategy			9.115***(6.726)			6.170**(5.223)
Selling asset coping strategy			.106***(.091)			.088***(.080)
Looking for aid coping strategy			.478(.298)			.282**(.179)
Reducing consumption coping strategy			2.087(1.365)			2.027(1.313)
Tabia fixed effects	No	Yes	Yes	No	Yes	Yes
Number of observations	1300	1300	1300	1300	1300	1300
Log likelihood	-558.241	-544.573	-500.57	-558.24118	-548.329	-500.57778
Wald chi2(36)	225.68	9463.54	5696.90	225.68	5518.60	5409.84
Prob > chi2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pseudo R2	0.3746	0.390	0.4392	0.3746	0.386	0.4392

*, **, ** are level of significance at 10%, 5%, and 1%, respectively. Figures in parentheses are robust standard errors adjusted for household level clustering effects. Tabia fixed effects are left out of the presentation to reduce table size.

Table 6
Multinomial logit estimates of relative risk of share cropping versus owner cultivation

Variable description	Sharecropping versus Owner cultivation		
	With village level variables	With village fixed effect	With village fixed effects and coping mechanisms
Household head's sex (1=male)	.084***(.027)	.080***(.026)	.086***(.029)
Household head's age	1.034***(.010)	1.035***(.010)	1.036***(.010)
Female adult labor	1.162(.195)	1.168(.197)	1.232(.195)
Male adult labor	.661***(.083)	.667***(.083)	.610***(.081)
Education (literate) household members	.586***(.068)	.599***(.070)	.628***(.070)
Type of plot (1=irrigated, 0=rainfed)	1.128(.248)	1.041(.233)	1.128(.243)
Farm size per adult (ha.)	.999***(.000)	.999***(.000)	.999**(.000)
Oxen ownership (tlu)	.422***(.135)	.408***(.129)	.426***(.139)
Livestock ownership (tlu)	.913(.104)	.928(.107)	.880(.099)
Off-farm income (previous year)	.999(.000)	.999(.000)	.999(.000)
Household's access to credit (1=yes)	.614*(.181)	.623(.184)	.648(.186)
Household's food stock deficit in June 2005	.471(.374)	.423(.334)	.361(.290)
Mean annual rainfall (mm)	1.001(.001)		
Coefficient of rainfall variability	38.588**(58.760)		
Altitude of the tabia (meters above sea level)	.999(.001)		
Total population in the tabia	.999(.000)		
Daily labor as a coping strategy			.995(.327)
Migration as coping strategy			.267**(.138)
Selling animals as a coping strategy			.473**(.145)
Selling firewood as a coping strategy			1.477(.843)
Selling household asset as a coping strategy			1.205(.753)
Looking for aid as a coping strategy			1.696*(.494)
Reducing consumption as a coping strategy			1.030(.380)
Tabia fixed effects	No	Yes	Yes
Number of observation	1300	1300	1300
Log likelihood	-558.241	-548.329	-500.57778
Wald chi2(34)	225.68	7775.69	5696.90
Prob > chi2	0.0000	0.0000	0.0000
Pseudo R2	0.3746	0.386	0.4392

*, **, ** are level of significance at 10%, 5%, and 1%, respectively. Figures in parentheses are robust standard errors adjusted for household level clustering effects. The tabia fixed effects are left out to reduce table size.

Paper II

Does Irrigation Enhance and Food Deficits Discourage Fertilizer Adoption in a Risky Environment? Evidence from Tigray, Ethiopia

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Abstract

This paper assesses how rainfall risk, access to irrigation, and food deficits affect the probability and intensity of fertilizer use in the highlands of Tigray Region, Ethiopia. Using a Cragg (Double Hurdle) model, We found that households were significantly more likely to use fertilizer and that they used significantly higher amounts of fertilizer on irrigated plots than on rain-fed plots. Furthermore, households with access to irrigation were significantly more likely to use fertilizer, but those using fertilizer did not use more than households without irrigation. The probability and intensity of fertilizer use was significantly higher in areas with higher average rainfall and in areas with lower rainfall variability. Irrigation was significantly more important for fertilizer adoption and fertilizer intensity in lower rainfall areas. Irrigation had a stronger positive effect on intensity of fertilizer use in areas with high rainfall variability. A higher probability of households being food self-sufficient was significantly negatively associated with the probability of fertilizer use. Food deficit households predicted to have deficits were significantly less likely to use fertilizer. However, among these households, those that decided to use fertilizer used significantly more fertilizer than households that did not have a food deficit.

Keywords: Tigray, irrigation Average rainfall, Rainfall variability, food deficit, fertilizer use.

1. Introduction

There have been many studies on the effect of irrigation on fertilizer adoption (Abdoulaye and Sanders, 2005; FAO, 2002; Fox and Rockstrom, 2000; IFA, 2002; Morris *et al.*, 2007 ; Shah and Singh, 2001; Smith, 2004; Wichelns, 2003; Yao and Shively, 2007). Some of these studies suggest strong complementarities between irrigation and fertilizer. For example, Abdoulaye and Sanders (2005) argued that fertilizer and water are issues that need to be handled simultaneously because, when water is a limiting factor, fertilizer may have no positive effect or may indeed have an adverse effect. Shah and Singh (2001) considered irrigation as a major catalyst for agricultural growth through the adoption of Green Revolution technologies in India. FAO (2002) and Morris et al (2007) have also argued that households with access to irrigation benefit more because of the complementarities of irrigation and fertilizer. However, irrigation and the Green Revolution have not been nearly as successful in Africa as in Asia (Feder *et al.*, 1985).

Differing from findings from other parts of the world and the expectation of the regional government, previous studies in Tigray (Pender *et al.*, 2002) report that irrigation has an insignificant effect on fertilizer adoption. Furthermore, using Deaton's (1997) approach to correct selection bias, Hagos (2003) finds a negative relationship between irrigation and fertilizer adoption. More recent work by Pender and Gebremedhin (2007) reports that fertilizer use on irrigated plots is less likely than on plots with stone terraces. Hence, the impact of irrigation on agricultural production was found to be statistically insignificant.

However, these previous studies from Tigray suffer from small sample size for irrigated plots, which constitute only 1% of the sample plots of Hagos (2003) and only 5.6% of that of Pender et al. (2002) and Pender and Gebremedhin (2007). Comparing such a small sample of irrigated plots with a large and heterogeneous sample of rain-fed plots makes it difficult to uncover any causal effect of irrigation. This makes estimation unreliable and more dependent on model specification and spurious correlations, while estimation results are susceptible to bias (Ho *et al.*, 2007). Pender and Gebremedhin (2007) acknowledge this problem and suggest the need for further research. Their paper does not properly control for the effect of bio-physical factors, such as soil type, slope, and land quality. Given that farmers consider environmental and plot characteristics as a basis for their decision to invest in inputs, the omission of such variables may lead to omitted variable bias in the estimated parameters (Sherlund *et al.*, 2002).

The effect of production risk and food deficit on technology adoption in general and fertilizer use in particular is mixed in the literature. The standard theory and view has been that producers' risk aversion leads to low adoption of new technologies (Dercon and Christiaensen, 2007; Feder *et al.*, 1985; Sandmo, 1971). On the other hand, Finkelshtain and Chalfant (1991) and Fafchamps (1992) showed that poor households do not systematically produce less if they think that adoption of the new technology may help them to become more food self-sufficient. Finkelshtain and Chalfant (1991) demonstrated that food-deficit households producing, a normal good that they consume have an ambiguous response to higher risk but that higher risk aversion increases the probability that they respond to higher risk by producing more. Our study area and data represent an excellent opportunity to test this.

Different studies have empirically investigated the determinants of fertilizer adoption in Ethiopia. Among others, Kassie et al. (2008) used output variance as a proxy of production risk and found that higher output variance and probability of crop failure were negatively related to the probability and intensity of fertilizer adoption. Consistent with this, they found that farmers' output (return) was positively related to the probability and amount of fertilizer use. Fufa and Hassan (2006), on the other hand, have investigated the factors that affect the probability and intensity of fertilizer use on maize production in the Dadar district in eastern Ethiopia. They found that the age of the farm household's head and fertilizer price were negatively related to the probability and intensity of fertilizer use. On the other hand, farmers' expectation of good rainfall was positively associated with fertilizer use. Demeke et al.(1998) has controlled for the effect of a wide range of factors affecting farm households' fertilizer use in four major crop producing regions (Amhara, Ormiya, SNNPR and Tigray) of Ethiopia. Among other factors, access to fertilizer distribution centers, access to credit and extension services were found to be important in influencing whether farm households in the wereda have used fertilizer. In the same study, teff (a staple crop in Ethiopia) was positively related to fertilizer use. This could be because the cultivated teff area covered the largest proportion of the total cultivated area. However, since growing teff is an endogenous decision of the farm household, the result could be susceptible to a problem of endogeniety. Surprisingly, Demeke et al. (1998) found no significant relationship between average rainfall and fertilizer use.

Despite their importance in informing policy makers, these studies have not adequately examined the role of irrigation in reducing production risk due to adverse climatic conditions and its effect on fertilizer adoption. They have not assessed the effect of average annual rainfall and rainfall variability on fertilizer adoption. This paper attempts to fill some of the gaps by analyzing the effect of production risk and role of irrigation to reduce such production risks and then to enhance fertilizer adoption. We tried to capture production risk through average annual rainfall and rainfall variability. New in this paper is also an examination of the effect of food deficit on fertilizer adoption. Since we lack a good measure of households' risk preference and risk aversion behavior, we could not control for its effect on fertilizer adoption. But the response to food deficit may also give a hint about households' risk preferences. The paper has also attempted to address some of the gaps of the previous studies in Tigray by controlling for the effect of agro-ecological factors on fertilizer use. The analysis is based on plot level data of both irrigated and rain-fed plots using a Cragg (Double Hurdle) model. We find a positive and significant effect of irrigation on the probability and intensity of fertilizer use.

The objectives of this paper are to: (1) analyze the effect of production risk due to rainfall scarcity and rainfall variability on fertilizer adoption, (2) investigate the role of irrigation in hedging against production risk and then to stimulate fertilizer adoption, and (3) investigate the effect of food deficit (consumption shocks) on fertilizer adoption.

The rest of the paper is structured as follows. Section 2 presents a review of related literature in relation to production uncertainty and technology adoption. In section 3, we present the analytical framework followed by estimation methods in section 4. In section 5, we give a description of the study area, data collection and descriptive statistics of the data. Results and related discussion are presented in section 6 before we conclude in section 7.

2. Literature Review: Risk and Technology Adoption

Sandmo (1971) has shown that a risk averse profit maximizing firm reduces investment in purchased inputs and production, compared to what would be if it were risk neutral and maximizes the expected profit. This implies that firms without perfect insurance under-invest in purchased inputs and hence under-produce. This explanation has attracted attention among economists working on technology adoption. Producers' resistance to risk has been used to explain the failures of farm households to adopt new technologies (Feder *et al.*, 1985). But, this view has been challenged in the sense that poor households do not systematically under-produce (Fafchamps, 1992; Finkelshtain and Chalfant, 1991). Fafchamps (1992) has showed that if people are poor and concerned about their survival, the solution may not be to under-invest and under-produce. However, they may even adopt risk increasing technologies if they think that it helps them to become food self-sufficient. Finkelshtain and Chalfant (1991) extended the analysis of Sandmo (1971) by assessing the behavior of a producer-consumer household rather than a pure producer, assessing the effect of being a net seller or net buyer producing an inferior or a normal good that is also consumed by the household, and varying the level of risk aversion. They derive an alternative measure of the risk premium, taking into account the covariance between income and price of output and show that the Sandmo result only holds strictly when $\eta > r > 0$, where η is the income elasticity of the household's demand for home-consumption of the farm crop and r is the relative risk aversion. They show that a net buyer of food who is risk neutral or slightly risk-averse has the same qualitative response as in the Sandmo model, while a more risk-averse producer increases output with increased risk. Furthermore, an increase in relative risk aversion is associated with increased output for a given level of risk. This suggests that net-selling producers use less inputs and produce less under risk than under certainty, while net-buying households with severe risk aversion increase their input use and production (Finkelshtain and Chalfant, 1991).

There is an agreement that fertilizer adoption, or modern input use in general, is crucial in achieving agricultural productivity growth and ensuring food security, especially in Sub-Saharan Africa, where agriculture is characterized by low use of modern technology and low productivity (Franklin, 2006; Kassie *et al.*, 2008). In the adoption literature, production uncertainty (risk) and risk avoidance behavior of poor people are often associated with low adoption of modern inputs (Franklin, 2006; Hazell, 1988; Kassie et al., 2008; Rosenzweig and Binswanger, 1993). The most common factor for the low adoption of modern inputs is risk and farmers' resistance to technological innovations, which raises both the mean and variability of income (Hagos, 2003; Koundouri *et al.*, 2006). Uncertainty associated with the adoption of modern inputs has two dimensions: the riskiness of farm yield after adoption and price uncertainty related to agricultural production itself (Koundouri et al., 2006).

Hazell (1988) has suggested that, despite the fact that production risk is prevalent everywhere, it is particularly burdensome to smallholder farmers in developing countries. They try to avoid it through different mechanisms, such as diversifying their crops, using traditional farming techniques (avoiding less familiar modern inputs) and using other risk sharing mechanisms such as sharecropping contracts. The types and levels of risk vary with the type of farming system, climate, degree of market integration, policy and institutional characteristics (Hazell, 1988). When farmers are constrained by either ex-ante resource constraints or limited by ex-post coping (insurance) mechanisms, they become hesitant to invest in modern technology such as fertilizer (Just and Pope, 1979; Rosenzweig and Binswanger, 1993). This may lead to a risk induced poverty trap, as those who are better endowed with ex-ante resources can self-finance their investment or can easily insure their consumption against ex-post income shocks and thereby take advantage of modern technology. On the other hand, those who are poor and resource constrained are engaged in low risk and low yield activities and may therefore be trapped in poverty (Kassie et al., 2008; Rosenzweig and Binswanger, 1993). Since low agricultural productivity causes persistent poverty, interventions that can help poor households to hedge against shocks and then adopt modern inputs might be an effective poverty reduction strategy (Dercon and Christiaensen, 2007).

Market imperfections such as those in labor and credit markets, can substantially influence farmers' technology adoption. This is important in developing countries in general and in sub-Saharan Africa in particular, where rural infrastructures such as roads and communication networks are underdeveloped (Shiferaw *et al.*, 2006). Imperfect markets are characterized by high transactions costs due to asymmetric information and imperfect competition that leads to non-separability of production and consumption decisions of households (de Janvry *et al.*, 1991; Singh *et al.*, 1986). When markets are imperfect, households' resource endowments become important determinants of investment and production decisions (Holden *et al.*, 2001), implying that resource poor households are less likely to adopt purchased inputs. For example, an imperfect labor market leads households to equate their demand for labor with their family labor. Households with larger labor endowments are likely to adopt more labor intensive technologies than labor poor households. For example, Abdoulaye and Sanders (2005) found that fertilizer application also needs high labor input for weeding in Niger, indicating that labor rich farm households are more likely to adopt fertilizer.

An imperfect credit market also affects households' investment and production decisions. For example, fertilizer adoption requires an initial investment. With limited access to credit, poor households may not have the capacity to purchase it. Hence, wealthier households with accumulated savings in the form of cash or capital (such as livestock) are more likely to invest in fertilizer and reap the benefits. For example, Wills (1972) has reported that shortage of financing is a major limiting factor of fertilizer use. However, credit alone may not limit technology adoption, particularly if the technology requires small amount of resources (Feder et al., 1985).

Consumption risk is another important determinant of fertilizer adoption. Production risk is one major source of income fluctuations for rural households, especially in developing countries (Giné and Yang, 2008). This is due to the fact that output variability affects total agricultural output, which influences food security at household level. Households lacking insurance against shocks in food stock are likely to stick to their traditional production techniques. Since ensuring food security is important for subsistence-producing households, farmers may prefer inputs that are stable in output at different moisture levels (Kaliba et al., 2000). This implies that, despite enhancing productivity, the fertilizer also increases income variability. Hence, households experiencing a food deficit may decide not to adopt it, because they are ill-equipped to cope with shocks (Dercon and Christiaensen, 2007; Giné and Yang, 2008). Farm households may make their decision to adopt or not to adopt fertilizer based on its *ex-ante* and *ex-post* consumption plans. In general, food deficiency may affect households' fertilizer use in two dimensions. First, food insecure households may have stocks or savings that partially facilitate consumption smoothing. Second, poor farm households that aim to minimize consumption fluctuations due to covariate shocks (such as drought) may opt for less risky inputs in order to avoid permanent damages (Dercon and Christiaensen, 2007; Giné and Yang, 2008). However, higher returns in good years may help to bridge the deficit in bad years, meaning that risky inputs may be preferred and result in higher food security overall.

In general, output variability causes substantial consumption risk under subsistence production, especially when production depends on rainfall. This is relevant in areas where insurance against production risk is absent and credit markets are imperfect. Dercon and

Christiaensen (2007) reported that farmers in a semi-arid district of western Tanzania with limited options to smooth ex-post consumption were found to grow lower return, but safer crops. Gafsi and Roe (1979) have reported that poor farmers in Tunisia preferred domestically developed varieties to the imported varieties which are less known to them.

Based on this review of the theoretical and empirical literature, an analytical framework is developed in the next section relating production risk and irrigation to farm households' consumption needs and fertilizer adoption.

3. Analytical Framework

The framework focuses on a production environment where rainfall is scarce and erratic, markets are imperfect, peasant households are poor and strive for subsistence, and are net food buyers. With access to irrigation, a farm household produces on its irrigated and rain-fed plots. Assuming that the household i has p plots with $p = n + m$, where n represents irrigated and m represents rain-fed plots, income from agricultural production is specified as:

$$\begin{aligned} Y_i = &\sum_{n=1}^{n} p_q \theta^{(I)} Q_{ip}^{(I)} \left(x_{ip}^{f(I)}, x_{ip}^{nf(I)}; z_h, A_c, \psi_i \right) + \sum_{m=1}^{m} p_q \theta^{(R)} Q_{ip}^{(R)} \left(x_{ip}^{f(R)}, x_{ip}^{nf(R)}; z_h, A_c, \psi_i \right) \\ &- p_f \left(\sum_{n=1}^{n} x_{ip}^{f(I)} + \sum_{m=1}^{m} x_{ip}^{f(R)} \right) - p_{nf} \left(\sum_{n=1}^{n} x_{ip}^{nf(I)} + \sum_{m=1}^{m} x_{ip}^{nf(R)} \right) \end{aligned} \quad (1)$$

where Y is the stochastic net income (Birr[9]) of household i produced on irrigated and rain-fed plots, Q is a vector of crop production outputs and p_q is a vector of output price. The variable x represents purchased inputs (such as hired labor, oxen, seed, chemicals and pesticides, etc.) used by household i on plot p where the superscripts f and nf represent fertilizer and other inputs, respectively, where p_f is price of fertilizer and p_{nf} is price of

[9] Birr is an Ethiopian currency

other inputs. The superscripts (I) and (R) indicate irrigated and rain-fed agriculture, respectively. Variable z_h represents household-specific characteristics (such as age, gender and education), the household's labor and capital endowments (such as, livestock and oxen) and the household's food stocks. These are included due to market imperfections leading to household-specific shadow prices for these endowment variables. Variable A_c captures plot characteristics, and ψ_i is unobserved household heterogeneity that captures unreported household characteristics, such as farming experience and skills, risk aversion, and other factors that affect households' input use and production decisions in an environment with imperfect markets. Production risk is represented by the random variable θ, which has mean 1 and variance $\theta_{\text{var}} = \sigma_{\theta}^{2}$. The distribution of this random variable is exogenous to the farmer's decision. The effect of the random variable (production risk) depends on the type of plot (i.e., whether a plot is irrigated or rain-fed), implying that $\theta_{\text{var}}^{(I)} < \theta_{\text{var}}^{(R)}$.

When rainfall is variable and unpredictable, it affects agricultural production and causes production risk in two ways. First, shocks in weather conditions (θ) cause direct crop failure. On the other hand, if rainfall is unpredictable, the risk of investment in fertilizer becomes high, because when water (i.e., moisture) is not available at the right time and in the amount, fertilizer use may even have an adverse effect (Abdoulaye and Sanders, 2005), therefore, increasing production risk. Production risk due to adverse weather conditions may also affect prices (Holden and Shiferawl, 2004). Self-sufficient households or even surplus producers in normal years may become net buyers in drought years, when food prices tend to be higher because a larger area may face the same problem. In order to meet their food needs, households may have to sell some of their livestock, which creates a downward pressure on livestock prices. The indirect negative effects through changes in crop and livestock prices may be as big as the direct production loss effect (Holden and Shiferaw, 2004). With access to irrigation, the negative effect of stochastic environment and associated production risk should be lower. This implies that production risk on irrigated plots is less than that on rain-fed plots $\left(\theta^{(I)} < \theta^{(R)}\right)$.

We assume that both output and input prices are non-random (i.e., farmers are assumed to be price takers in both markets). Risk averse farm households maximize the expected utility of gross output specified as follows:

$$\max_{x_{ip}^{f(I)},x_{ip}^{f(R)},x_{ip}^{nf(I)},x_{ip}^{nf(R)}} EU\left[\begin{array}{l}\sum_{n=1}^{n} p_q \theta^{(I)} Q_{ip}^{(I)}\left(x_{ip}^{f(I)}, x_{ip}^{nf(I)}; z_h, A_c, \psi_i\right) + \sum_{m=1}^{m} p_q \theta^{(R)} Q_{ip}^{(R)}\left(x_{ip}^{f(R)}, x_{ip}^{nf(R)}; z_h, A_c, \psi_i\right) \\ -\left[p_f\left(\sum_{n=1}^{n} x_{ip}^{f(I)} + \sum_{m=1}^{m} x_{ip}^{f(R)}\right) - p_{nf}\left(\sum_{n=1}^{n} x_{ip}^{nf(I)} + \sum_{m=1}^{m} x_{ip}^{nf(R)}\right)\right]\end{array}\right] \quad (2)$$

where E is the expectation operator and U is a well-behaved concave and non-decreasing utility function of total income. The last term in square bracket of equation (2) represents the costs that include fertilizer and other purchased inputs. Other variables are as explained above. The utility maximization problem of the farm household is subject to a cash constraint specified as:

$$\left[p_f\left(\sum_{n=1}^{n} x_{ip}^{f(I)} + \sum_{m=1}^{m} x_{ip}^{f(R)}\right) + p_{nf}\left(\sum_{n=1}^{n} x_{ip}^{nf(I)} + \sum_{m=1}^{m} x_{ip}^{nf(R)}\right)\right] + p_q Q^D\left(z_h, \psi_i\right) \le \bar{C}\left(z_h, \psi_i\right) \quad (3)$$

where $p_q Q^D\left(z_h, \psi_i\right)$ is household's food consumption deficit and $\bar{C}(.)$ captures the farm household's cash constraint, both of which are conditioned by a household's characteristics, consumption preferences, access to credit and other unobserved household heterogeneities. Therefore, with a binding cash constraint, the maximization problem is specified as follows:

$$
\max_{x_{ip}^{f(I)},x_{ip}^{f(R)}} L = EU\left[\begin{array}{l} \sum_{n=1}^{n} p_q \theta^{(I)} Q_{ip}^{(I)}\left(x_{ip}^{f(I)}, x_{ip}^{nf(I)}; z_h, A_c, \psi_i\right) + \sum_{m=1}^{m} p_q \theta^{(R)} Q_{ip}^{(R)}\left(x_{ip}^{f(R)}, x_{ip}^{nf(R)}; z_h, A_c, \psi_i\right) \\ -\left[p_f\left(\sum_{n=1}^{n} x_{ip}^{f(I)} + \sum_{m=1}^{m} x_{ip}^{f(R)}\right) - p_{nf}\left(\sum_{n=1}^{n} x_{ip}^{nf(I)} + \sum_{m=1}^{m} x_{ip}^{nf(R)}\right)\right] \end{array}\right]
$$

$$
+\lambda\left[\bar{C}(z_h,\psi_i) - p_f\left(\sum_{n=1}^{n} x_{ip}^{f(I)} + \sum_{m=1}^{m} x_{ip}^{f(R)}\right) - p_{nf}\left(\sum_{n=1}^{n} x_{ip}^{nf(I)} + \sum_{m=1}^{m} x_{ip}^{nf(R)}\right) - p_q Q^D\left(z_h,\psi_i\right)\right]
$$

(4)

Given that $Y = p_q\theta^{(I)}Q^{(I)} + p_q\theta^{(R)}Q^{(R)}$, the first order conditions (FOCs) for x_f^I and x_f^R are:

$$
\frac{\partial L}{\partial x^{f(I)}} = \frac{\partial EU}{\partial Y}\left[p_q\theta^{(I)}\frac{\partial Q^{(I)}}{\partial x^{f(I)}} - p_f\right] - \lambda p_f = 0 \tag{5}
$$

$$
\frac{\partial L}{\partial x^{f(R)}} = \frac{\partial EU}{\partial Y}\left[p_f\theta^{(R)}\frac{\partial Q^{(R)}}{\partial x^{f(R)}} - p_f\right] - \lambda p_f = 0 \tag{6}
$$

Equations (5) and (6) show the marginal benefit minus marginal cost of fertilizer used on irrigated and rain-fed plots, respectively. λp_f is the opportunity cost of reducing current consumption due to investment in fertilizer. Variable λ is a markup shadow price of fertilizer. From equations (5) and (6), we see that the marginal cost of production and the opportunity cost of reduction in current consumption are the same in both irrigated and rain-fed agriculture. Given that other inputs remain the same, we assume that expected income from irrigated agriculture is greater than rain-fed agriculture, i.e. $E\left(p_q\theta^{(I)}Q^{(I)} - C^{(I)}\right) > E\left(p_q\theta^{(R)}Q^{(R)} - C^{(R)}\right)$. This is due to the fact that the effect of random shocks is less in irrigated agriculture than in rain-fed agriculture $\left(\theta_{\text{var}}^{(I)} < \theta_{\text{var}}^{(R)}\right)$. Accordingly, we expect that

$$
\frac{\partial EU}{\partial Y} p_q\theta^{(I)}\frac{\partial Q^{(I)}}{\partial x^{f(I)}} = \frac{\partial EU}{\partial Y} p_q\theta^{(R)}\frac{\partial Q^{(R)}}{\partial x^{f(R)}}, Q^{(I)} > Q^{(R)}, x^{f(I)} > x^{f(R)} \tag{7}
$$

Equation (7) implies that the average return to fertilizer used in irrigated agriculture is greater than the average return to fertilizer used in rain-fed agriculture.

$$EU\left(Y \middle| x^f > 0\right) > EU\left(Y \middle| x^f = 0\right) \tag{8}$$

Based on the theory that we review and the theoretical framework, we have developed the following hypotheses for empirical testing:

H1: *Farm households are more likely to use fertilizer on irrigated plots than on rain-fed plots.* Testable implication: the dummy variable plot type (1=irrigated) has a positive and significant effect on the likelihood of household's fertilizer use.

H2: *Access to irrigation enhances fertilizer use*. The implication is that, controlling for the effect of other plot characteristics, farm households use more fertilizer on irrigated plots than rain-fed plots. Therefore, the coefficient of plot type (1=irrigated) is positive and statistically significant in the intensity regression.

H3: *Rainfall risk hypotheses*

H3a: *Lower average rainfall leads to less use of fertilizer.* The implication is that the coefficient of mean rainfall is positive and statistically significant in both the probability and intensity models.

H3b: *Higher rainfall variability leads to lower fertilizer use.* The implication is that the coefficient of rainfall variability is negative and statistically significant in both the probability and intensity regressions.

H4: *Irrigation and rainfall risk interaction hypotheses*

H4a: *Irrigation stimulates greater fertilizer use in low rainfall areas than in high rainfall areas*. The implication is that the interaction effect of irrigation and rainfall (*rainfallirr*) on fertilizer use is negative. Thus, the marginal benefit of irrigation investment is lower in high rainfall areas. Its effect on fertilizer adoption is less there as well.

H4b: *Irrigation stimulates greater fertilizer use in areas with high rainfall variability relative to areas with low rainfall variability.* The implication is that the interaction effect of irrigation and rainfall variability (*cvirr*) on fertilizer use is positive and significant.

H5: *Food deficit impact hypotheses:*

H5a: *The probability of food self-sufficiency is positively associated with fertilizer use.*

H5b: *Households predicted to have a food deficit use less fertilizer than households that do not have a food deficit.* This is because such households are less able to bear *ex-post* consumption fluctuations and fund fertilizer use (Dercon and Christiaensen, 2007).

H5c: *Food deficit households use more fertilizer than other households in order to reduce their food deficit* (Finkelshtain and Chalfant, 1991).

4. Study area, Data and Descriptive Statistics

4.1. The Study Area and Data

The data used in this paper came from a large rural household sample survey targeting small-scale irrigation projects in the Tigray region, northern Ethiopia. Our study area covers six communities/*tabias*[10], each consisting about four villages. These sites were selected to represent different agro-ecological settings, water typologies (source of irrigation water), irrigation water distribution and management systems.

The sample was established through a three-stage stratified random sampling process. First, all *tabias* in the region with irrigation projects were identified based on the type of irrigation technology. Altitude, size of irrigable land and experience (years since irrigation was started) were also used as a basis for stratification. Among the six sites, two use micro-dams, and two use river diversion, as a source of irrigation water. The remaining two use ground water, with

[10] The tabia is the lowest administrative unit in the structure of the Regional Government of Tigray.

one of them using pressurized tube irrigation infrastructure. At the second stage, all farm households in each *tabia* were stratified based on their access to irrigation.

In the final step, we selected 100 sample households from each *tabia*, with the exception of *Kara-Adishawo (in Raya Azebo),* from which we have 113 sample households. The number of households with and without access to irrigation was determined based on the proportion of total farm households that have and have not access to irrigation in each *tabia*. This approach enabled us to have households with and without irrigated plots, with the second group serving as a counterfactual. In this paper, we dropped rented in and rented out plots. Hence, we used 1782 owner-operated plots, of which 1419 and 363 are rain-fed and irrigated, accounting for 79.6 and 20.4%, respectively. A plot is defined as a distinct management unit based on the type of crop planted during 2004/2005 agricultural season.

Data on plot characteristics include soil type, land quality and slope (as perceived by the farm households) and recall data on inputs and output from the past harvest season.[11] Plot size was not physically measured, but farmers were asked to report the size of the plot in the local measurement unit (*tsimdi*[12]). Size was subsequently converted into hectares. Since farmers have land certificates indicating the size and boundaries of their plots, we trust that the size of plots that they reported is quite accurate.

4.2. Descriptive Statistics

Table 1 presents a summary of variables used in the regression. We see that about 77% of the sample households are headed by males. Households with access to irrigation have higher shares of female labor. About 62% of pure rain-fed cultivating and 66% of irrigating

[11] Data collection was carried out during October-December, 2005
[12] Four tsimdi is approximately equal to one hectare.

households have access to credit. The overall average plot size is about 1.2 hectares and the average size of rain-fed and irrigated plot is 1.4 and 0.41 hectares, respectively. On average, about 22, 20, 23 and 35 percent of rain-fed plots, and 17, 33, 27 and 24 percent of irrigated plots are found in Baekel, Walka, Hutsa and Mekayhi soils, respectively (for soil characteristics see Appendix 2). On the other hand, about 9% of irrigated and 19% of rain-fed plots are found in plain area, while farmers believe that about 82% of their irrigated and 60% of rain-fed plots are of good quality. Overall, average fertilizer use is about 10.5 Kg/ha, about 18.2 and 8.5 Kg/ha on irrigated and rain-fed plots, respectively. Finally, we see no statistical difference in the village level variables, except that 28% of rain-fed plots and 35% of irrigated plots are found in lowland (Kola) areas.

5. Estimation Methods

In order to test the effects of households' food self-sufficiency and actual food deficits on households' fertilizer adoption, we first ran a probit model to predict the probability that households were food self-sufficient. We had data whether a farm household had sufficient food at the beginning of the rainy season (June), but this variable was likely endogenous and dependent on structural characteristics (such as household wealth, composition and general agro-climatic conditions). It may also be affected by potential community-wide shocks (like droughts) or individual households (like health problems affecting the labor force during the production season). The results of the probit model are presented in Appendix 1.To capture shocks in households' food availability and examine the effect of a food deficit on households' fertilizer use, we used the residual (=dummy for actual food self-sufficiency minus the predicted food self-sufficiency) to generate two dummy variables. The first of these (*D1foodaversi*) was set equal to one if the value of the residual is greater than -0.5 and less than 0. This captures food deficit households that were predicted to be in food deficits.

The second (*D2foodaversi*) was set equal to one if the value of the residual is less than -0.5 and captures food deficit households that were predicted to be food self-sufficient. Therefore, their actual food deficit may be attributable to a shock. For a clear exposition of how the two dummy variables were generated, see the following procedure.

Predicted food availability (yhat)	Food availability in June (Y)	
	Yes = 1	No = 0
	Y-yhat = (+)	Y-yhat = (-), D1=1 if 0>D1>-0.5
	Y-yhat = (+)	Y-yhat = (-), D2=1 if D2<-0.5

The more negative the residual is, the less likely that the household is facing a food deficit; i.e., such households are wealthier and subsequently more self-sufficient. We use both variables in the fertilizer adoption models to test whether food deficits are expected to affect farm households' ability to invest in fertilizer as a strategy to become food self-sufficient.

In our sample data, fertilizer use has been reported in about 30% of irrigated and 32% of rain-fed plots (see Table 1). In such conditions, estimating the parameters using OLS regression fails to account for the qualitative difference between zero and continuous observations and leads to biased estimates. This is sometimes referred to as "substantial bias"(Franklin, 2006; Smits, 2003). On the other hand, restricting the analysis to observations where fertilizer has been applied (i.e., $f > 0$) will yield biased and inconsistent parameter estimates. This is known as "heterogeneity bias" (Smits, 2003) because it ignores the process that generated the observed fertilizer use (Yilma and Berger, 2006).

We assessed whether it is appropriate to use a one-shot or two-stage model for fertilizer use by comparing the results of a censored Tobit model and a Cragg (double hurdle) model. In the double hurdle model, we first estimated the probability that the farm household adopts fertilizer. We estimated the intensity of fertilizer use in the second stage. We performed a likelihood ratio test to see whether the censored Tobit model nests the two-stage model. The likelihood ratio test rejected the censored Tobit model in favor of the double hurdle model ($\chi^2_{(22)} = 316.75,\ prob = 0.000$).

Given our two-stage model, there is also a risk of selection bias related to clustering at zero due to selection rather than censoring. A Heckman selection test was used to test for selection bias. We found no significant selection bias in the Heckman selection model and hence present only the results from the Cragg (double hurdle) model.

6. Results and Discussion

We found that households with access to irrigation are significantly (at 10% level) more likely to use fertilizer than households without access to irrigation. Our first hypothesis (**H1**) stated that farmers are more likely to use fertilizer on their irrigated plots than on rain-fed plots. We see from Table 2 that farm households were significantly (at 1% level) more likely to use fertilizer on irrigated plots than on rain-fed plots. Furthermore, our second hypothesis (**H2**) stated that access to irrigation enhances fertilizer intensity. We found that farm households use significantly (at 1% level) higher amounts of fertilizer on irrigated plots than on rain-fed plots (see Table 3). Therefore, we are clearly not in a position to reject these hypotheses, contrary to earlier findings in this part of Ethiopia. One possible explanation may be that there is a learning curve in relation to production on irrigated land, as it is a relatively new technology, and the advantages have become stronger in our more recent data. Another explanation is that we have better quality data, allowing us to do a more rigorous test than was possible in earlier studies.

Hypothesis three (**H3a and H3b**) stated that fertilizer adoption is lower in areas with low rainfall and in areas with high rainfall variability. We found that the probability of fertilizer use was significantly (at 1% level) higher in areas with higher average rainfall (*rainfall*) and lower rainfall variability (*cv*), in line with our hypotheses. Similarly, the intensity of fertilizer use is significantly (at 5% level) higher in high rainfall and low rainfall variability areas (see Table 2 and 3). The results imply that rainfall risk is an important constraint to fertilizer adoption in Tigray.

Hypothesis four (**H4a, H4b**) stated that irrigation stimulates greater fertilizer use in low rainfall and high rainfall variability areas relative to areas with high average annual rainfall and low rainfall variability. To test these, we use the interaction effect of irrigation with average annual rainfall (*rainirr*) and rainfall variability (*cvirr*). From Table 2, the significance (1% level) of the first interaction variable indicates that the effect of irrigation on the probability of fertilizer use is higher in low rainfall areas than in high rainfall areas, while the second interaction variable was insignificant. Both interaction variables were significant (at 5 and 10% levels) with negative and positive signs in the intensity model (Table 3). This provides clear evidence of the higher importance of irrigation availability for fertilizer adoption in low rainfall areas and weak evidence of more fertilizer use in areas with more rainfall variability. These findings imply that irrigation is more important for fertilizer adoption in drought-prone areas than in areas with sufficient precipitation. This may have policy implications for where to allocate irrigation investments, but it must be combined with overall cost-benefit analyses where investment costs, crop productivity effects and transportation costs are taken into account.

Hypothesis five (**H5a, H5b, H5c**) stated that food deficits may affect fertilizer adoption positively or negatively and that expected (predicted) food deficits may have a different effect than actual food deficits (e.g., due to shocks). From Table 2, we see that the higher probability of households' being food self-sufficient (*yhat*) was negatively related to the probability of fertilizer adoption (significant at 1% level). This indicates that expected food deficits stimulate fertilizer adoption as a means to reduce the deficit. However, food deficit households predicted to be so (*D1foodaversi*) were significantly (at 1% level) less likely to use fertilizer. This may indicate that particularly poor households experiencing a food deficit may be forced to use scarce resources to buy food to satisfy current consumption, rather than to invest in fertilizer adoption to reduce future food deficits.

On the other hand, in regards to the intensity of fertilizer use (Table 3), food deficit households predicted to have a food deficit used significantly (at 1% level) higher amounts of fertilizer than food self-sufficient households. The food deficit may not have come as a shock to these households; they may be less liquidity constrained and thus appear to try to reduce future food deficits by using higher levels of fertilizer. We should remember that the sample size here has been restricted to those using fertilizer, meaning that those who were unable to buy fertilizer due to poverty/liquidity constraints have been eliminated from the sample. These finings are in line with the model of Finkelshtain and Chalfant (1991) and Fafchamps (1992), showing that net buyers of food respond differently to risk than net sellers or firms (Sandmo (1971). This adds empirical evidence to the presumed effect of consumption risk on technology adoption in general and fertilizer, in particular.

There are some additional observations that we can make in Tables 2 and 3. Households with more livestock (oxen and other livestock) and households with more literate members were significantly more likely to use fertilizer, demonstrating significant market imperfections causing wealth to affect production decisions. Households with older household heads were significantly less likely to use fertilizer. This could have several explanations. Old age could imply lower working capacity, less capacity to access fertilizer, poorer knowledge about the use of fertilizer and more skepticism towards fertilizer use. This is in line with findings in Malawi (Franklin, 2006). We see also that female-headed households were significantly (at 1% level) less likely to use fertilizer than male-headed households. This can be related cultural norms that female labor in Ethiopia is not used for cultivation, except for weeding and harvesting. Moreover, female-headed households are among the poor households (Croppenstedt *et al.*, 2003) that lack access to resources to invest in fertilizer. We refrain from commenting on the remaining significant control variables.

7. Conclusion

We used a simple theoretical framework and drew on relevant theory for behavior of producer-consumer households that produce for their own consumption and may be net sellers or net buyers of food. We used theory to derive relevant hypotheses to test the effects of investment in irrigation, rainfall and rainfall variability and food self-sufficiency and food deficits on adoption and intensity of fertilizer use on irrigated and rain-fed land.

We found strong positive effects for adoption and intensity of fertilizer use on irrigated land, contrasting with earlier studies that did not find such a positive effects of irrigation. Our study is based on more solid data, and we think that these new results provide evidence of significant positive effects of irrigation investment on fertilizer use.

We found that production risk due to adverse climatic conditions (rainfall scarcity and variability) is an important determinant of farmers' fertilizer adoption. We also found that predicted food self-sufficiency was negatively related to fertilizer adoption, indicating that expected food deficits had a positive effect on fertilizer adoption. This contrasts the prediction of the pure producer model of Sandmo (1971), but it is in line with the predictions of the producer-consumer household model of Finkelshtain and Chalfant (1991), indicating that risk averse net buyers of food may respond to higher risk by producing more (through use of more inputs). We also assessed the effects of actual food deficits, whether they were expected or not, and found a contrasting effect on adoption of fertilizer vs. intensity of fertilizer use. Food deficit households predicted to be in food deficits were less likely to use fertilizer, possibly due to liquidity constraints and the need to buy food to meet urgent food needs rather than reducing future food deficits. However, when assessing the fertilizer use of those households that still managed to buy fertilizer, we found that they used significantly more fertilizer than other households. These households are likely to be less cash constrained and therefore more able and willing to use fertilizer to reduce future expected food deficits, a sign of their high relative risk aversion (Finkelshtain and Chalfant 1991). Overall, we may conclude that liquidity or credit constraints may inhibit fertilizer adoption of food deficit households. However, the covariance between income and price risk may cause the risk premium to be negative for food deficit households and induce them to adopt and use more fertilizer to reduce their future food deficits. Furthermore, both investment in irrigation and provision of credit can be important policy instruments to enhance food security in semi-arid and drought-prone areas like the one in our study, where fertilizer can enhance food self-sufficiency.

References

Abdoulaye, T., Sanders, J. H., 2005. Stages and determinants of fertilizer use in semiarid African agriculture: the Niger experience Agricultural Economics. 32 (2), 167–179.

Croppenstedt, A., Demeke, M., Meschi, M. M., 2003. Technology Adoption in the Presence of Constraints: the Case of Fertilizer Demand in Ethiopia. Review of Development Economics. 7(1), 58–70.

de Janvry, A., Fafchamps, M., Sadoulet, E., 1991. Peasant household behavior with missing markets: Some paradoxes explained. The Economic Journal. 101, 1400–1417.

Demeke, M., Kelly, V., Jayne, T. S., Said, A., Vallée, J. C. L., Chen, H., 1998. Agricultural Market Performance and Determinants of Fertilizer Use in Ethiopia. Working Paper 10. Grain Market Research Project Ministry of Economic Development and Cooperation, Addis Ababa.

Dercon, S., Christiaensen, L., 2007. Consumption risk, technology adoption and poverty traps: evidence from Ethiopia.

Fafchamps, M., 1992. Cash crop production, food price volatility and rural market integration in the third world. American journal of agricultural economics. 74(1), 90-99.

FAO, 2002. Water and Fertilizer Use in Selected Countries (Discussion Paper). Food and Agriculture Organization Of The United Nations, Rome.

Feder, G., Just, R. E., Zilberman, D., 1985. Adoption of Agricultural Innovations in Developing Countries: A Survey. Economic Development and Cultural Change 33(2), 255-298.

Finkelshtain, I., Chalfant, J. A., 1991. Marketed Surplus under Risk: Do Peasants Agree with Sandmo? American Journal of Agricultural Economics. 73(3), 557-567.

Fox, P., Rockstrom, J., 2000. Water-harvesting for supplementary irrigation of cereal crops to overcome intra-seasonal dry-spells in the Sahel. Physics and Chemistry of the Earth Part B: Hydrology, Oceans and Atmosphere 25(3), 289-296.

Franklin, S., 2006. Can Risk-aversion towards fertilizer explain part of the non-adoption puzzle for hybrid maize? Empirical evidence from Malawi. (accessed 20,04,08 http://mpra.ub.uni-muenchen.de/1241/1/MPRA_paper_1241.pdf).

Fufa, B., Hassan, R., 2006. Determinants of fertilizer use on maize in Eastern Ethiopia: A weighted endogenous sampling analysis of the extent and intensity of adoption. Agrekon. 45(1).

Gafsi, S., Roe, T., 1979. Adoption of Unlike High-Yielding Wheat Varieties in Tunisia. Economic Development and Cultural Change. 28(1), 119-133

Giné, X., Yang, D., 2008. Insurance, Credit, and Technology Adoption: Field Experimental Evidence from Malawi.

Hagos, F., 2003. Poverty, Institutions, Peasant Behavior and Conservation Investment in Northern Ethiopia. PhD Thesis. Agricultural University of Norway, Department of Economics and Resource Management, Ås, Norway.

Hazell, P. B. R., 1988. Risk and Uncertainty in Domestic Production and Prices. In: Mellor, J. W., Ahmed, R. (Eds.), Agricultural Price Policy for Developing Countries. Published for the International Food Policy Research Institute by the Johns Hopkins University Press, Baltimore and London.

Ho, D. E., Imai, K., King, G., Stuart, E. A., 2007. Matching as Nonparametric Preprocessing for Reducing Model Dependence in Parametric Causal Inference. Political Analysis 15, 199–236.

Holden, S., Shiferaw, B., Pender, J., 2001. Market Imperfections and Land Productivity in the Ethiopian Highlands. Journal of Agricultural Economics. 52(3), 53-70.

Holden, S., Shiferawl, B., 2004. Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: a bio-economic model with market imperfections. Agricultural Economics 30, 31-49.

IFA, 2002. Water Availability and Fertilizer Use. IFA's Position Papers (accessed http://www.fertilizer.org/ifa/Form/pub_position_papers_8.asp on o5,10,2007).

Just, R. E., Pope, R. D., 1979. Production Function Estimation and Related Risk Considerations. American Journal of Agricultural Economics. 61(2), 276-284.

Kaliba, A. R. M., Verkuijl, H., Mwangi, W., 2000. Factors Affecting Adoption of Improved Maize Seeds and Use of Inorganic Fertilizer for Maize Production in the Intermediate and Lowland Zones of Tanzania. Journal of Agricultural & Applied Economics. 32(1), 35-47.

Kassie, M., Yesuf, M., Köhlin, G., 2008. The Role of Production Risk in Sustainable Land-Management Technology Adoption in the Ethiopian Highlands. (accessed 20,04,08 http://www.rff.org/rff/Documents/EfD-DP-08-15.pdf).

Koundouri, P., Nauges, C. e., Tzouvelekas, V., 2006. TECHNOLOGY ADOPTION UNDER PRODUCTION UNCERTAINTY: THEORY AND APPLICATION TO IRRIGATION TECHNOLOGY. American Agricultural Economics Association. 88(3), 657–670.

Morris, M., Kelly, V. A., Kopicki, R. J., Byerlee, D., 2007 Fertilizer Use in African Agriculture: Lessons Learned and Good Practice Guidelines. The International Bank for Reconstruction and Development / The World Bank.

Nyssen, J., Naudts, J., Geyndt, K. D., Haile, M., Poesen, J., Moeyersons, J., Deckers, J., 2007. SOILS AND LAND USE IN THE TIGRAY HIGHLANDS (NORTHERN ETHIOPIA). land degradation & development, Published online in Wiley InterScience (www.interscience.wiley.com).

Pender, J., Gebremedhin, B., 2007. Determinants of Agricultural and Land Management Practices and Impacts on Crop Production and Household Income in the Highlands of Tigray, Ethiopia. JOURNAL OF AFRICAN ECONOMIES.

Pender, J., P.Jagger, Gebremedhin, B., Haile, M., 2002. Agricultural Change and Land Management in the Highlands of Tigray: Causes and Implications. Policies for Sustainable Land Management in the Highlands of Tigray, Northern Ethiopia:Summary of Papers and Proceedings of Workshop held at Axum Hotel, Mekelle, Etiopia, 28-29 March 2002. Socio-economic and Policy Research Working Paper 54. ILRI (Internationa Livestock Research Institute), Nairobi. 75 pp.

Rosenzweig, M. R., Binswanger, H. P., 1993. Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments. The Economic Journal. 103(416), 56-78

Sandmo, A., 1971. On the Theory of the Competitive Firm Under Price Uncertainty. The American Economic Review. 61(1), 65-73.

Shah, T., Singh, O. P., 2001. Can Irrigation Eradicate Rural Poverty in Gujarat? Water Policy Research Highlight No. 10, IWMI-TATA Water Policy Program (accessed 20,03,07 http://www.iwmi.cgiar.org/iwmi-tata_html/PM2003/PDF/10_Highlight.pdf).

Sherlund, S. M., Barrett, C. B., Adesina, A. A., 2002. Smallholder technical efficiency controlling for environmental production conditions. Journal of Development Economics 69, 85– 101.

Shiferaw, B., Obare, G., Muricho, G., 2006. Rural Institutions and Producer Organizations in Imperfect Markets: Experiences from Producer Marketing Groups in Semi-Arid Eastern Kenya. CAPRi Working Paper No. 60 International Crops Research Institute for the Semi Arid Tropics, Cali, Colombia.

Singh, I., Squire, L., Strauss, J. (Eds.), 1986. Agricultural household models, extensions, applications and policy. The World Bank and The Johns Hopkins University Press.

Smith, L. E. D., 2004. Assessment of the contribution of irrigation to poverty reduction and sustainable livelihoods Water Resource Development. 20(2), 243-257.

Smits, J., 2003. Estimating the Heckman two-step procedure to control for selection bias with SPSS. (accessed 02 July 2008: http://home.planet.nl/~smits.jeroen/selbias/Heckman-SPSS.doc).

Wichelns, D., 2003. Policy Recommendations to Enhance Farm-Level Use of Fertilizer and Irrigation Water in Sub-Saharan Africa. Journal of Sustainable Agriculture. 23(2).

Wills, I. R., 1972. Projections of Effects of Modern Inputs on Agricultural Income and Employment in a Community Development Block, Uttar Pradesh, India American Journal of Agricultural Economics 54(3), 452-460

Yao, R. T., Shively, G. E., 2007. Technical Change and Productive Efficiency: Irrigated Rice in the Philippines. Asian Economic Journal. 21(2), 155-168.

Yilma, T., Berger, T., 2006. Complementarity between Irrigation and Fertilizer Technologies: A justification for increased Irrigation Investment in the Less-Favored Areas of SSA. Contributed paper prepared for presentation at the International Association of Agricultural Economists Conference, Gold Coast, Australia, August 12-18, 2006.

Table 1
Summary statistics of variables

variable	Description	Total owner operating households	Households who have no access to irrigation	Households who have access to Irrigation	*t-test*
	Household level Variables				
Jnenough	Household has enough food in June (1=yes)	0.436 (0.021)	0.4160 (0.030)	0.455 (0.030)	-0.897
Hhage	Household age	46.813 (0.657)	46.814 (0.928)	46.811 (0.933)	0.002
Hheadsex	Household sex (1=male)	0.765 (0.018)	0.766 (0.026)	0.764 (0.026)	0.059
Litrate	Literate household members	1.375 (0.062)	1.223 (0.079)	1.524 (0.096)	-2.418**
Femwl	Household member female labor	1.585 (0.039)	1.561 (0.054)	1.607 (0.058)	-0.582
Mamwl	Household member male labor	1.426 (0.044)	1.431 (0.064)	1.422 (0.062)	0.106
Oxen	Oxen ownership	1.246 (0.045)	1.197 (0.067)	1.295 (0.061)	-1.079
Totaltlu	Livestock ownership (tlu)	3.131 (0.143)	3.002 (0.227)	3.257 (0.176)	-0.887
Farasso	Household's access to credit (1=yes)	0.638 (0.021)	0.617 (0.030)	0.658 (0.029)	-0.996
Adueqcoworo	Adult equivalent consumer worker ratio	1.561 (0.039)	1.508 (0.055)	1.613 (0.054)	-1.369
Farmzpadu	Owner operated land holding per adult equivalent (ha)	1.125 (0.038)	1.318 (0.061)	0.936 (0.042)	5.195***
Obs.	Number of households	544	269	275	
	Plot level variables	**Total plots**	**Rain-fed plots**	**Irrigated plots**	
Plottype	Plot type (1=irrigated)	0.204 (0.010)	----	----	-----
Plotsize	Plot size in ha.	1.198 (0.025)	1.400 (0.029)	0.409 (0.008)	19.545***
Yhat	Predicted probability of food availability in June	0.464 (0.004)	.469 (0.005)	0.443 (0.010)	3.256***
D1foodaveresi	Food deficit households predicted to be so	0.384 (0.012)	.384 (0.013)	0.383 (0.026)	0.180
D2foodaveresi	Food deficit households predicted to be food self-sufficient	0.144 (0.008)	.145 (0.009)	0.140 (0.018)	-0.668
Baekel	Soil type, 1=baekel)	0.210 (0.010)	0.222 (0.011)	0.165 (0.020)	3.481***
Walka	Soil type (1=walka)	0.224 (0.010)	0.198 (0.011)	0.325 (0.025)	-4.598***
Hutsa	Soil type (1=hutsa)	0.240 (0.010)	0.233 (0.011)	0.270 (0.023)	-2.896***
Mekayhi	Soil type (1=mekayhi)	0.325 (0.011)	0.347 (0.013)	0.240 (0.022)	3.808***
Slope1	Slope of plot (1=plain)	0.168 (0.009)	0.189 (0.010)	0.088 (0.015)	4.805***
Landqual1	Plot quality (1=good, 0=poor)	0.646 (0.011)	0.601 (0.013)	0.824 (0.020)	-7.985***
Ferzuse	Fertilizer has bee applied (1=yes)	0.311 (0.011)	0.315 (0.012)	0.298 (0.024)	0.059
Fertzperha	Fertilizer used (Kg/hectare)	10.476 (0.565)	8.513 (0.475)	18.152 (2.016)	-8.542***

Table 1 (Cont'd)

	Village level variables				
Mktwalkdis	Walking distance to all weather roads	0.935 (0.006)	0.937 (0.006)	0.926 (0.014)	
Popdensi	Population density (Km^2)	104.514 (1.058)	105.296 (1.220)	101.455 (2.049)	0.852
Degua	Agro-ecology, 1=highland, 0=otherwise	0.221 (0.010)	0.228 (0.011)	0.190 (0.021)	1.209
Wdegua	Agro-ecology, 1=mid-altitude, 0=otherwise	0.488 (0.012)	0.495 (0.013)	0.463 (0.026)	0.897
Kola	Agro-ecology, 1=lowland, 0=otherwise	0.291 (0.011)	0.277 (0.012)	0.347 (0.025)	-2.064**
Rainfall	Average annual rainfall (mm)	779.535 (2.972)	781.150 (3.349)	773.223 (6.436)	0.920
Cv	Coefficient of rainfall variability	0.334 (0.003)	0.334 (0.004)	0.331 (0.007)	-0.287
Rainirri	Rainfall-irrigation interaction	141.226 (6.799)	0 (0)	693.290 (7.691)	- 20.028***
Cvirri	Rainfall variability-irrigation interaction	0.068 (0.003)	0 (0)	.331 (0.007)	- 18.599***
loca1	Tabia (1=Adis Alem)	0.1765 (0.016)	0.160 (0.022)	0.193 (0.024)	-1.005
Loca2	Tabia (1=Kara-Adishawo)	0.175 (0.016)	0.234 (0.026)	0.116 (0.019)	3.657***
loca3	Tabia (1=Laelay Agulae)	0.127 (0.014)	0.052 (0.014)	0.2 (0.024)	-5.308***
loca4	Tabia (1=Adi-Ha)	0.175 (0.016)	0.1450 (0.022)	0.204 (0.024)	-1.804*
loca5	Tabia (1=Adidedena)	0.182 (0.017)	0.227 (0.026)	0.138 (0.021)	2.690***
loca6	Tabia (1=Maiadrasha)	0.165 (0.016)	0.182 (0.024)	0.1491 (0.022)	1.037
popdensi	Population density (people/Km^2)	100.118 (1.821)	96.539 (2.725)	103.619 (2.410)	-1.949*
Obs.	Number of plots	1419	363	1782	

* Significance level is 10%, ** significance level is 5%, *** significance level is 1%, Figures in parenthesis are standard errors.

Table 2
Probability of fertilize use

Variable	Variable description	Coefficient	Std. Error
hhaccirr	Household has access to irrigation (1=yes)	0.118*	0.070
plottype	Plot type (1=irrigated)	2.101***	0.450
hhage	Household age	-0.018***	0.004
hheadsex	Household sex (1=male)	0.822***	0.128
litrate	Literate household members	0.080***	0.025
femwl	Household member female labor	0.044	0.042
mamwl	Household member male labor	0.031	0.035
oxen	Oxen ownership	0.163**	0.066
totaltlu	Livestock ownership (tlu)	0.050*	0.027
farasso	Household's access to credit (1=yes)	-0.048	0.097
plotsize	Plot size (ha)	0.077*	0.046
farmzpadu	Owner operated land holding per adult equivalent (ha)	0.033	0.060
yhat	Predicted probability of food availability in June	-2.875***	0.959
D1foodaversi	Food deficit households predicted to be so	-0.290***	0.091
D2foodaversi	Food deficit households predicted to be food self-sufficient	-0.066	0.103
landqual1	Plot quality (1=good, 0=poor)	0.080	0.081
slope1	Slope of plot (1=plain)	-0.220**	0.101
Baekel	Soil type, 1=baekel)	-0.302**	0.120
Walka	Soil type (1=walka)	-0.038	0.124
Hutsa	Soil type (1=hutsa)	-0.093	0.124
rainfall	Average annual rainfall (mm)	0.026***	0.003
cv	Coefficient of rainfall variability	-14.711***	1.874
rainirri	Rainfall-irrigation interaction	-0.002***	0.001
cvirri	Rainfall variability-irrigation interaction	-1.114	0.758
Degua	Agro-ecology, 1=highland, 0=otherwise	4.133***	0.425
Wdegua	Agro-ecology, 1=mid-altitude, 0=otherwise	1.346***	0.193
mktwalkdis	Walking distance to all weather roads	-0.059	0.149
cons	Constant	-16.390***	1.499
	Number of observation	1782	
	Log likelihood	-859.800	
	Wald chi2(27)	1257.790	
	Prob > chi2	0.000	
	Pseudo R2	0.222	

Table 3
Intensity of Fertilize use

Variable	Variable description	Coefficient	Std. Error
Hhaccirr	Household has access to irrigation (1=yes)	8.517	8.246
Plottype	Plot type (1=irrigated)	163.562***	60.259
Hhage	Household age	0.824	0.563
Hheadsex	Household sex (1=male)	-9.795	13.736
Litrate	Literate household members	0.102	2.844
Femwl	Household member female labor	1.068	4.669
Mamwl	Household member male labor	5.193	3.515
Oxen	Oxen ownership	-11.969	8.369
Totaltlu	Livestock ownership (tlu)	-0.073	3.246
farasso	Household's access to credit (1=yes)	-12.054	12.181
Plotsize	Plot size (ha)	-64.328***	12.220
farmzpadu	Owner operated land holding per adult equivalent (ha)	-17.430**	7.878
Yhat	Predicted probability of food availability in June	120.973	117.566
D1foodaversi	Food deficit households predicted to be so	43.402***	12.930
D2foodaversi	Food deficit households predicted to be food self-sufficient	14.178	8.727
landqual1	Plot quality (1=good, 0=poor)	13.851	8.512
Slope1	Slope of plot (1=plain)	-17.063	12.598
Baekel	Soil type, 1=baekel)	1.050	12.174
Walka	Soil type (1=walka)	-18.946*	10.291
Hutsa	Soil type (1=hutsa)	-13.093	11.023
Rainfall	Average annual rainfall (mm)	0.860**	0.368
Cv	Coefficient of rainfall variability	-592.664**	246.848
Rainirri	Rainfall-irrigation interaction	-0.228**	0.104
Cvirri	Rainfall variability-irrigation interaction	147.986*	88.269
Degua	Agro-ecology, 1=highland, 0=otherwise	112.454**	54.475
Wdegua	Agro-ecology, 1=mid-altitude, 0=otherwise	12.659	25.451
Mktwalkdis	Walking distance to all weather roads	4.970	17.206
Cons	Constant	-571.251***	217.913
	Number of observation	555	
	Log likelihood	-2396.732	
	Wald chi2(27)	85.400	
	Prob > chi2	0.000	

Appendix 1

Probability of food availability in June (Probit model)

Variable	Variable description	Coefficient	Std. Error
hhage	Household age	-0.010**	0.004
hheadsex	Household sex (1=male)	0.184	0.154
litrate	Literate household members	-0.010	0.046
femwl	Household member female labor	0.036	0.067
mamwl	Household member male labor	-0.039	0.067
Oxen	Oxen ownership	0.111	0.078
totaltlu	Livestock ownership (tlu)	0.069**	0.027
farasso	Household's access to credit (1=yes)	-0.163	0.122
adueqcoworo	Consumer worker ratio (adult equivalent)	-0.060	0.083
farmzpadu	Owner operated land holding per adult equivalent (ha)	0.076	0.074
loca1	Tabia (1=Adis Alem)	-0.030	0.205
loca3	Tabia (1=Laelay Agulae)	-0.987*	0.599
loca4	Tabia (1=Adi-Ha)	-0.584	0.550
loca5	Tabia (1=Adidedena)	0.279	0.201
loca6	Tabia (1=Maiadrasha)	-1.041	1.178
popdensi	Population density (people/Km^2)	0.013	0.011
Cons	Constant	-1.012	0.754
	Number of observation	544	
	Log likelihood	-344.833	
	Wald chi2(16	47.950	
	Prob > chi2	0.000	
	Pseudo R2	0.074	

Appendix 2

Classification of soils in Tigray

Local name	Scientific name	General characteristics
Baekel	Cambisol	• Normally found in moderately steep slope, good drainage, poor fertility, low compaction, Easy to plough (good workability)
Walka	Vertisol	• Normally found in valley bottom, good soil depth, rich in chemical soil minerals, poor drainage, difficult to plough (tough workability)
Hutsa	Leptosol	• Extremely poor soil fertility, found in steep slope (susceptible to erosion), high drainage, low water absorbing capacity, shallow soil depth and easy to plough.
Mekayhi	Luvisol	• Found in moderate slope, deep soil, well drained, moderate fertility, easy to plough (good workability)

Source: (Nyssen *et al.*, 2007)[13]

[13] Additional information was used based on informal discussion with a soil scientist, who is familiar to the region.

Paper III

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

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Abstract

This paper estimates stochastic production frontiers of irrigated and rain-fed smallholder agriculture in Tigray, Ethiopia. A nearest neighbor matching method was used to get rain-fed plots comparable to irrigated plots. This helps us to control for the effect of bio-physical factors on a farm's technical efficiency. We use a single-step estimation method to estimate the inefficiency effects. We find that investment in irrigation increases the production frontier of smallholder agriculture in Tigray. However, we also find that farmers are more inefficient on their irrigated plots than on rain-fed plots. Therefore, we recommend improving the technical efficiency of small-scale irrigation as a cost-effective strategy to achieve increased agricultural production, at least in the short run. The joint effects of access to credit, extension services, all-weather roads, and education were found to be statistically significant determinants of the technical efficiency of irrigated agriculture. Our results indicate that farmers in Tigray are relatively efficient on their rain-fed plots, where they produce close to their production frontier. This suggests that the productivity of rain-fed agriculture in Tigray is maximal under current conditions; hence, new investments are needed to raise the production frontier. Together with improving the efficiency levels of existing irrigated farms, investment in new irrigation projects could be an important strategy to produce enough food

to meet poverty reduction objectives. This may have an impact on producing enough food supplies and then curbing down the recent surge in food prices that threatens in particular the low-income group in this society.

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

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1. Introduction

Smallholder agriculture is the main source of income and employment in developing countries. Despite economists' skepticism about peasants' willingness to adopt new technologies and the role of agriculture in the 1950s, the importance of agricultural surplus for economic development has been recognized since the 1960s (Hayami and Ruttan, 1971). 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. Hence, given that developing countries lack resources and technology to make new investments, improving the efficiency of existing production activity can be a cost-effective strategy, at least in the short run. This is especially important in sub-Saharan Africa, where poverty is widespread and capital to make new investments is scarce.

Furthermore, land scarcity due to high population density makes the expansion of agricultural land increasingly difficult, leading to small landholdings in densely populated areas. Poverty is a persistent and widespread problem that calls for the production of enough food. Poverty could have been aggravated by the recent worldwide high food prices, which may have severely affected less developed countries and the poor. This implies the need for improvements in the efficiency of existing production activity in order to foster production. 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 excessively on environmental conditions, most empirical studies estimate the effect of conventional inputs without controlling for the effect of stochastic exogenous factors in an analysis of stochastic frontier production functions.

Ethiopia is one of the abundant water-receiving countries in the east African region (Makombe *et al.*, 2007); it has approximately 12 river basins with an annual runoff of 122 billion m^3 and with 2.6 billion m^3 of ground water (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). Investment in irrigation development has been considered 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[14] 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[15] per micro-dam, each of which can irrigate 100 hectares, and 1.17 million Birr per river diversion project, each of which can irrigate 45 hectares of land (Abraha, 2003). Despite such high investment and the lofty expectations that irrigation can improve agricultural productivity and increase the production frontier in the region, there has been no empirical study of the productivity and efficiency of irrigated agriculture in the region.

On the other hand, although improving the efficiency of existing production activities can be cost-effective, policymakers usually attempt to increase agricultural production by making new investments. Since the choice of development strategies partly depends on policymakers' conceptions of farmers' performance, understanding the level of efficiency of existing production activities is important for informed policymaking.

Therefore, the main objectives of this paper were 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 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.

[14] Commission for Sustainable Agricultural and Environmental Rehabilitation of Tigray.
[15] Birr is an Ethiopian currency. 1 USD was equal to 8.65 Birr at the time data were collected in December 2006.

The rest of the paper is organized as follows. Section 2 provides a brief literature review on stochastic frontier and technical efficiency analysis. In section 3, we discuss the stochastic frontier analytical framework, followed by a presentation of the estimation methods. Section 4 presents a description of the study area, data collection, and summary statistics. Results and related discussion are presented in section 5. Finally, we conclude in section 6.

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). The concept of efficiency began with Farrell (1957). Since then, the measurement of efficiency has been applied to a wide variety of problems, while undergoing many refinements and improvements. A significant subset of these refinements focuses on smallholder agriculture (Ali and Byerlee, 1991; Battese, 1992; Bravo-Ureta and Pinheiro, 1993; Coelli, 1995). Most of the research on the efficiency of small farmers has been triggered by the popular *'poor-but-efficient hypothesis'* (Schultz, 1964): the idea that small farmers in traditional agricultural settings are reasonably efficient in allocating their resources and respond positively to price incentives. This has had profound implications for the choice of a development strategy by the policymakers: if farmers are reasonably efficient, as hypothesized by Schultz, then increases in productivity require new inputs and technology to raise the production frontier. 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 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. For example, Ahmed et al. (2002), Alene and Hassan (2003), Belete et al. (1993), Haji (2006), Seyoum et al. (1998), and Wubeneh and Ehui (2006) are among those reporting significant technical inefficiencies among Ethiopian smallholder farmers.

Sherlund et al. (2002) 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 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.

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 (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). For example, Gebreegziabher et al. (2004) reported small productivity differences among farmers located in the *Enderta* and *Hintalo-Wajerat* districts of the Tigray region. Makombe et al. (2007) analyzed the technical efficiency of irrigated smallholder farming in the Rift Valley area 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 raises the production frontier of smallholder farmers.

Most of the studies conducted in Ethiopia employed different analytical methodologies. For instance, 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, implying that the entire difference between the observed output and the frontier is assumed to be due 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 bio-physical production conditions at the plot level. Agricultural output, at both the plot and farm levels, depends heavily 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. Moreover, farmers will adjust commonly measured inputs, such as labor, land, and fertilizer, in response to such bio-physical conditions (Pender and Gebremedhin, 2007).

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. Moreover, 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. Analytical Framework

3.1. 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:

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

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 (Aigner et al. 1977) 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

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

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:

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

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

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

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:

$$\sigma^2 = \sigma_u^2 + \sigma_v^2 \tag{5}$$

$$\gamma = \frac{\sigma_u^2}{\sigma_u^2 + \sigma_v^2} \tag{6}$$

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:

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

The variables included in Equation (7) can be conveniently sorted into two: the input variables (X_i), and the managerial (inefficiency) variables (Z_i). 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. For a detailed exposition of how failing to consider this last group of variables affects the model, see Sherlund et al. (2002).

The environmental production conditions of smallholder agriculture should therefore inform the estimation of production frontiers. In practice, however, few farm production data sets contain detailed farm or plot-specific information on the environmental conditions that producers face. Lack of data forces analysts to omit potentially relevant environmental variables. 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).

We assume that irrigated plots are more homogeneous in terms of soil type and quality; the slope and agro-ecological characteristics implying that stochastic frontier analysis may be better suited to capture inefficiency in irrigated agriculture than in the heterogeneous rain-fed plots. In order to tacklethis problem and allow comparisons of technical efficiency between irrigated plots and rain-fed plots, we use a non-parametric 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 (see Appendix 1). In the preprocessed data set, the treatment variable--in this case, irrigation--is closer to being independent of the background covariates and provides any parametric adjustment (Ho *et al.*, 2007). Since most of the adjustment for potentially confounding control variables is done non-parametrically, the potential for bias 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. Therefore, we assume irrigation, as a new production technology, to be the main source of efficiency differences, if any differences exist.

Based on this, we hypothesized the following to test empirically:

H1: *Irrigation raises the production frontier*. 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 $\left(AP_{iI} > AP_{iR}\right)$, 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 plots than on rain-fed plots*. This is because irrigation technology is newer than rain-fed agricultural technologies; therefore, farmers need more time to learn the new technology and become efficient at it. Farmers should therefore be more efficient on rain-fed plots, where they have had more time to practice and learn to use the rain-fed production technologies.

3.2 Estimation Methods

We lack good data on bio-physical production conditions in Tigray, which would allow us to control for their effects on smallholders' technical efficiency. To overcome this problem, we used a nearest neighbor matching method to identify rain-fed plots that are comparable with irrigated plots. We used plot characteristics and agro-ecological factors as matching variables (see Appendix 1). After the matching, 562 of 1727 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 comparative analysis.

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). We specified a general form of a translog functional form as follows:

$$\begin{aligned} &\ln\left(Y_i\right)=\beta_0+\sum_{k=1}^{k}\beta_k \ln\left(X_{ik}\right)+\frac{1}{2}\sum_{k=1}^{k}\sum_{j=1}^{k}\gamma_{jk}\ln\left(X_{ij}\right)\ln\left(X_{ik}\right)-U_i+V_i, \\ &U_i=Z_i\delta+\omega_i \end{aligned} \qquad (8)$$

where the subscript i represents the i[th] plot in the sample and *ln* refers to the natural logarithm.

Y = the logarithm of the value of output

X_1 = the logarithm of the size of cultivated land (in tsimdi)[16]

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 (labor 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

[16] Four *tsmidi* are equivalent to approximately one hectare.

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.

We also performed 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 favor of the alternative hypotheses that at least one irrigated and one rain-fed plot are not fully technically efficient. Tests 4 and 7 test 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[17] with four degrees of freedom.

The final tests, tests 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,

[17] The likelihood ratio test statistic, $\gamma = -2\{\log[Likelihood(H_0)] - \log[Likelihood(H_1)]\}$ 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 1.

are equal to zero. The test result for the stochastic frontier production function of irrigated plots suggests that the following factors, when present together, have a statistically significant effect on the inefficiency of irrigated agriculture: access to credit, number of educated household members, access to a market, and access to extension. The individual effect of some of these variables, however, may not be significant. On the other hand, the likelihood ratio test confirms that the inefficiency of rain-fed agriculture in Tigray is not a function of the effect of a the 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.

We used plot- and village-level variables to match and non-parametrically generate comparable rain-fed and irrigated sample plots. 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 futures, where priority was given to drought prone areas. We assumed that village- and plot-level characteristics capture factors that determine access to irrigation. Irrigation projects are commonly found in lowland areas with upstream catchments. We estimated a propensity score using plot- and village-level variables as control variables. The common support option and balancing properties were verified (see Appendix 1). Finally, we estimated an OLS regression on agricultural output, controlling for the effect of village and plot chrematistics (see Appendix 2). 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.

4. Study Area, Data and Descriptive Statistics

4.1. Study Area and Data Collection

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*[18] 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, two of which used earth dams for irrigation, two used river diversions, and two used groundwater. Of the two ground water sites, one was the *Kara-Adi-Shawo* irrigation project, which uses modern irrigation systems (drip/sprinkler).

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 number of plots operated by the sample households during the 2004-2005 production year were 2194, of which 426 were irrigated. However, since we used the non-parametrically matched plots, only 562 rain-fed plots were found to be comparable with the irrigated plots. In the final analysis, therefore, we used 562 rain-fed and 426 irrigated plots.

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

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 not physically measured, but the survey asked farmers to state it in the local unit of measurement (*tsimdi)*. The survey also included detailed questions concerning the household and the plot. In addition to asking our respondents about input and output prices, 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.

4.2. Descriptive Statistics

Table 1 presents summary statistics of data on production and input used in the analysis. The average size of cultivated irrigated (rain-fed) land is 1.6 (5.8) tsimdi or 0.4 (1.5) hectares. The average value of production from the cultivated irrigated (rain-fed) land is approximately 1063 (461) Birr. Based on this, the proportion of production per hectare is approximately 3014 and 451 Birr/ha on irrigated and rain-fed plots, respectively. We also see that the average amount of fertilizer, seed, labor, and oxen used in the cultivated irrigated (rain-fed) plots are: 8.4 (7.8) kg, 84.1 (53.4) Birr, 21 (34) labor days, and 7 (8) oxen days, respectively.

In addition, we see that there is no significant difference between irrigation and rain-fed agriculture in terms of education (number of educated household members), access to credit, access to extension services, or access to market. This may indicate that irrigated and rain-fed plots were well-matched in the analysis, and that irrigation raises the production frontier and increases actual production. Furthermore, the insignificant difference in the farm-specific variables for the irrigated and rain-fed agriculture may indicate that any difference in technical efficiency is likely due to differences in access to irrigation.

5. Results and Discussion

The estimated results of the Cobb-Douglas stochastic frontier production functions of irrigated and rain-fed plots are presented in Table 3. Among the inputs used in the stochastic frontier production function of irrigated agriculture, the three inputs of land, seed, and oxen are significantly different from zero at 5, 1, and 5 percent levels of significance, respectively. For rain-fed agricultural land, seed and labor are significant at 5, 10, and 5 percent, respectively.

5.1. Average and Marginal Products

Our first hypothesis was that irrigation increases the production frontier of smallholder agriculture. Table 4 presents the average and marginal products of inputs used in the stochastic frontier production models for irrigated and rain-fed agriculture. Since irrigation and rain-fed plots have different production frontiers, evaluation of the frontiers is made based on the means of the variable inputs (Makombe *et al.*, 2001). From Table 4, we see that irrigated agriculture requires approximately 1.6 *tsimdi* of land, 8.4 kg of fertilizer, 84 Birr worth of seed, 21.1 labor days, and 6.8 oxen days to produce 1063.2 Birr worth of agricultural product. On the other hand, in rain-fed agriculture, approximately 5.8 *tsimdi* of land, 7.8 kg of fertilizer, 53.4 Birr worth of seed, 33.6 labor days, and 8.0 oxen days were required to produce 461.0 Birr worth of product. Thus, the average inputs of land, fertilizer, seed, labor, and oxen are higher in irrigated agriculture than in rain-fed agriculture. These results clearly indicate that the production frontier of irrigated agriculture is higher than that of rain-fed agriculture. This is consistent with our hypothesis (**H1**) that investment in irrigation raises the production frontier.

Furthermore, the marginal products of the inputs are also indicative. From Table 4, we can see that 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. Theoretically, a negative marginal product implies excess use of inputs (i.e. greater than the optimum level). However, based on our data and previous studies (Hagos, 2003; Pender and Gebremedhin, 2004), this cannot explain our observations, particularly for fertilizer. For instance, the amount of fertilizer used on less than half of a hectare of irrigated plot is 8.4 kg, whereas the amount of fertilizer used on approximately one and half hectare of rain-fed plot is only 7.8 kg. The overall average of fertilizer use in Tigray is only approximately 10 kg/ha (Hagos, 2003). Hence, excessive use of fertilizer or seed cannot justify the negative marginal product. Instead, the negative marginal product may result from moisture scarcity.

5.2. Technical Efficiency

We hypothesized (**H2**) that farmers are less efficient on irrigated plots than on rain-fed plots. Table 5 presents a summary of the average (mean) technical efficiency and potential output that can be gained by improving technical efficiency. We aggregated the average technical efficiency levels into frequencies (see 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 percent, respectively. These figures indicate that rain-fed agriculture operates close to its production frontier, while irrigated agriculture produces less than 50% of its potential. This supports our hypothesis that farmers are technically more efficient on rain-fed plots than on irrigated plots. Since irrigation is newer than rain-fed production technology for smallholder farmers in Tigray, this finding suggests that farmers need more time to learn and make efficient use of irrigation resources.

The results of this paper are important for their policy implications. The high technical efficiency of rain-fed agriculture suggests that improving efficiency and productivity of rain-fed agriculture is unlikely; hence, attempts to improve the efficiency of rain-fed agriculture may not be a good long-term strategy, unless some new technology for rain-fed agriculture can be identified that increases production and food security. This may call for new investment in order to raise the production frontier of rain-fed agriculture, such as investment in irrigation. On the other hand, the results indicate the presence of huge untapped potential in irrigated agriculture that can be used to increase production and food security. Thus, improving the efficiency of existing irrigated agriculture may be a wise policy option. For example, assuming a constant return to scale, 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 1299.5 Birr without any additional input or cost. On the other hand, if an average rain-fed plot increases its efficiency to that of the most efficient rain-fed plot, its level of output can increase by 67.5 Birr. In conclusion, the sample mean of technical efficiencies indicates that, on average, output falls short of the maximum level by 55% in irrigated agriculture and by 18% in rain-fed agriculture. This suggests that by drawing on the existing input level and technology, there is huge potential for increasing agricultural production, especially from irrigated agriculture.

In summary, the results indicate that rain-fed plots are technically more efficient than irrigated plots. 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% (see Figure 1).

5.3. Trends in Technical Inefficiencies

Given the data and model specification, the results indicate that the inefficiency variables included in the technical inefficiency model contribute significantly, both as a group and individually, to the explanation of technical inefficiencies of irrigated plots. Discussion of the trends of inefficiencies is presented in section 3.2.

The technical inefficiencies are consistent with the results of maximum likelihood estimation, summarized in the lower panel of Table 3. Most of the coefficients of the inefficiency variables are significant in the stochastic frontier production function of irrigated agriculture, while this is not the case in the stochastic frontier production model of rain-fed agriculture. All the inefficiency variables in the stochastic frontier of irrigation, except access to extension service, have the expected sign and are statistically significant, whereas all the inefficiency variables in the stochastic frontier of rain-fed are statistically insignificant, except access to extension service. The negative and significant effect of access to credit (*farasso*) in the technical inefficiency of irrigated agriculture indicates that credit programs may alleviate farmers' liquidity constraints and give them the opportunity to invest in modern technologies. The policy implication is that technically inefficient irrigators may improve their efficiency if affordable credit is made available to them.

We also assessed the effect of education on technical efficiency. Estimation results show that the number of *literate* household members, used here as a proxy for level of education, had a negative and significant effect (at 1% level) on the technical inefficiency of irrigated agriculture. This may imply that farm households with more educated members have greater managerial skill and superior understanding of good farming practices and efficient use of inputs. Education may also enhance farmers' ability to interpret and make good use of information about markets and prices in environments where such attributes are particularly necessary. This is especially true for irrigated farming, where most of the products are vegetables (perishable) and demand timely decisions in relation to marketing and prices. Table 3 indicates that distance to roads has a positive and significant (at 5% level) effect on the technical efficiency of irrigated plots. On the other hand, we found that access to extension services was significant, only at 10% level and with a negative coefficient in rain-fed agriculture.

5.4. Output Elasticities

Economic interpretation of estimated coefficients of the Cobb-Douglas production function can be made on the basis of production elasticities. Table 3 shows the elasticity of output with respect to each input for irrigated and rain-fed agriculture. For most of the inputs except labor, the absolute values of elasticities are higher for irrigated agriculture than for rain-fed agriculture. The elasticities of output with respect to inputs at the point of approximation are given by the first-order coefficients of the Cobb-Douglas production function. From the estimates of the first-order coefficients reported in Table 3, the elasticities of irrigated (rain-fed) output with respect to each input have the following values: land, 0.334 (0.220); fertilizer, 0.006 (-0.003); seed, 0.181 (-0.106); labor, 0.094 (0.181); and oxen, 0.247 (0.034). The estimated elasticities of irrigated (rain-fed) land for fertilizer and labor (fertilizer and oxen) are quite low and statistically insignificant. These results indicate that the contribution of these inputs to the technical efficiency of the respective production functions was insignificant during the production period. In contrast, output elasticity of land, oxen, and seed in irrigated agriculture—, seed, and labor in the case of rain-fed agriculture--are statistically significant, but the elasticity of seed in rain-fed agriculture is negative. The elasticity of land in irrigated agriculture has the highest value, followed by oxen and seed. Similarly, the output elasticity of land in rain-fed agriculture has the highest value, followed by labor. This may indicate that, in order of importance, the most significant inputs in irrigated agriculture are land, oxen, and seed, while the most important inputs in rain-fed agriculture are land and labor. In fact, seed has a significant but negative effect on rain-fed agriculture.

6. Conclusion

In this paper, we use a single-step analysis to estimate both the stochastic frontier and inefficiency models simultaneously using data on matched plots from a sample of 988 plots, 426 of which are irrigated, in Tigray northern Ethiopia. The results show that the average technical efficiency is 45 and 82% for irrigated and rain-fed agriculture, respectively. The potential to increase production by improving technical efficiency is immense in irrigated agriculture, while rain-fed agriculture seems to be near its production limit for existing input use and technology. Although we have not assessed the technical and economic feasibility of existing irrigation projects in the study region, the findings of this paper may hint at the need for new investment in rain-fed agriculture to raise the production frontier. Average input productivities are higher for irrigated agriculture than for rain-fed agriculture, suggesting that irrigation raises the production frontier of smallholders.

Based on the findings of this paper, the following recommendations may be made to improve the technical efficiency of agriculture, especially irrigated agriculture.

Currently, irrigated plots are producing at only 45% of their potential. In fact, agricultural production on irrigated land can be more than doubled without additional inputs. The following interventions are needed to improve production efficiency of irrigated plots in the study areas.

Educated farmers have greater managerial ability. They are better technology adopters and have better knowledge of how to make efficient use of inputs and of technology. They can easily understand and interpret information needed to respond to market signals. This is consistent with previous findings in rural Ethiopia. For example, Weir (1999) has reported that schooling considerably increases farm productivity if school enrollment in the area increases. Ahmed et al. (2002) also indicated that the ability to read and write can make a substantial difference in improving the technical efficiency of farming. Therefore, improving farmers' education can be an appropriate policy instrument to improve the production efficiency of irrigated agriculture.

Access to credit has a significant and positive effect on the technical efficiency of irrigated plots. This indicates that the availability of affordable and timely credit solves liquidity constraints of the farm household, thus improving farmers' market participation and competitiveness. In fact, access to credit can have a twofold effect. First, it raises the production frontier 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.

Access to market favors the production of high-value cash crops, which are usually associated with irrigated agriculture. It also promotes innovation and business networking.

Therefore, with access to roads and other infrastructure, farmers can enter into business contracts with retailers in urban areas, thereby obtaining a secured market. Such market opportunities may help them to take steps to improve their production efficiency.

References

Abraha, Z., 2003. Business Plan: First Draft, Executive Summary. Tigray Regional National State Bureau of Water Resource Development (Irrigation Construction Interprise), Mekelle.

Admassie, A., Heidhues, F., 1996. Estimation of Technical Efficiency of Smallholder Farmers in the Central Highlands of Ethiopia. Ethiopian Journal of Agricultural Economics.

Ahmed, M. M., Gebremedhin, B., Benin, S., Ehui, S., 2002. Measurement of Sources of technical efficiency of land tenure contracts in Ethiopia. Environmental and Development Economics 7, 507-527.

Alene, A. D., Hassan, R. M., 2003. The determinants of farm-level technical efficiency among adopters of improved maize production technology in estern Ethiopia. Sabinet Online. 42(1), 1-14.

Ali, M., Byerlee, D., 1991. Economic Efficiency of Small Farmers in a Changing World: A Survey of Recent Evidence. Journal of International Development. 3, 1-27.

Aigner, D., Lovell, C. A. K., Schmidt, P., 1977. Formulation and estimation of stochastic frontier production function models. Journal of Econometrics. 6(1), 21-37.

Awulachew, S. B., Menker, M., Abesha, D., Atnafe, T., Wondimkun, Y., 2006. Background: About the Symposium and Exhibition. Best practices and technologies for small scale agricultural water management in Ethiopia: MoARD/MoWR/USAID/IWMI symposium and exhibition, held at Ghion Hotel, Addis Ababa 7-9 March. International Water Management Institute (IWMI).

Awulachew, S. B., Yilma, A. D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T., 2007. Water Resources and Irrigation Development in Ethiopia. Working Paper 123. International Water Management Institute.

Battese, G. E., 1992. Frontier production functions and technical efficiency: a survey of empirical applications in agricultural economics. Agricultural Economics. 7, 185-208.

Battese, G. E., Coelli, T. J., 1995. A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data. Empirical Economics. 20, 325-332

Belete, A., Dillon, J. L., Anderson, F. M., 1993. Efficiency of small-scale farmers in Ethiopia: a case study in the Baso and Warana sub-district. Agricultural Economics. 8 199-209.

Binam, J. N., Tonye, J., Wandji, N., Nyambi, G., Akoa, M., 2004. Factors affecting the technical efficiency among smallholder farmers in the slash and burn agriculture zone of Cameroon. Food Policy 29 (531–545).

Bravo-Ureta, B. E., Evenson, R. E., 1994. Efficiency in agricultural production: the case of peasant farmers in eastern Paraguay. Agricultural Economics 10, 27-37.

Bravo-Ureta, B. E., Pinheiro, A. E., 1993. Efficiency Analysis of Developing Country Agriculture: A Review of the Frontier Function Literature. Agricultural and Resource Economics Review. 22(1), 88-101.

Coelli, T., Rao, D. S. P., Battese, G. E., 1998. An Introduction to Efficiency and Productivity Analysis. Kluwer Academic Publishers, Boston/Dordrecht/London.

Coelli, T. J., 1995. Recent Development in Frontier Modelling and Efficiency Measurement. Australian Journal of Agricultural Economics. 39(3), 219-245.

Coelli, T. J., 1996. A guide to Fontier Version 4.1: A computer program for stochastic frontier production and cost funtion estimation. Department of Economics, University of New England Armidale, Australia.

Farrell, M. J., 1957. The Measurement of Productive Efficiency. Journal of the Royal Statistical Society. Series A (General). 120(3), 253-290.

FDRE, 1999. Poverty Analysis, Addis Ababa. Ministry of Economic Development and Co-operation (MEDaC).

Gebreegziabher, Z., Oskam, A., Woldehanna, T., 2004. Technical Efficiency of Peasant Farmers in northern Ethiopia: A stochastic frontier approach.

Hagos, F., 2003. Poverty, Institutions, Peasant Behavior and Conservation Investment in Northern Ethiopia. PhD Thesis. Agricultural University of Norway, Department of Economics and Resource Management, Ås, Norway.

Haji, J., 2006. Production Efficiency of Smallholders' Vegetable-dominated Mixed Farming System in Eastern Ethiopia: A Non-Parametric Approach. JOURNAL OF AFRICAN ECONOMIES. 16(1), 1–27.

Hayami, Y., Ruttan, V. W., 1971. Agricultural Development: An International Perspective. The Johns Hopkins University Press, Baltimore and London.

Ho, D. E., Imai, K., King, G., Stuart, E. A., 2007. Matching as Nonparametric Preprocessing for Reducing Model Dependence in Parametric Causal Inference. Political Analysis 15, 199–236.

Kodde, D. A., Palm, F. C., 1986. Wald Criteria for Jointly Testing Equality and Inequality Restrictions. Econometrica. 54(5), 1243-1248.

Koopmans, T. C. (Ed.), 1951. An analysis of production as an efficient combination of activities. Activity analysis of production and allocation, Cowles Commission for Research in Economics, Monograph n. 13. Wiley., New York.

Kopp, R. J., Smith, V. K., 1980. Frontier Production Function Estimates for Steam Electric Generation: A Comparative Analysis. Southern Economic Journal. 46(4), 1049-1059.

Kumbhakar, S. C., Ghosh, S., McGuckin, J. T., 1991. A Generalized Production Frontier Approach for Estimating Determinants of Inefficiency in U.S. Dairy Farms. Journal of Business & Economic Statistics. 9(3), 279-286.

Kumbhakar, S. C., Lovell, C. A. K., 2000. Stochastic Frontier Analysis. Cambridge University Press, Cambridge.

Makombe, G., Kelemework, D., Aredo, D., 2007. A comparative analysis of rainfed and irrigated agriculture production in Ethiopia. Irrigation and Drainage Systems: Published online. 21, 31-44.

Makombe, G., Meinzen-Dick, R., Davies, S. P., Sampath, R. K., 2001. An evaluation of bani (dambo) systems as a smallholder irrigation development strategy in Zimbabwe. Canadian Journal of Agricultural Economics. 49, 203-216.

Pender, J., Gebremedhin, B., 2004. Impacts of Policies and Technologies in Dryland Agriculture: Evidence from Northern Ethiopia. In: Challenges and Strategies for Dryland Agriculture. CSSA Special Publication no. 32.

Pender, J., Gebremedhin, B., 2007. Determinants of Agricultural and Land Management Practices and Impacts on Crop Production and Household Income in the Highlands of Tigray, Ethiopia. JOURNAL OF AFRICAN ECONOMIES.

Schultz, T. W., 1964. Transforming Traditional Agriculture. Yale University Press, New Haven and London.

Seyoum, E. T., Battese, G. E., Fleming, E. M., 1998. Technical efficiency and productivity of maize producers in eastern Ethiopia: a study of farmers within and outside the Sasakawa-Global 2000 project. Agricultural Economics. 19, 341-348.

Sherlund, S. M., Barrett, C. B., Adesina, A. A., 2002. Smallholder technical efficiency controlling for environmental production conditions. Journal of Development Economics 69, 85– 101.

Thiam, A., Bravo-Ureta, B. E., Rivas, T. E., 2001. Technical efficiency in developing country agriculture: a meta-analysis. Agricultural Economics 25, 235–243.

Weir, S., 1999. The effects of education on farmer productivity in rural Ethiopia. The Centre for the Study of African Economies Working Paper Series, University of Oxford (http://www.bepress.com/cgi/viewcontent.cgi?article=1092&context=csae).
Wubeneh, N., Ehui, S., 2006. Technical Efficiency of Smallholder Dairy Farmers in the Central Ethiopian Highlands. The International Association of Agricultural Economists Conference, Gold Coast, Australia, August 12-18, 2006.

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*[a]
		Coefficient	Std.Err.	Coefficient	Std.Err.	
Produperha	Value of agricultural product (Birr/ha.)	3013.924	333.528	451.010	23.482	-8.790***
Land	Average cultivated land size (Tsimdi)	1.637	0.028	5.781	0.183	19.546***
Plotsiz	Average cultivated land size (ha.)	0.409	0.007	1.445	0.046	19.546***
Fertzperha	Fertilizer use (kg/ha.)	19.002	1.891	7.383	0.711	-6.322***
Seedperha	Seed used (Birr/ha.)	179.201	26.205	38.679	4.568	-6.004***
Laboperha	Labor used (labor day/ha.)	41.818	3.009	26.867	1.051	-5.184***
Oxenperha	Oxen used (oxen day/ha.)	30.073	11.511	9.878	5.013	-1.747*
Produpertsi	Value of agricultural product (Birr/tsimdi)	753.481	83.382	112.751	5.870	-8.790***
Litrate	Educated household members	1.495	0.074	1.628	0.068	1.313
Farasso	Access to credit	0.951	0.039	0.952	0.032	0.025
Extewdis	Walking distance to extension service (in minutes)	64.730	2.111	62.367	1.750	-0.868
Mktwalkdis	Walking distance to all weather road (in minutes)	0.927	0.013	0.932	0.011	0.315

* Significance at 10% level. ** Significance at 5% level. *** Significance at 1% level. Figures in parentheses are standard errors.
[a] Values are the *t-statistic*

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				Accept H_0
1) $H_0 : \beta_6 = \beta_7 = \beta_8 =,...,= \beta_{20} = 0$	22.064	15	24.996	
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 Ho
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)

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	5.269***	5.674 ***
			(0.175)	(0.211)
LnA	Land (tsimdi = 0.25 ha.)	β_1	0.334**	0.220**
			(0.091)	(0.062)
LnF	Chemical fertilizer (kg)	β_2	0.006	-0.003
			(0.013)	(0.012)
LnS	Seed (Birr)	β_3	0.181 ***	-0.106*
			(0.037)	(0.045)
LnL	Labor (labor days)	β_4	0.094	0.181**
			(0.067)	(0.067)
LnO	Oxen (oxen days)	β_5	0.247**	0.034
			(0.070)	(0.079)
	Returns to Scale		0.861	0.326
Variance parameters				
	$\sigma_s = \sigma_u^2 + \sigma_v^2$		0.898	20.960
			(0.048)	(11.261)
	$\gamma = \sigma_u^2 / \left(\sigma_u^2 + \sigma_v^2\right)$		0.005	0.974***
			(0.012)	(0.015)
Inefficiency effects				
Cons	Intercept	δ_0	0.648**	-31.571
			(0.166)	(18.479)
farasso	Access to credit from farmer association (1 = yes,)	δ_1	-0.273 ***	0.315
			(0.045)	(0.366)
Litrate	Number of literate household members	δ_2	-0.129 ***	1.972
			(0.022)	(1.119)
Allwthrodwdis	Walking distance to all-weather road in minutes	δ_3	0.004 **	0.052
			(0.001)	(0.028)
extewdis	Walking distance to extension service in minutes	δ_4	-0.002	-0.044*
			(0.001)	(0.020)
Log likelihood Function			-577.181	-772.775

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

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]		**1063.207**			**461.034**	
Land (tsimdi)	1.637	649.485	216.993	5.781	79.750	17.569
Fertilizer (kg)	8.359	127.193	0.712	7.769	59.341	-0.160
Seed (Birr)	84.121	12.639	2.281	53.425	8.630	-0.912
Labor (man days)	21.124	50.332	4.721	33.567	13.735	2.482
Oxen (oxen days)	6.840	155.439	38.440	7.961	57.913	1.940

[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.

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[b]	1063.21	461.03
Potential Output (Birr)/average size of cultivated land	2362.68	528.50
Potential Increment in Output (Birr)/average size of cultivated land	1299.47	67.47

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

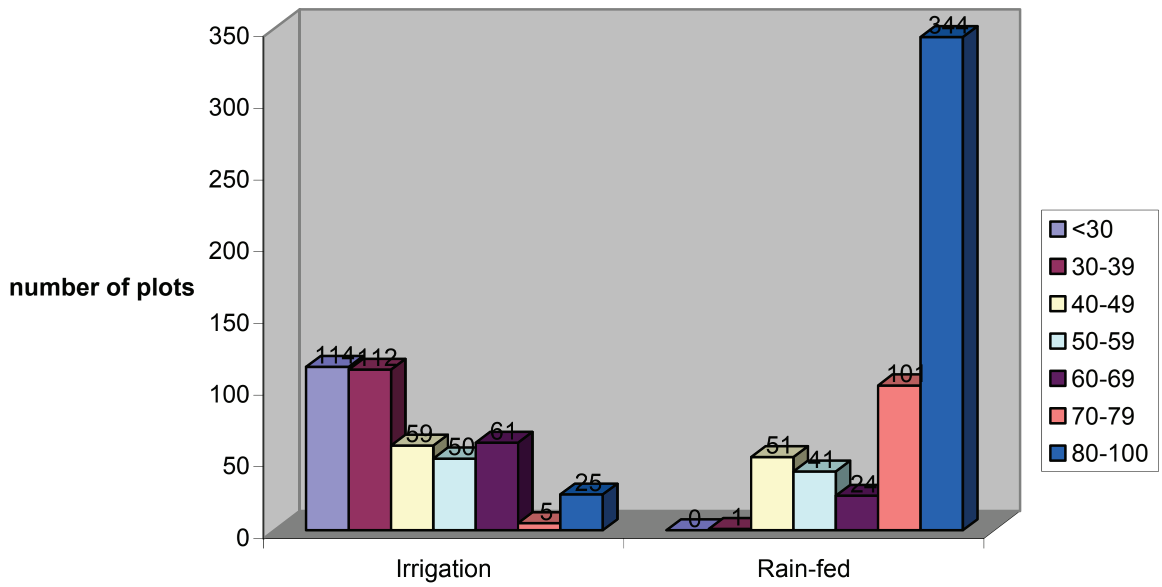

Figure 1 Frequency Distributions of Technical Efficiency Indices for Irrigated and Rain-fed Farms

Appendix 1
STATA program output of the estimation of the propensity score

```
****************************************************
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

------------------------------------------------------------------------------
  irrigation |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
  ownership1 |   .3925052   .1704408     2.30   0.021     .0584474     .726563
```

```
  ownership2 |   .4099115   .3728426     1.10   0.272    -.3208465     1.14067
   soiltype1 |  -.0442967   .1801247    -0.25   0.806    -.3973346    .3087412
   soiltype2 |   .4359981    .155088     2.81   0.005     .1320313     .739965
   soiltype3 |   .6398343   .1635901     3.91   0.000     .3192035    .9604651
   soildept1 |   .6527585   .1687156     3.87   0.000     .3220821     .983435
      slope1 |  -.4360765   .1972914    -2.21   0.027    -.8227607   -.0493924
   landqual1 |   .4376706   .1823276     2.40   0.016      .080315    .7950262
   suscepti1 |  -.3207419   .5001139    -0.64   0.521    -1.300947    .6594633
   degreeso1 |   .9488908   .3963284     2.39   0.017     .1721015     1.72568
agroecology1 |  -.2003768   .1778889    -1.13   0.260    -.5490326    .1482791
agroecology2 |  -.0587315   .1310939    -0.45   0.654    -.3156709    .1982079
          cv |  -.5386024   .4880896    -1.10   0.270     -1.49524    .4180356
    hheadsex |  -.0978094   .1424242    -0.69   0.492    -.3769558    .1813369
       _cons |   -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 the region of common support

                 Estimated propensity score
-------------------------------------------------------------
      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 block

**********************************************************
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
*******************************************

end of do-file
```

Appendix 2

OLS regression of agricultural output

Variable	Description	Irrigated Agriculture Coefficient	Std. Err.	Rain-fed Agriculture Coefficient	Std. Err.
LnQ	Dependent Variable: Log of gross value of output				
LnA	Land (tsimdi)	.225**	0.090	0.054	0.077
LnF	Log of chemical fertilizer (kg)	0.022	0.014	0.002	0.014
LnS	Seed (Birr)	.140***	0.039	0.025	0.054
LnL	Log of labor (labor days)	0.010	0.063	0.097	0.077
LnO	Log of oxen (oxen days)	0.192***	0.065	-0.065	0.085
Litrate	Number of literate household members	0.106***	0.032	-0.032	0.029
Frassoc	Access to credit from farmer association (1 = yes)	0.360***	0.098	-0.001	0.097
Allwthrodwdis	Walking distance to all-weather road in minutes	0.010***	0.002	0.007**	0.003
Extewdis	Walking distance to extension service in minutes	-0.024***	0.004	-0.013**	0.005
Lnmeanrainfall	Log of mean rainfall	-0.350	0.351	0.442	0.373
Lncv	Log of rainfall variability	-0.877***	0.162	-0.613***	0.159
Soiltype1	Soil type (1 = Baekel)	-0.203	0.153	-0.085	0.114
Soiltype2	Soil type (1 = Walka)	-0.184	0.121	-0.062	0.147
Soiltype3	Soil type (1 = Hutsa)	0.030	0.142	-0.006	0.122
Soildept1	Soil depth (1 = deep)	0.212	0.130	0.153	0.105
Slope1	Slope (1 = plain)	0.248	0.173	0.000	0.097
Landqual1	Land quality (1 = good)	0.089	0.149	-0.033	0.100
Cons	Constant	7.167***	2.459	2.124	2.641
Obs	Number of observations	426		562	
	F(20,967)	12.94		3.32	
	Prob > F	0.000		0.000	
	R-squared	0.350		0.094	
	Adjusted R-squared	0.323		0.066	

* Significance at 10% level. ** Significance at 5% level. *** Significance at 1% level.

Paper IV

Irrigation Investment and its Impact on Household Income: Empirical Evidence from Tigray, Ethiopia

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Abstract

Despite substantial investment in small-scale irrigation, there have been limited attempts to analyze whether these investments attained their stated objectives of increased household income and food security in Tigray, Ethiopia. This study was initiated to: (1) evaluate the impact of access to small-scale irrigation on farm household income and poverty status, (2) contribute to the literature on the irrigation-poverty reduction nexus in Ethiopia, and (3) provide information for policy makers. The study was based on a representative sample of 560 farm households (313 irrigators and 247 non-irrigators) selected using three-stage stratified random sampling. Matching and switching regression estimation methods were used. The results indicate that the mean income of irrigating households is significantly higher than that of non-irrigating households. The estimated results for the matching methods showed that the average income gain due to irrigation access ranges from 4090 to 4940 Birr per household per annum, but there were difference between the different types of irrigation technologies. Estimation results from the switching regression also showed a significant gain having average income of 4933 and 2570 Birr per irrigating and rain-fed households, respectively. Stochastic dominance analysis showed that the incidence (i.e., head count ratio) and depth (gap) of poverty are unambiguously lower for households with access to irrigation than households without access.

Keyword: Tigray, Irrigation, Poverty reduction, Matching Method

1. Introduction

In Ethiopia, smallholder rain-fed agriculture is the mainstay of the economy where about 85% of the population depends upon. On the other hand, low and erratic rainfall causes severe drought that threatens the livelihood of the rural poor. These problems are particularly serious in the Tigray region and have negative implications on agricultural production and households' food security (Hagos *et al*., 1999; Pender and Gebremedhin, 2004, 2007). Agricultural production remains below a ton/ha., and most rural households subsist on incomes of less than a dollar/day (Pender and Gebremedhin, 2007). Population pressure has also aggravated the problem due to small landholding, with the average landholding being only 1 hectare (Pender and Gebremedhin, 2007).

In recognition of these problems, poverty reduction in Tigray is at the core of the policy agenda of the Ethiopian government in general and the regional government of Tigray in particular. In line with this, there has been a general consensus that increases in agricultural production and poverty reduction in Tigray should result mainly from improved agricultural productivity. Intensive public-led soil and water conservation programs have been carried out to avoid soil degradation and to improve agricultural productivity (Hagos, 2003; Hagos *et al*., 1999), and investment in small-scale irrigation has been emphasized as a key poverty reduction strategy. To this end, the regional government of Tigray has embarked on an ambitious irrigation development program, especially since the establishment of the Commission for Sustainable Agricultural and Environment Rehabilitation of Tigray (Co-SAERT) in 1995.

Despite substantial investment made in small-scale irrigation, comprehensive empirical evidence to assess the impact of small-scale irrigation on household income and improved food security has been limited. The limited empirical evidence (Berg and Ruben, 2006;

Pender and Gebremedhin, 2007; Pender *et al*., 2002) is also at variance, generating doubts about the effects of investment in irrigation on the stated objective of improved food security and poverty reduction. For example, Berg and Ruben (2006) found that access to irrigation has a significantly positive effect on household expenditure. Pender *et al*. (2002) and Pender and Gebremedhin (2007), on the other hand, demonstrated no significant impact of access to irrigation on farming income.

The main objective of this paper is therefore to critically assess the impact of small-irrigation on household income and poverty reduction in Tigray and to contribute to the existing literature on irrigation and poverty reduction relationships. Since the existing literature and empirical studies on the role of irrigation in poverty reduction is predominantly of Asian origin, this paper may broaden our knowledge regarding this relationship by providing empirical evidence from Tigray, northern Ethiopia, which, to date, has not been extensively investigated. This paper may also contribute to informed policy making. To our knowledge, this study is the first of its kind in Ethiopia to analyze the poverty reduction impact of three irrigation technologies (i.e., micro-dam, river diversion and ground water) under different agro-ecological settings.

The literature studying the effect of irrigation investments on poverty reduction provides mixed evidence. Many studies also suffer as by-products of a more general analysis of agricultural growth and poverty (Saleth *et al*., 2003). For example, Fan *et al*. (2000) illustrated that government expenditure on irrigation had only a modest impact on agricultural production growth, and even less on rural poverty and inequality. Moreover, studies by Jin *et al*. (2002) and Rosegrant and Evenson (1992) revealed no link between irrigation, agricultural productivity, and poverty reduction in Asia in general and in China and India in particular.

In contrast, other studies (Chamber, 1994; Hussain *et al*., 2004; Kumar, 2003) found that irrigation improves agricultural productivity and has a positive impact on household income and poverty reduction. Chamber (1994) argued that reliable and adequate irrigation increases employment, and hence landless laborers as well as small farmers work more days per year, which ultimately contributes to food security. Kumar (2003) also stated that irrigated agriculture has significantly increased India's food production and created grain surpluses. Similarly, Hussain *et al*. (2004) showed that access to irrigation enables farmers to adopt new technologies that lead to higher productivity and increased household incomes. Irrigation also generates new on-farm and off-farm employment opportunities (Hussain *et al*., 2004). It is possible that irrigation investments resulted in lower output prices, potentially reducing the positive effects on producers and transferring them to consumers.

The lack of consensus about the impact of irrigation on household income and poverty reduction seems to mirror the general debate regarding the role of agriculture in economic development (Christiaensen *et al*., 2006; Diao *et al*., 2007). This can be substantially influenced by the type of data and methodology adopted. For example, studies based on macro-data (data aggregated at the national, regional, or district level) tend to find no significant link between investment in irrigation and poverty reduction, while studies based on micro-data are likely to establish a robust relationship between access to irrigation and poverty reduction (Saleth *et al*., 2003).

This paper is based on household level data obtained from 560 sample households in six rural communities/tabias[19] in Tigray, northern Ethiopia. We used non-parametric matching and parametric switching regression methods, as well as stochastic dominance analysis to assess the impact of irrigation on household income and poverty status. Although propensity score matching (PSM) is a widely used impact assessment method, there is significant skepticism regarding this approach due to its potential sensitivity to selection bias due to unobservables. Hence, an endogenous switching regression method is used after matching to test and correct for selection bias and to assess the robustness of the results. We found that irrigation has a significant and positive effect on household income.

The rest of the paper is structured as follows. In section 2, we describe a simple conceptual framework for examining the effect of irrigation on household income. In the second part of this section, we briefly discuss some problems that surround impact evaluation. In section 3, we present the estimation methods used in this paper, followed by a description of the study area and data collection. Results and related discussions are presented in section 5, followed by conclusions in section 6.

2. Analytical Framework

2.1. Framework for Examining the Effect of Irrigation on Household Income

To estimate the effect of irrigation on household income while holding other factors constant, the total income of a farm household with and without access to irrigation is specified in equations (1) and (2), respectively.

$$Y_1 = p_q^I q_1^I\left(A_1^I, L_1^I, \psi_1^I\right) + p_q^R q_1^R\left(A_1^R, L_1^R, \psi_1^R\right) + wL_1^{off} - \left[w\left(L_1^I + L_1^R\right) + p_\psi\left(\psi_1^I + \psi_1^R\right)\right] \qquad (1)$$

[19] A *tabia* is a word used in the local language to designate the smallest administrative unit in Tigray and represents a group of about four villages.

$$Y_0 = p_q^R q_0^R \left(A_0^R, L_0^R, \psi_0^R \right) + wL_0^{off} - \left[wL_0^R + p_\psi \psi_0^R \right] \tag{2}$$

where Y is total household income that comprises agricultural and non-agricultural (off-farm) income. Variable q represents crop production, which is a function of land (A), labor (L) and other inputs, such as oxen, seed, etc (ψ). p_q, p_ψ and w are output prices, input prices and the daily wage rate, respectively. In areas with good access to markets, irrigation enables the production of high-value perishable crops, such as vegetables; hence, we assume that p_q^I and p_q^R may be different. The subscripts 1 and 0 indicate that the household has or does not have access to irrigation, respectively. On the other hand, the superscripts I, R and off indicate irrigated agricultural production, rain-fed agricultural production and off-farm activities, respectively. The last terms of equations (1) and (2), i.e., $[\cdot]$, capture the production costs with and without irrigation, respectively. Assuming that the farm household can allocate its labor and other inputs in irrigated, rain-fed or off-farm activities, household production and income is conditioned by the following constraints:

(1) Land constraint: $\bar{A}_0 = A_0^R$ (non-irrigator), and $\bar{A}_1 = A_1^I + A_1^R$ (irrigator).

(2) Labor constraint: $\bar{L}_0 = L_0^R + L_0^{off}$ (non-irrigator), and $\bar{L}_1 = L_1^I + L_1^R + L_1^{off}$ (irrigator).

(3) Other input constraint: $\bar{\psi} = \psi_0^R$ (non-irrigator), and $\bar{\psi} = \psi_1^I + \psi_1^R$ (irrigator).

To understand how access to irrigation affects a household's income and poverty status, it is essential to identify the complex and diverse pathways through which the impact is transmitted. Accordingly, we assume that irrigation affects agricultural production by affecting input use, cropping intensity (multiple crops per year), production risk (shock minimizing effect of irrigation), and improved land and labor productivity. This implies that even when assuming the same level of input use, $p_q^I q^I > p_q^R q^R$ which should result in higher income $(Y_1 > Y_0)$ and poverty reduction when prices are constant, the external shock minimizing effect is particularly relevant for locations such as the highlands of Tigray, where rainfall is unreliable with regard to both the amount and seasonal distribution (see Figure 1). The type of irrigation technology may affect the efficiency and production levels, and this may also impact the benefits of irrigation. Cuswell and Zilberman (1985) argue that adoption and use of sprinkler and drip irrigation technologies may be important for improving production efficiency. Since Tigray (the study area) is a drought prone area, agricultural production is vulnerable to water shortage; hence, the use of water saving and efficient irrigation technologies may improve the effectiveness of irrigation by increasing household income and reducing poverty.

Another way of conceptualizing irrigation benefits is through their effects on employment. Due to higher cropping intensity, several crops can grow on the same irrigated land over the course of one year, in contrast to only one crop under rain-fed production, allowing for more land- and labor-intensive production. Thus, irrigation generates a greater demand for labor, through which land-poor farm households can benefit due to more employment opportunities (Chamber, 1994; Hussain *et al*., 2004). Norman *et al*., (2008) also reported that most smallholder irrigation systems utilizing surface irrigation employ earthen canals and manual operation, which may increase households' demand for on-farm labor and reduce demand for off-farm employment and income. The implication is that non-irrigating farm households are more likely to participate in off-farm activities than irrigators; hence, $wL_0^{off} > wL_1^{off}$. Assuming that the extra income due to irrigation surpasses extra income from off-farm activities, $Y_1 > Y_0$ and the impact of irrigation on household income may be specified as:

$$\Delta Y = Y_1 - Y_0 = \begin{Bmatrix} p_q^I q_1^I \left(A_1^I, L_1^I, \psi_1^I \right) + p_q^R q_1^R \left(A_1^R, L_1^R, \psi_1^R \right) + wL_1^{off} \\ -\left[w\left(L_1^I + L_1^R \right) + p_\psi \left(\psi_1^I + \psi_1^R \right) \right] \end{Bmatrix} - \begin{Bmatrix} p_q^R q_0^R \left(A_0^R, L_0^R, \psi_0^R \right) + wL_0^{off} \\ -\left[wL_0^R + p_\psi \psi_0^R \right] \end{Bmatrix} \quad (3)$$

In addition to the direct benefits (accrued to the farming community), the benefits of irrigation may include indirect benefits (accrued to the wider sector of the economy), such as backward linkage effects of irrigation. Such effects stem from the demand for additional inputs (labor and other material inputs) used in irrigated agriculture due to improved crop productivity made possible by better access to irrigation. Thus, irrigation has income and employment effects in the agro-industry and non-farm sectors of the rural economy. The indirect benefits of irrigation can spread to the region's economy as a whole, resulting in increased production of allied agricultural sector activities, as well as in other rural-based agro-services and marketing activities in the economy. An additional tertiary layer of benefits (spillover effects) due to irrigation are highlighted by increased household spending in the local economy stemming from increased income and employment. These spillover effects of irrigation are called induced effects of irrigation, from which not only the agricultural sector, but also the industrial and service sectors can benefit substantially. Such an economic integration (linkage) effect of irrigation on poverty reduction is important, but in most cases remains masked. Saleth *et al*. (2003) illustrated the basic relationship capturing the major pathways and layers inherent in the irrigation-poverty pathways.

In the present analysis, we are mainly concerned with the direct effects of irrigation on household income. The paper does not cover the indirect and induced effects of irrigation. To capture the full range of induced irrigation effects, an economy-wide Social Accounting Matrix (SAM) and Computable General Equilibrium model analyses are needed, but are beyond the scope of this paper.

Accordingly, we summarize the following hypotheses to be tested empirically:

H1: *Access to irrigation improves household income.* Ceteris paribus the predicted/estimated mean income of households with access to irrigation should be significantly greater than the mean income of households with no access.

H2: *Access to irrigation reduces poverty.* The incidence of poverty (head count ratio) and poverty gap should be dominantly lower for households with access to irrigation compared to those with no access.

H3: *Access to irrigation reduces off-farm employment and off-farm income.* Due to higher cropping intensity and labor-intensive production, irrigation generates greater demand for labor and reduces off-farm labor allocation, which in turn reduces off-farm income.

H4: *Access to ground water-based irrigation has a greater impact on household income than micro-dam and river diversion irrigation.* The use of ground water-based irrigation technologies (pressurized tube and manually operated shallow-well) may reduce water losses due to run-off and excess percolation and improves water use efficiency, leading to improved productivity and production. On the other hand, it is expected that water loss is high in micro-dam and river diversion irrigation projects utilizing earthen canals, which may then reduce irrigated land size and length of irrigation time. The testable implication is that in the decomposed matching estimates, the average treatment effect of access to ground water-based irrigation is greater than that of micro-dam and river diversion.

2.2. The Impact Evaluation Problem

In studying the impact of irrigation, a frequently-observed methodological problem is the tendency to assume that the whole income difference observed between households with and without access to irrigation is attributed to the irrigation factor (Dhawan, 1988). Quantitative methods for evaluating the impact of anti-poverty programs have been critically reviewed by Ravallion (2005). He argued that no single method dominates and that rigorous, and hence policy-relevant, evaluations should be open-minded with regard to methodology, problem setting, and data constraints.

Experimental methods construct the counterfactual by randomly assigning a group of project participants (the treatment group) and a group of non-participants (the control group). Due to the random assignment of project participation, the treatment group is, on average, identical to the control group, except with respect to participation in the project (in this paper, access to irrigation). Randomization effectively eliminates all pre-existing differences between the treatment and control groups; therefore, the effect of the project is isolated. However, although randomized evaluations are considered as the golden standard of impact evaluation methods, they may not be applicable to all types of interventions. For example, it is difficult to randomize evaluations of large infrastructure projects or projects designed to benefit a large part of the population. The literature has long recognized that impact evaluation is essentially a problem of missing data. A group of non-participants may therefore be used as the control group and to represent the counterfactual.

Non-experimental methods can derive the counterfactual through statistical techniques. For example, assume that impact evaluation involves measuring the impact of irrigation on household income, specified as:

$$Y_i = \alpha + \beta I_i + \delta X_i + \varepsilon_i \tag{4}$$

where Y is the income of household i and I is the treatment indicator (access to irrigation), where $I = 1$ when a household has access to irrigation and $I = 0$ when a household has no access to irrigation. X_i captures the exogenous explanatory variables, such as household characteristics and agro-climatic production conditions; $\alpha, \beta,$ and δ are estimated parameters. Variable ε_i is the usual error term that captures unobservable factors and potential measurement errors that affect Y.

For households that have access to irrigation $(I=1)$, income is equal to:

$$\left(Y_{1i} \middle| I_i = 1\right) = \alpha + \beta + \delta X_i + \varepsilon_i \qquad \text{(5a)}$$

and for households that have no access to irrigation $(I=0)$:

$$\left(Y_{0i} \middle| I_i = 0\right) = \alpha + \delta X_i + \varepsilon_i \qquad \text{(5b)}$$

The difference between (5a) and (5b), β, is the impact of access to irrigation on household income. In such a simple linear regression, the OLS of Y on the independent variables may yield unbiased estimates of β if there is no selection bias, such as when treatment is randomly assigned. By definition, OLS assumes that the expected value of the error term is equal to zero, and unbiased estimates of impact (β) imply: $E\left(\varepsilon_i \middle| I=1\right) = E\left(\varepsilon_i \middle| I=0\right) = E\left(\varepsilon_i\right) = 0$. This suggests that $E\left(Y_{0i} \middle| I=1\right) = E\left(Y_{0i} \middle| I=0\right)$ (Cobb-Clark and Crossley, 2003). However, this is impractical when participation is not random (such as access to irrigation in this paper) because access to irrigation (participation) can be related to many other factors, such as unobserved household characteristics, that may result in biased estimates of β. In this paper, we consider farm households that have and do not have access to irrigation, the incomes of which are denoted by Y_{1i} and Y_{0i}, respectively. For many farm households, we must estimate the average outcome across all sample households with and without access to irrigation to obtain the expected value of the average treatment effect, specified as:

$$ATE = E\left(Y_{1i} - Y_{0i}\right) \qquad \text{(6a)}$$

where $E(\cdot)$ denotes the expected value and the sample equivalent is given by:

$$ATE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{1i} - Y_{0i}\right) \tag{6b}$$

The average treatment effect (ATE) measures the effect of access to irrigation assuming a randomized sample drawn from the population, which has limited significance for policy (Wooldridge, 2002). Our interest in this paper is to measure the average gain of access to irrigation on household income compared to what the income could have been if these households had no access to irrigation, specified as:

$$ATT = E\left(Y_{1i} - Y_{0i} \,|\, I_i = 1\right) = E\left(Y_{1i} \,|\, I_i = 1\right) - E\left(Y_{0i} \,|\, I_i = 1\right) \tag{7}$$

Equation (7) is the average treatment effect on the treated (ATT), where the sample equivalent is written as:

$$ATT = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{1i} - Y_{0i}\right)|I_i = 1 = \frac{1}{n}\left(\sum_{i=1}^{n}\left(Y_{1i} \,|\, I_i = 1\right) - \left(Y_{0i} \,|\, I_i = 1\right)\right) \tag{8}$$

However, this formulation is affected by the problem of how to capture the unobservable income, since survey data do not allow for observation of the same individual in different states at the same time. For example, the observed income (Y_i) of a household with and without access to irrigation can be summarized as:

$$Y_i = I_i Y_{1i} + \left(1 - I_i\right) Y_{0i} \tag{9}$$

This implies that it is impossible to observe Y_{0i} for those who actually have access to irrigation and Y_{1i} for those who do not have access to irrigation (Cobb-Clark and Crossley, 2003; Heckman *et al*., 1998; Ravallion, 2001, 2005; Wooldridge, 2002).

Therefore, a simple comparison of Y_{1i} and Y_{0i} by comparing households with and without irrigation would yield biased estimates when irrigation was not randomly distributed. There are essentially two sources of bias: bias due to differences in unobservable and bias due to differences in observable characteristics (Ravallion, 2001). The first bias is related to factors such as managerial capabilities, while the later is related to lack of an appropriate comparison group, i.e., lack of common support between the treated and control groups. In general, the basic problem of impact evaluation is the estimation of the counterfactual.

3. Estimation Methods

3.1. Matching Method

Matching is a non-parametric method that is widely used in the impact evaluation literature (Cobb-Clark and Crossley, 2003; Heckman *et al*., 1998; Ravallion, 2005). Matching methods aid in creating a counterfactual from the control group. The basic assumption when using a counterfactual is that the untreated samples approximate the treated samples if they had not been treated, i.e., $E\left(Y_{0i} \mid I=1\right)$ (Heckman *et al*., 1998). For the matching method to be valid, the assumption of Conditional Independence (CIA) is critical and must hold true. The CIA argues that testament is random and conditional on observed variables (X) specified as:

$$\left(Y_1, Y_0\right) \perp I \mid X \qquad (10)^{20}$$

This assumption implies that the counterfactual outcome for the treated group is the same as the observed outcomes for the non-treated group given the control variables (X). In the present case, this means that the counterfactual income is the same as the income level that would have existed if the household had no access to irrigation, specified as:

[20] Subscript i was eliminated here for clarity.

$$E\left(Y_0 \mid X, I=1\right)=E\left(Y_0 \mid X, I=0\right)=E\left(Y_0 \mid X\right) \qquad (11)^{21}$$

The first term of equation (11) represents the counterfactual income of the treated group and is equal to the observed income of the untreated (control) group.

This assumption rules out selection into the program and gains from irrigation on the basis of unobservables. The CIA requires that the set of X's contain all variables that jointly influence the outcome with no treatment, as well as the selection into the program. Under conditional independence, therefore, the average treatment effect on the treated (*ATT*) can be computed as:

$$ATT=E\left(Y_1-Y_0 \mid X, I=1\right)=E\left(Y_1 \mid X, I=1\right)-E\left(Y_0 \mid X, I=1\right) \qquad (12)$$

However, matching of households based on observables may not be feasible when the dimension of control variables is large. To overcome this problem of dimensionality, Rosenbaum and Rubin (1983) argued that one can match along a single index variable given by the propensity score, $p(X)$, which summarizes the multi-dimensional variables. This is the conditional probability that household i has access to irrigation given the conditioning variables[22], written as:

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[21]This implies that $E\left[\Delta Y \mid I=1\right]=E\left[Y_1 \mid I=1\right]-E\left[Y_0 \mid I=0\right]$. By subtracting and adding $E\left[Y_0 \mid I=1\right]$, we obtain $E\left[Y_1 \mid I=1\right]-E\left[Y_0 \mid I=0\right]-E\left[Y_0 \mid I=1\right]+E\left[Y_0 \mid I=1\right]$. By rearranging this, we obtain $E\left[Y_1-Y_0 \mid I=1\right]+E\left[Y_0 \mid I=1\right]-E\left[Y_0 \mid I=0\right]=E\left[\Delta Y \mid I=1\right]+\left\{E\left[Y_0 \mid I=1\right]-E\left[Y_0 \mid I=0\right]\right\}$, where the first term denotes the impact of access to irrigation, and the second term, i.e., $\{\cdot\}$ captures the bias. However, if Y_0 is the mean independent of irrigation (I), i.e., $E\left(Y_0 \mid I=1\right)=E\left(Y_0 \mid I=0\right)$, the bias disappears and $ATT=E\left(\Delta Y \mid I=1\right)$ is identified and is unbiased (Cobb-Clark and Crossley, 2003).

[22] In Tigray (the study area), access to irrigation is mainly determined by the proximity of the land to the command area, as priority is given to farmers whose land falls within the command area. On the other hand, since farmers are entitled to land in their village (kushet), we assume that a household's location in the community (*tabia)* is an important determinant of the household's access to irrigation. Hence, we use village (*kushet*) dummies as control variables for the treatment (access to irrigation).

$$p(X) = pr(I = 1)|X \tag{13}$$

The ATT in equation (12) can then be written as:

$$ATT = E\left(Y_1 \middle| p(X), I = 1\right) - E\left(Y_0 \middle| p(X), I = 1\right) \tag{14}$$

For the propensity score to be valid, the balancing properties need to be satisfied. It is intuited that two households with the same probability of access to irrigation will be placed in the treated (with access to irrigation) and untreated (without access to irrigation) samples in equal proportions. The propensity score is estimated by a binary choice model, which, in this paper, is represented by a binary logit model. Once the propensity score (pscore) is estimated, the data is split into equally spaced pscore intervals, implying that, within each of these intervals, the mean pscore of each conditioning variable is equal for the treated and control households, known as the balancing property. Since the pscore is a continuous variable, exact matching may not be possible, in which case a certain distance between households with and without access to irrigation must be accepted. In the present study, households with and without access to irrigation were, therefore, matched based on their propensity scores (pscore) using the nearest neighbor, kernel and stratification matching methods. These methods identify the closest match for each irrigating household (i.e., with the closest propensity score) among households that have no access to irrigation, and then compute the effect of irrigation as a mean difference of household income between the two households. A brief description of the three matching methods used in this study is given below (Becker and Ichino, 2002).

a) Nearest neighbor matching method: Each treated observation is matched with an observation in the control group that exhibits the closest propensity score. In nearest neighbor matching, it is possible that the same household in the control group can neighbor more than one household in the treated group. Therefore, after matching, the difference between their incomes is calculated as the average effect of access to irrigation on household income (ATT).

b) Kernel matching method: All treated observations are matched with households in the control group based on the weighted average that is inversely proportional to the distance between the propensity scores of the treated and control groups.

c) Stratification matching method: The dataset is divided into intervals having, on average, the same propensity score. The treated and control groups within that interval are placed under one block, and the mean difference of the outcome between the treated and control groups provides the average treatment effect of irrigation on household income (ATT).

It is important to note that each matching method has its own strengths and limitations. Although one may consider any of them alone for impact estimation, their utilization in combination has the advantage of testing the robustness of impact estimates (Becker and Ichino, 2002).

3.2. Switching Regression

The non-parametric matching method is flexible because it does not rely on a specific functional or distributional form. However, it comes at the cost of assuming no measurement or sampling error (Sherlund *et al.*, 2002). Furthermore, propensity score matching cannot correct for hidden bias because pscore comparison only controls for observed variables, assuming that they are perfectly measured (Cai *et al.*, 2008). Therefore, to address selection bias due to unobservable, selection models such as endogenous switching regression can be used. In a switching regression framework, equations are estimated separately for the incomes of households with and without access to irrigation, defined as follows:

$$\begin{aligned} &I = 1 \quad if \quad \gamma z_i + \mu > 0 \\ &I = 0 \quad if \quad \gamma z_i + \mu \leq 0 \qquad \mu \sim (0,1) \end{aligned} \tag{15}$$

where z_i is a vector of household characteristics that affect access to irrigation.

Given the selection equation defined by equation (15), the income of households with and without access to irrigation can be specified as:

$$E\left(Y_1 \middle| I = 1\right) = X\beta_1 + E\left(\varepsilon_1 \middle| \mu > -\gamma z_i\right) \tag{16}$$

$$E\left(Y_0 \middle| I = 0\right) = X\beta_0 + E\left(\varepsilon_0 \middle| \mu \leq -\gamma z_i\right) \tag{17}$$

where Y_1 and Y_0 are household incomes with and without access to irrigation, respectively, and X is a vector of household characteristics that affect income. γ, β_1 and β_0 are parameters to be estimated, and μ, ε_1 and ε_0 are three random error terms. We assume that access to irrigation in Tigray is predominantly determined exogenously by the physical location (closeness) of a plot to the command area. Thus, access to irrigation is based on the notion that farmers are heterogeneously dispersed in their location (village) in the community/tabia, and not all find it possible to access irrigation. Since access to irrigation is a dichotomous choice variable, the decision to access irrigation is modeled as a probit model that depends on the household's location in the tabia (village dummies) and the head of the household's age and sex, from which we estimated the inverse Mills ratio.

The error terms (i.e., μ, ε_1 and ε_0) are assumed to follow a trivariate normal distribution having a zero mean and covariance matrix (Fuglie and Bosch, 1995):

$$\begin{bmatrix} \sigma_1^2 & \sigma_{10} & \sigma_{1\mu} \\ \sigma_{10} & \sigma_0^2 & \sigma_{0\mu} \\ \sigma_{1\mu} & \sigma_{0\mu} & 1 \end{bmatrix} \tag{18}$$

where $\mathrm{var}(\varepsilon_1) = \sigma_1^2$, $\mathrm{var}(\varepsilon_0) = \sigma_0^2$, $\mathrm{var}(\mu) = 1$, $\mathrm{cov}(\varepsilon_1, \varepsilon_0) = \sigma_{10}$, $\mathrm{cov}(\varepsilon_1, \mu) = \sigma_{1\mu}$, and $\mathrm{cov}(\varepsilon_0, \mu) = \sigma_{0\mu}$. If the second terms in equation (16) and (17) are nonzero, OLS estimates of Y_1 and Y_0 on X will yield biased estimates of β_1 and β_0 due to selectivity. In contrast, if $\sigma_{1\mu} = \sigma_{0\mu} = 0$, equation (16) and (17) are defined as endogenous switching regimes. Given these assumptions, the expected values of the truncated error terms $(\varepsilon_1 | I = 1)$ and $(\varepsilon_0 | I = 0)$ are estimated as follows (Fuglie and Bosch, 1995):

$$E(\varepsilon_1 | I = 1) = E(\varepsilon_1 | \mu > -\gamma z) = \sigma_{1\mu} \frac{\phi(\gamma z / \sigma)}{\Phi\left(\gamma z / \sigma\right)} = \sigma_{1\mu}\lambda_1 \tag{19}$$

$$E(\varepsilon_0 | I = 0) = E(\varepsilon_0 | \mu \le -\gamma z) = \sigma_{0\mu} \frac{-\phi(\gamma z / \sigma)}{1 - \Phi\left(\gamma z / \sigma\right)} = \sigma_{0\mu}\lambda_0 \tag{20}$$

ϕ and Φ are pdf and cdf, respectively, of the standard normal distribution. The ratio of pdf and cdf evaluated at γz is the inverse Mills ratio denoted by λ_1 and λ_0, where their sum is equal to one, or $\lambda_0 = 1 - \lambda_1$. Note that the covariance between μ and ε_0 cannot be estimated because there is no observation that appears in the treatment and control groups at a time. Therefore, after the parameters are estimated, we can estimate the following models.

$$E(Y_1 | I = 1, X) = X\beta_1 + \sigma_{1\mu}\lambda_1 + \varepsilon_1 \tag{21}$$

$$E(Y_0 | I = 0, X) = X\beta_0 + \sigma_{0\mu}\lambda_0 + \varepsilon_0 \tag{22}$$

Since λ_1 and λ_0 are generated regressors, the residuals (i.e., ε_1 and ε_0) in equations (21) and (22) cannot be used to determine the variance of the two-stage estimates (Fuglie and Bosch, 1995; Kassie, 2005). Standard errors in the second stage are corrected by bootstrapping both equations. Equation (21) shows the income of farm households that have access to irrigation, while equation (22) shows the predicted values of Y_0 for these households, i.e., the expected income value if the farm household had no access to irrigation or the counterfactual income specified as $E\left(Y_0 \middle| I=1, X\right)=X\beta_0+\sigma_{0\mu}\lambda_0$. It follows that (Cai *et al.*, 2008; Fuglie and Bosch, 1995; Kassie, 2005) the mean income difference in household income due to irrigation access can then be estimated as:

$$\Delta Y=E\left(Y_1 \middle| X, I=1\right)-E\left(Y_0 \middle| X, I=1\right)=X\left(\beta_1-\beta_0\right)+\sigma_{1\mu}\lambda_1-\sigma_{0\mu}\lambda_0 \qquad (23)$$

where ΔY is the impact.

3.3. Stochastic Dominance Analysis

The stochastic dominance analysis was used to compare the welfare statues of households who have access to irrigation with those who have not. Such comparison involves the choice of a welfare measure, such as poverty line(s) and selection of poverty indices to enable aggregation of poverty. We used household income data and calculated income per adult equivalent using standards adopted from (WHO, 1985).

The Foster-Greer-Thorbecke (FGT) class of poverty measure is given as:

$$P_\alpha=\frac{1}{n}\sum_{i=1}^{q}\left(\frac{z-y_i}{z}\right)^\alpha \qquad (24)$$

where $\alpha=$ Poverty aversion parameter

$n=$ Total number of individuals in the population

$q=$ Total number of poor individuals

$z=$ Poverty line

$y_i=$ Income of individuals (per capita income) below poverty line $i=1, 2\ldots$q

If $\alpha = 0 \rightarrow P_0 = \frac{q}{n}$. This index is a head count ratio index that reflects the proportion of poor households (whose their members' per capita income is below the poverty line) measuring the incidence of poverty in the sample households. The advantage of the head count ratio index is that the overall progress in reducing poverty can be assessed directly.

If $\alpha = 1 \rightarrow P_1 = \frac{1}{nz}\sum_{i=1}^{q}(z - y_i)$. This measure is known as poverty gap and estimates the average distance of mean income of the poor from the poverty line. This may indicate, on average how much income is needed to uplift the income of the poor to the level of the poverty line and is sensitive to the depth of poverty.

We used a poverty line or minimum income required to purchase the minimum caloric content required for subsistence (i.e., 2200 kcal) and other essential non-food goods and services adopted from Hagos (2003). The official national poverty line was 1075 Birr in the 1995/96 constant national average prices (Weldehanna, 2004); however, the regional poverty line (for the Tigray region) was estimated at 1033.5 Birr (Hagos, 2003).

4. Study Area, Data Collection and Descriptive Statistics

4.1. Study Area and Data Collection

The data used in this paper was obtained from a survey performed to evaluate the impact of small-scale irrigation in Tigray, northern Ethiopia. The sample selection process involved three-stage stratified random sampling. First, all *tabias* in the region with irrigation projects were stratified based on irrigation technology, altitude, irrigable land size, and experience. In total, six sites were selected, among which two utilized micro-dams for irrigation, two river diversions, and two ground water. Of the two ground water sites, one was the *Kara-Adi-Shawo* irrigation project in *Golgol Raya*, which is electrified and uses modern (drip/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*. This approach enabled us to collect information about irrigating households that are comparable in basic characteristics to the non-irrigators serving as counterfactual. From the total of 613 sample households, 331 had access to irrigation and 282 were purely rain-fed cultivators[23].

A survey instrument was designed and distributed to the sample households to collect information on household and plot level data. Data regarding farm input and output was collected by asking each household head to recall her/his activities and productivity in a particular plot during the harvest year immediately prior. Data collection was performed during October-December, 2005. A plot was defined as a distinct management unit based on the type of crop planted during the 2004/2005 agricultural season. Plot size was not physically measured, but farmers were asked to estimate their size based on local measurement units (*tsimdi)*. Four *tsimdi* is equivalent to approximately one hectare. We asked each respondent about her/his input prices and agricultural output, but also randomly checked in the nearby market, from which we calculated the average price for each product type. Based on the output and price information, we calculated the total value of the agricultural

[23] Because we eliminated households that rented and rented out irrigated plots, the number of households used in this paper was 560, among which 313 had access to irrigation.

product for each household. The survey instrument was also designed to capture households' non-crop income, such as income from non-crop agricultural activities, off-farm employment, and food aid. Finally, we combined all household incomes to obtain the total income used as the outcome indicator, as access to irrigation likely affects both farming and non-farming incomes.

4.2. Descriptive Statistics

Household characteristics and resource endowments: There were some differences between irrigating and rain-fed farmers regarding household demographic characteristics (Table 1). Irrigating households demonstrated a larger family size, and also hired more labor compared to households with no access to irrigation. This may indicate the labor absorption capacity of irrigation. No significant differences were observed between the two groups in the total cultivated land or the number of oxen, cows, or other livestock (tlu) owned.

Comparison of the level and sources of income, consumption, and poverty incidence: Irrigating households had significantly (at 1% levels) higher farming income and total income than rain-fed farming households. Table 1 indicates that the mean farming income of irrigating households (i.e., 2278 Birr) is almost twice that of rain-fed farming households (i.e., 1464 Birr). This constitutes, on average, about 51 percent of the total average household income of those with access to irrigation and 57 percent of the total average income of households with no access to irrigation. The mean off-farm income, on the other hand, was higher for rain-fed households compared to irrigating households, although no significant difference was observed.

Furthermore, Table 1 shows that the average total income of irrigating and rain-fed households was estimated to be 5472 and 2564 Birr, respectively, revealing a statistically significant (at 1% level) difference. This may indicate that access to irrigation more than doubled household income. The mean income of households with no access to irrigation was estimated to be only 47% of the mean income of households with access to irrigation. The difference in the total consumption expenditure between the two groups, although significant at the 5% level, was not as pronounced as the income differences. The consumption expenditure was approximately 10% higher among irrigators. From Table 1, we see that the predicted poverty incidence rate (based on our sample data) for rain-fed households was equivalent to the regional average (for the Tigray region) and significantly higher than the national average (see Appendix 1).

In summary, the descriptive statistics indicate that irrigators are better off in terms of income and other welfare indicators. But this does not imply that the difference is solely due to access to irrigation. Other factors (both observable and unobservable) might have contributed to the income or poverty status difference between irrigators and non-irrigators.

5. Results and Discussion

The logit estimates of propensity score (pscore) are presented in Appendix 2 along with the STATA program output. The common support option was selected and the balancing property was satisfied.

Our first hypothesis (**H1**) stated that access to irrigation improves household income. Table 2 presents the non-parametric matching estimates of the average treatment effect of access to irrigation on the treated (ATT). Based on the alternative matching methods adopted for assessing the robustness of the estimated results, the overall average income gain due to irrigation access ranged between 4090 and 4940 Birr and was significant at the 10, 1, and 1%

levels based on the nearest neighbor, kernel, and stratified matching methods, respectively. This may indicate that (relying on selection observables and assuming no selection bias) the mean income of farm households has significantly increased due to irrigation access. However, there is a risk that these estimates are biased due to unobservable characteristics. We used endogenous switching regression to test and control for such selection bias. Estimated results of the switching regression model are provided in Table 3. To estimate total household income, two models were independently used for irrigating and rain-fed households. The predicted average incomes (*yincome*) were 4933 and 2570 Birr for irrigating and rain-fed households, respectively, demonstrating a significant (at 1% level) difference. The difference is substantially lower than the difference from the matching methods, but still large and significant.

Hypothesis two (**H2**) stated that access to irrigation reduces poverty. We simulated a range of poverty lines to make poverty comparisons between irrigating and rain-fed households using stochastic dominance tests that enabled us to test the robustness of the poverty orderings. The results are provided in Figures 2 and 3. Comparing the head count ratio, the stochastic dominance test (Figure 2), unambiguously establishes that the incidence of poverty is lower for irrigating households compared to rain-fed households. The second order stochastic dominance test (Figure 3) assesses the depth of poverty among those living below the poverty line. This also revealed that the depth of poverty is unambiguously lower for irrigating households compared to rain-fed households. This may indicate a positive impact of irrigation on poverty reduction.

Hypothesis three (**H3**) stated that access to irrigation reduces off-farm employment and off-farm income. The reasoning behind this is that irrigation generates a high demand for labor as a consequence of high cropping intensity (i.e., several crops grown on the same irrigated land in one year rather than one cropping season on rain-fed land) and labor-intensive production; therefore, irrigating households may face labor shortages, preventing participation in off-farm activities and generation of off-farm income. We tested this hypothesis using the matching method and found no significant effect of access to irrigation on off-farm income or off-farm labor allocation. Explanations for this are: (1) there may not be enough off-farm employment opportunities in the area that provide a chance for rain-fed households to generate income, and (2) irrigation plots of households are so small that most households can manage them without extra labor.

Hypothesis four (**H4**) stated that the income effect of ground water-based irrigation is higher than the income effect of micro-dam and river diversion based irrigation. The argument in support of this is that the use of ground water-based irrigation technologies (pressurized tube and manually operated shallow-well) may reduce water losses due to run-off and excess percolation and improve water use efficiency, and has fewer collective action problems in managing the water distribution, leading to improved productivity and production. On the other hand, it implies that water loss is high in micro-dam and river diversion irrigation projects, which primarily utilize earthen canals. This may reduce the size of irrigated land and the length of irrigation time. To test this, we decomposed the three types of irrigation technologies (i.e., micro-dam, river diversion, and ground water) to non-parametrically estimate the effect of irrigation on household income; off-farm income, and off-farm employment (see Tables 4.1, 4.2, and 4.3). As expected, the overall income gain of irrigating households in areas where ground water is the source of irrigation ranges between 7960 and 8255 Birr and was significant (at 1% levels) based on the nearest neighbor, kernel, and stratified matching methods (see Table 4.3). However, the income gains were not significant in areas where the sources of irrigation water are micro-dam and river diversion. Average ATTs were high in the case of micro-dams but also the standard errors of ATTs were large, leading ATTs to be insignificant. This may indicate that this technology has potential but this potential is far from fully utilized in many locations. In the case of river diversions both ATTs and the standard errors of ATTs were small, and only with one of the matching methods was significant positive ATT found. This may indicate that the potential of this irrigation technology is lower.

This suggests that water availability in the micro-dam and river diversion irrigation systems is unreliable or varies from season to season, depending on the amount of run-off obtained. Moreover, the water storing capacity of some of these irrigation projects could be reduced due to sedimentation problems that reduce the size of irrigable land. For example, every year before the project is opened for irrigation around December, the water committees together with the Development Agent assess the volume of water in the reservoir and then decide upon the size of land that can be irrigated during that particular year. Accordingly, the size of irrigated land depends on the volume of water in the reservoir (system); hence, some lands that would have been irrigated could be left out due to a shortage of water in the system. Furthermore, since the frequency of irrigation time is likely to decrease, there may not be sufficient work for the household to fully occupy all family members. Loss of water due to run-off and excess percolation may also aggravate the problem of water shortage. Most micro-dam and river diversion irrigation projects (in the study areas) use earthen canals that are poorly maintained resulting in significant water loss. This may explain some of the inefficiency in irrigated agriculture. The ground water projects, on the other hand, use semi-automated tubes (in Kara Adishawo) and human labor (in Mai-Adrasha) to transport water from the source, which substantially reduces water loss.

Another explanation for the income difference could be a management problem. Unlike ground water (for which individuals are less apt to cheat or be cheated), no farmer has control of the amount of water he or she receives from a micro-dam or river diversion irrigation infrastructure. This may imply that those who are near the source/canal may have a greater chance of withdrawing more water (i.e, to cheat), while those located far from the source obtain less water, which is not enough to produce efficiently. Hence, some members of the household may be diverted to other activities other than irrigated agriculture. However, there was also no significant effect on off-farm employment and income for ground water irrigation (Table 4.3) where such effect could have been expected to be stronger. In general, this could be related to issues such as water management (collective action) and the effectiveness of enforcement mechanisms, which were not covered in this paper. Therefore, we suggest that further research is required to study these and inefficiencies identified (chapter 3) and more robustly assess the effect of irrigation technology on poverty reduction.

Determinants of access to irrigation and its effect on household income

Since the non-parametric matching method cannot correct for hidden bias, an endogenous switching regression was used to account for unobservable selection biases. We used a probit model to examine factors that affect a household's access to irrigation. From Table 5, we see that the likelihood of a households' access to irrigation is positively and significantly (at 1% level) related to the number of plots. This may indicate that as the number of plots owned by the household increases, the probability that at least one of them falls in the command area increases. The significant dummy variables in the probit model (Table 5) provide thoughtful insight supporting our presumed assumption that access to irrigation is exogenously determined based on the proximity of the land to the command area. Most of the statistically significant village dummies were found close to the command areas.

In the switching regression estimates, the household head's age was negatively related to irrigating household income. This may hint that the elderly are less efficient or may be resistant to the use of improved technologies and farming systems. This may also suggest that older household heads lack the necessary labor to carry out the labor-intensive irrigation farming activities. Among the tabia dummies, only Kara-Adishawo was found positively related to the irrigating household's income. This may capture the effect of village characteristics, such as land quality. It may also indicate the effect of irrigation technology (pressurized tube irrigation is used in the tabia), which may improve water use efficiency.

6. Conclusion

We analyzed the impact of irrigation on household income in the Tigray region, Ethiopia. The estimated results of the non-parametric matching and parametric switching regression methods indicated that the mean income of households with access to irrigation was significantly higher than the mean income of households with no access to irrigation. The stochastic dominance analysis also showed that the incidence (i.e., head count ratio) and depth (gap) of poverty were unambiguously lower for households with access to irrigation. Unlike previous findings from Tigray, we found a positive and significant effect of investment in small-scale irrigation with regard to enhancing household income and reducing poverty in Tigray, Ethiopia. However, there were clear differences between the different types of irrigation technologies with positive effects of groundwater irrigation while the effects of micro-dam and river diversion irrigation technologies was found to be insignificant. Unlike our expectation, we found no significant effect of access to irrigation on off-farm income or off-farm labor allocation. Explanations for this are: (1) there may not be enough off-farm employment opportunities in the area that provide a chance for rain-fed households to generate income, and (2) irrigation plots of households are so small that most households can manage them without extra labor.

We assessed and compared the effects of different types of irrigation technologies and found that the identification and selection of appropriate irrigation technologies might enable greater impact of irrigation and increased gain from investment in irrigation. In general, the technology-related assessment indicates that water management (collective action) and its enforcement mechanisms could be important, and suggests that more rigorous study is needed to robustly assess and explain the limited effects of some types of irrigation technology on income and poverty.

References

Becker, O. S., Ichino, A., 2002. Estimation of Average Treatment Effects based on Propensity Scores. The Stata Journal. 2(4), 358-377.

Berg, M. V. D., Ruben, R., 2006. Small-Scale Irrigation and Income Distribution in Ethiopia. Journal of Development Studies. 42(5), 868–880.

Cai, J., Ung, L., Setboonsarng, S., Leung, P., 2008. Rice Contract Farming in Cambodia: Empowering Farmers to Move Beyond the Contract Toward Independence. Discussion Paper, 109. Asian Development Bank (ADB) Institute.

Caswell, M., Zilberman, D., 1985. The Choices of Irrigation Technologies in California. American Journal of Agricultural Economics. 67(2), 224-234.

Chamber, R., 1994. Irrigation against rural poverty. In: GujarJaipur, R. (Ed.), Socioeconomic dimension and Irrigation. Priintwell, India.

Christiaensen, L., Demery, L., Kühl1, J., 2006. The Role of Agriculture in Poverty Reduction An Empirical Perspective: Policy Research Working Paper 4013. 4013. World Bank

Cobb-Clark, D. A., Crossley, T., 2003. Econometrics for Evaluations: An Introduction to Recent Developments. The Economic Record. 79(247), 491-511.

Dhawan, B. D., 1988. Irrigation in India's Agricultural Development: Productivity, Stability and Equity. Sage Publications India Pvt. Ltd, New Delhi.

Diao, X., Hazell, P., Resnick, D., Thurlow, J., 2007. The Role of Agriculture in Development Implications for Sub-Saharan Africa. International Food Policy Research Institute, Research Report No. 153.

Fan, S., Zhang, L., Zhang, X., 2000. GROWTH AND POVERTY IN RURAL CHINA: THE ROLE OF PUBLIC INVESTMENTS. Environment and Production Technology Division, International Food Policy Research Institute: EPTD DISCUSSION PAPER NO. 66.

FDRE, 1999. Poverty Analysis, Addis Ababa. Ministry of Economic Development and Co-operation (MEDaC).

FDRE, 2002. Food Security Strategy, Addis Ababa, Ethiopia.

Fuglie, K. O., Bosch, D. J., 1995. Economic and Environmental Implications of Soil Nitrogen Testing: A Switching-Regression Analysis. American Journal of Agricultural Economics. 77(4), 891-900.

Hagos, F., 2003. Poverty, Institutions, Peasant Behavior and Conservation Investment in Northern Ethiopia. PhD Thesis. Agricultural University of Norway, Department of Economics and Resource Management, Ås, Norway.

Hagos, F., Pender, J., Gebreselassie, N., 1999. 'Land Degradation in the Highlands of Tigray and Strategies for Sustainable Land Management', Socioeconomic and Policy Research Working Paper No. 25. International Livestock Research Institute, Ethiopia.

Heckman, J. J., Ichimura, H., Todd, P., 1998. Matching as an Econometric Evaluation Estimator The Review of Economic Studies 65(2), 261-294

Hussain, I., Namara, R., Madar, S., 2004. Water for food security for the poor. A collection of thematic papers. Asian Development Bank.

Jin, S., Huang, J., Hu, R., Rozelle, S., 2002. The creation and spread of technology and total factor productivity in China's agriculture. American Journal of Agricultural Economics. 84, 916-930

Kassie, M., 2005. Technology Adoption, Land Rental Contracts and Agricultural Productivity. PhD. Norwegian University of Life Sciences, Department of Economics and Resource Management, Ås.

Kumar, M. D., 2003. Food Security and Sustainable Agriculture in India: The Water Management Challenge. Working Paper 60. International Water Management Institute.

Norman, W. R., McCann, I., Al-Ghafri, A., 2008. On-farm labour allocation and irrigation water use: case studies among smallholder systems in arid regions. Irrig Drainage Syst 22, 79–92.

Pender, J., Gebremedhin, B., 2004. Impacts of Policies and Technologies in Dryland Agriculture: Evidence from Northern Ethiopia. In: Challenges and Strategies for Dryland Agriculture. CSSA Special Publication no. 32.

Pender, J., Gebremedhin, B., 2007. Determinants of Agricultural and Land Management Practices and Impacts on Crop Production and Household Income in the Highlands of Tigray, Ethiopia. JOURNAL OF AFRICAN ECONOMIES.

Pender, J., P.Jagger, Gebremedhin, B., Haile, M., 2002. Agricultural Change and Land Management in the Highlands of Tigray: Causes and Implications. Policies for Sustainable Land Management in the Highlands of Tigray, Northern Ethiopia:Summary of Papers and Proceedings of Workshop held at Axum Hotel, Mekelle, Etiopia, 28-29 March 2002. Socio-economic and Policy Research Working Paper 54. ILRI (Internationa Livestock Research Institute), Nairobi. 75 pp.

Ravallion, M., 2001. The Mystery of the Vanishing Benefits: An Introduction to Impact Evaluation. The World Bank Economic Review. 15(1), 115-140.

Ravallion, M., 2005. Evaluating Anti-Poverty Programs. World Bank Policy Research, Development Research Group. Working Paper 3625.

Rosegrant, M., Evenson, R., 1992. Agricultural productivity and sources of growth in south Asia. American Journal of Agricultural Economics. 74, 757-761

Rosenbaum, P. R., Rubin, D. B., 1983. The Central Role of the Propensity Score in Observational Studies for Causal Effects. Biometrika. 70(1), 41-55.

Saleth, R. M., Namara, R. E., Samad, M., 2003. Dynamics of Irrigation-Poverty Linkage in Rural India: Analytical Framework and Empirical Analysis. Water Policy. 5, 459-473.

Sherlund, S. M., Barrett, C. B., Adesina, A. A., 2002. Smallholder technical efficiency controlling for environmental production conditions. Journal of Development Economics 69, 85– 101.

Weldehanna, T., 2004, May 6-8 THE EXPERIENCES OF MEASURING AND MONITORING POVERTY IN ETHIOPIA. Poverty Analysis and Data Initiative (PADI), Mombassa, Kenya. at http://www.worldbank.org/afr/padi/ethiopia_paper.pdf, accessed on 13,07,07.

WHO, 1985. ENERGY AND PROTEIN REQUIREMENTS: Report of a Joint FAO/WHO/UNU Expert Consultation. World Health Organization Technical Report Series 724. World Health Organization, Geneva.

Wooldridge, J. M., 2002. Econometric Analysis of Cross Section and Panel Data. The MIT Press, U.S.A.

Table 1: Summary statistics of selected variables used in estimating the treatment effect

Variable	Description	Total		Rain-fed		Irrigation		*t-test*
		Coefficient	St. error	Coefficient	St. error	Coefficient	St. error	
Familysize	Family size (member)	4.889	0.087	4.681	0.127	5.066	0.120	-2.206**
Hheadsex	Household head's sex	0.744	0.018	0.723	0.027	0.761	0.023	-1.071
Hhage	Household head's age	46.328	0.651	46.482	0.966	46.196	0.881	0.219
Femwl	Adult female household members	1.573	0.037	1.539	0.051	1.601	0.053	-0.841
Mamwl	Adult male household members	1.370	0.042	1.351	0.062	1.387	0.056	-0.425
Litrate	Literate household members (member)	1.349	0.059	1.259	0.081	1.426	0.084	-1.418
Oxen	Household's oxen ownership	1.196	0.043	1.121	0.066	1.260	0.056	-1.625
Totaltlu	Household's total livestock ownership (TLU)	3.084	0.140	2.935	0.239	3.211	0.161	-0.984
Milcow	Household's milk cow ownership (number)	0.657	0.046	0.660	0.075	0.656	0.057	0.043
Frassoc	Household's access to credit (1=yes)	0.305	0.019	0.301	0.027	0.308	0.025	-0.180
Tothilab	Hired labor (labor days)	4.113	0.494	2.858	0.535	5.181	0.789	-2.353**
Farmsiz	Cultivated farm size (ha)	4.775	0.124	4.223	0.202	4.735	0.151	0.354
Irriplotsize	Cultivated irrigated land size in 2005/06 (ha)	0.332	0.017	0.000	0.000	0.601	0.023	-23.083***
Ranfedplotsize	Cultivated rain-fed land size in 2005/06 (ha)	4.444	0.124	4.807	0.203	4.134	0.149	2.723***
Totalincome97	Household's total income in 2005/06 (Birr)	4134.401	885.257	2564.465	180.262	5471.931	1629.795	-3.639***
Incomeagriactiv97	Household's non-farming agricultural income in 2005/06 (Birr)	1212.890	866.110	321.073	55.536	1972.686	1603.240	-0.950
Farmingincome	Household's total farming income in 2005/06 (Birr)	2173.605	175.232	1464.154	149.059	2778.032	294.854	-3.777***
Offincome97	Household's total off-income in 2005/06 (Birr)	747.906	47.514	779.238	75.234	721.213	60.355	0.608
Rainfeinco97	Household's income from rain-fed Agriculture in 2005/06 (Birr)	1374.154	106.685	1464.154	149.059	1372.010	168.674	0.022
Irriinco97	Household's income from irrigated Agriculture in 2005/06 (Birr)	799.452	108.215	0.000	0.000	1406.022	189.079	-6.259***
Totalexp97	Household's total expenditure in 2005/06 (Birr)	3629.458	85.978	3438.101	128.049	3792.486	115.407	-2.060**
Tabia1	Tabia (1=Addis-Alem)	0.154	0.015	0.159	0.022	0.150	0.020	0.303
Tabia2	Tabia (1=Kara-Adishawo)	0.189	0.016	0.267	0.027	0.121	0.018	4.541***
Tabia3	Tabia (1=Laelay Agulae)	0.168	0.016	0.089	0.017	0.236	0.024	-4.836***
Tabia4	Tabia (1=Adi-ha)	0.166	0.015	0.111	0.019	0.214	0.023	-3.354***
Tabia5	Tabia (1=Adigedena)	0.168	0.016	0.204	0.025	0.137	0.019	2.140**
Tabia6	Tabia (1=Mai-Adrasha)	0.154	0.015	0.170	0.023	0.141	0.020	0.992
Percapinc	Per capita income (Birr)	1795.262	187.249	1288.317	83.436	2227.160	337.852	-2.510**
Poveinci	Poverty incidence (%)	0.493	0.020	0.560	0.030	0.435	0.027	3.111***
Povdepth	Average depth (gap) of poverty	433.538	25.067	486.806	34.178	354.138	33.585	2.654***

Table 2
Impact of irrigation on household total income, off-farm income, and off-farm labor allocation

Matching method and outcome	Number of treated group (Irrigating households)	Number of control group (rain-fed households)	Average treatment effect on the treated (ATT)	Standard error	t-statistics
Household income					
Nearest Neighbor matching	313	68	4090.471	2164.475	1.890*
Kernel Matching	313	224	4658.147	1441.209	3.232***
Stratified matching	313	236	4939.015	1661.538	2.973***
Household off-farm income					
Nearest Neighbor matching	313	68	-51.060	292.277	-0.175
Kernel Matching	313	224	-292.498	297.787	-0.982
Stratified matching	313	236	-35.473	100.104	-0.354
Household off-farm labor allocation					
Nearest Neighbor matching	313	68	10.645	23.413	0.455
Kernel Matching	313	224	6.754	13.872	0.487
Stratified matching	313	236	-0.856	8.384	-0.102

*, **, *** indicate significant differences at 10%, 5% and 1% levels, respectively; standard errors are bootstrapped.

Table 3
Determinants of household income (switching regression of household income with and without access to irrigation)

Variable	Variable description	Income of household with access to irrigation		Income of households without access to irrigation	
		Coefficient	Standard error	Coefficient	Standard error
		221.854	659.161	518.167	345.311
Hhage	Household age	-32.848***	12.436	-8.936	9.143
Femwl	Household member female labor	-153.273	339.594	-137.617	154.104
Mamwl	Household member male labor	441.103	604.839	212.945	162.811
Litrate	Literate household members	544.288	442.288	86.822	112.206
Plotsize	Plot size (ha)	-1340.527	1913.490	493.330	649.228
Oxen	Oxen ownership	447.679	476.529	564.122***	194.431
Totaltlu	Livestock ownership (tlu)	310.779	245.788	5.322	54.358
Frassoc	Access to credit (1=yes)	904.728	652.449	1262.225***	373.260
Frqcnext	Frequency of contact with development agent	716.464	462.923	-21.851	143.025
irrfrmsiz	Irrigation farm size (ha)	1881.136	2964.663	394.789	1600.679
rainfefarsiz	Rain-fed farm size (ha)	1599.779	1881.625	-306.978	616.946
Tabias	Tabia dummy variables	Yes		Yes	
Imr	Inverse Millis ratio one (λ_1)	1869.287	3970.831		
imr2	Inverse Millis ratio two (λ_0)			-481.079*	262.183
Cons	Constant	-2532.360	5420.456	802.688	779.209
	Number of observation	313		247	
	Wald chi2(15)	119.660		121.200	
	Prob > chi2	0.000		0.000	
	Adj R-squared	0.136		0.224	
Yincome	Predicted mean household income	4932.733	186.368	2569.648	60.078
Ttest	Significance of difference between predicted mean income of irrigating and pure rain-fed cultivating households	t = 15.200***			

*, **, *** indicate significance levels of 10%, 5% and 1%, respectively; standard errors are bootstrapped.

Table 4.1: Impact of Micro-dam irrigation technology

Matching method and outcome	Number of treated group (Irrigating households)	Number of control group (rain-fed households)	Average treatment effect on the treated (ATT)	Standard error	t-statistics
Household income					
Nearest Neighbor matching	90	24	7586.777	7063.586	1.074
Kernel Matching	90	94	7655.571	4553.655	1.681
Stratified matching	90	81	7185.874	5905.667	1.217
Household off-farm income					
Nearest Neighbor matching	90	24	185.253	332.951	0.556
Kernel Matching	90	94	237.319	211.582	1.122
Stratified matching	90	81	-75.710	333.389	-0.227
Household off-farm labor allocation					
Nearest Neighbor matching	90	24	3.844	50.008	0.077
Kernel Matching	90	94	14.602	30.957	0.472
Stratified matching	90	81	1.565	29.701	0.053

*, **, *** indicate significant differences at 10%, 5% and 1% levels, respectively; standard errors are bootstrapped.

Table 4.2: Impact of River diversion irrigation technology

Matching method and outcome	Number of treated group (Irrigating households)	Number of control group (rain-fed households)	Average treatment effect on the treated (ATT)	Standard error	t-statistics
Household income					
Nearest Neighbor matching	142	15	52.420	1334.411	0.039
Kernel Matching	142	25	61.420	1144.719	0.054
Stratified matching	142	55	1619.598	416.044	3.893***
Household off-farm income					
Nearest Neighbor matching	142	15	-54.593	292.961	-0.186
Kernel Matching	142	25	-68.730	206.465	-0.333
Stratified matching	142	55	-40.657	98.478	-0.413
Household off-farm labor allocation					
Nearest Neighbor matching	142	15	-15.507	47.586	-0.326
Kernel Matching	142	25	-11.294	37.384	-0.302
Stratified matching	142	55	-13.942	13.695	-1.018

*, **, *** indicate significant differences at 10%, 5% and 1% levels, respectively; standard errors are bootstrapped.

Table 4.3: Impact of groundwater irrigation technology

Matching method and outcome	Number of treated group (Irrigating households)	Number of control group (rain-fed households)	Average treatment effect on the treated (ATT)	Standard error	t-statistics
Household income					
Nearest Neighbor matching	83	19	7959.707	1844.601	4.315***
Kernel Matching	83	45	8068.921	2396.354	3.367***
Stratified matching	83	84	8255.354	1926.312	4.286***
Household off-farm income					
Nearest Neighbor matching	83	19	-1509.862	1661.772	-0.909
Kernel Matching	83	45	-1267.221	1481.364	-0.855
Stratified matching	83	84	126.269	245.386	0.515
Household off-farm labor allocation					
Nearest Neighbor matching	83	19	-40.831	54.959	-0.743
Kernel Matching	83	45	-29.813	46.172	-0.646
Stratified matching	83	84	17.503	22.671	0.772

*, **, *** indicate significant differences at 10%, 5% and 1% levels, respectively; standard errors are bootstrapped.

Table 5
Determinants of access to irrigation (Probit model)

Variable	Description	Coefficient	Std. error
hheadsex	Household head sex is (1=male)	-0.039	0.141
Hhage	Household age	-0.002	0.004
plotnumber	Number of plots	0.297***	0.044
adisasta	Village is addis-Alem (1=astahe)	1.420**	0.686
adisgonq	Village is addis-Alem (1=qonoquat)	0.231	0.667
adisatsig	Village is addis-Alem (1=atsegebta)	2.342***	0.731
adishante	Village is addis-Alem (1=hantebat)	-0.300	0.708
Kaka	Village is kara-adishwo (1=kara)	2.264***	0.669
kaadshwo	Village is kara-adishwo (1=adishawo)	0.079	0.867
kakoban	Village is kara-adishwo (1=koban)	-0.248	0.729
aguberki	Village is mesanu(1=berki)	1.943***	0.674
agulaelay	Village is mesanu(1=laelay-agulae)	1.666**	0.664
aguadngur	Village is mesanu(1=adngure)	1.943***	0.675
adihawkro	Village is adiha(1=wukro)	1.493**	0.681
adihakubaria	Village is adiha(1=kurbaria)	1.261*	0.678
adihaseqyen	Village is adiha(1=seqeyen)	1.858***	0.665
adihaaditsre	Village is adiha(1=aditsere)	1.142*	0.693
agedgulti	Village is adigedena(1=gulti)	2.159***	0.683
agedchiendog	Village is adigedena(1=cheadanuge)	-0.049	0.715
adgedadiged	Village is adigedena(1=adi-gedena)	-0.029	0.675
mdshaareada	Village is adigedena(1=areada)	1.309*	0.668
mdrshakinbro	Village is maiadrasha(1=adikenbro)	0.688	0.676
mdrshanadgi	Village is maiadrasha(1=adinekas adgi)	0.346	0.681
marshgushala	Village is maiadrasha(1=maigushala)	0.577	0.711
Cons	Constant	-2.007***	0.686
	Number of observation	560	
	Log likelihood	-257.850	
	Wald chi2(24	169.270	
	Prob > chi2	0.000	
	Pseudo R2	0.329	

*, **, *** indicate significant differences at 10%, 5% and 1% levels, respectively; standard errors are robust.

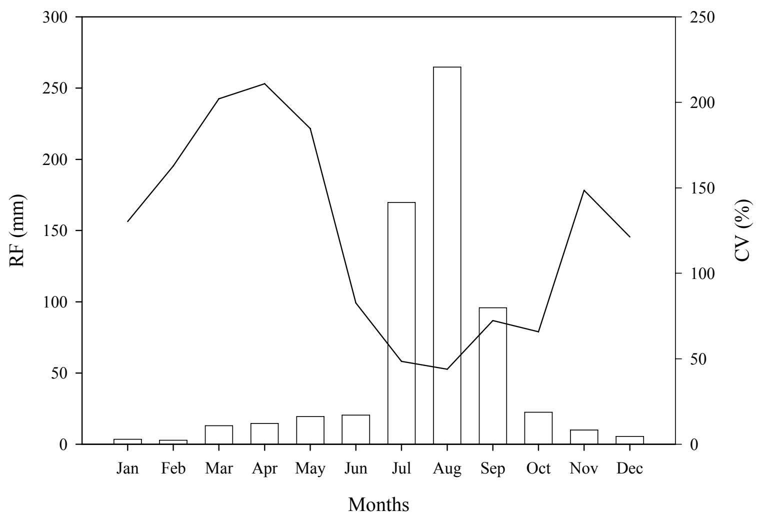

Figure 1. Average monthly rainfall and Coefficient of Variance (CV) in Tigray (1956-2006)

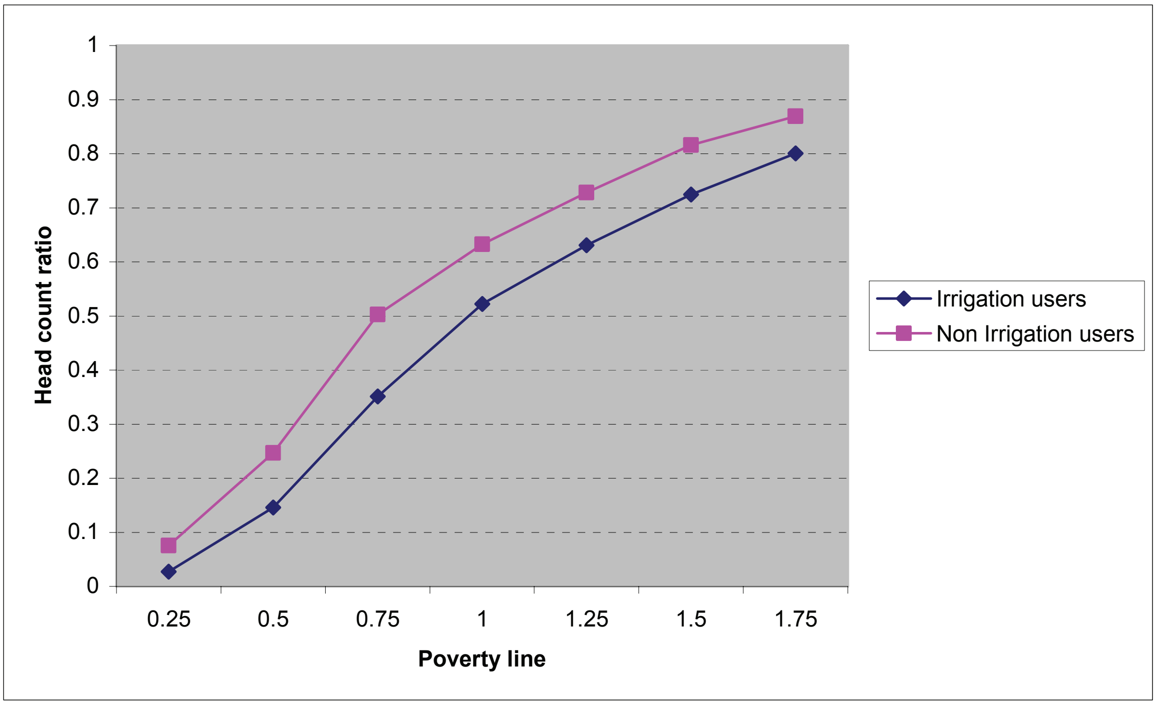

Figure 2. Poverty incidence (Head count ratio) of households with and without access to irrigation

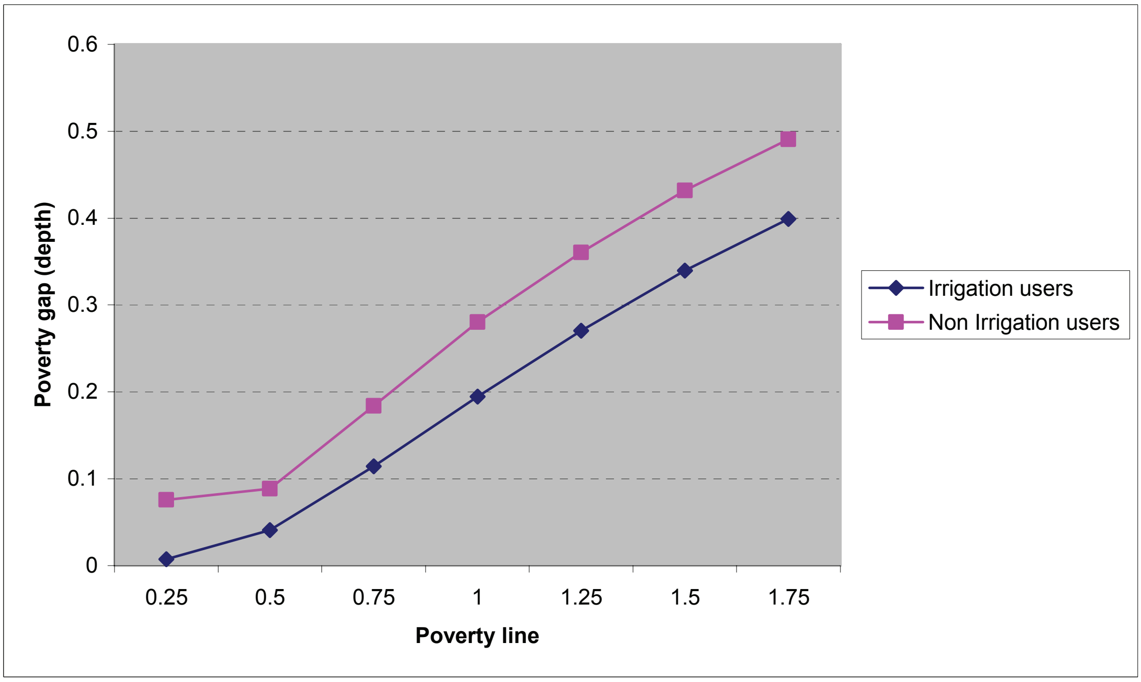

Figure 3. Poverty gap (depth) of households with and without access to irrigation

Appendix 1:

Poverty by region using the poverty line based on Basket of Kcal

Region	Per capita consumption expenditure (Birr) (1999)	Poverty Index (%)		Poverty Gap (2002)
		1999	2002	
Tigray	903.60	0.58	0.56	0.17
Afar	1105.6	0.52	0.33	0.10
Amhara	917.2	0.57	0.54	0.16
Oromia	1184.0	0.35	0.34	0.08
Somali	1166.4	0.35	0.31	0.07
Benshangul-Gumuz	1026.8	0.48	0.47	0.13
SNNPR	945.5	0.57	0.56	0.18
Gambela	1223.5	0.42	0.34	0.09
Harari	1459.7	0.29	0.22	0.05
Addis-Ababa	1569.0	0.30	0.30	0.09
Dire Dawa	1397.1	0.25	0.29	0.07
National	**1087.8**	**0.46**	**0.45**	**0.13**

Source: (FDRE, 1999, 2002)

Appendix 2:

STATA output of the propensity score matching

```
****************************************************
Algorithm to estimate the propensity score
****************************************************

The treatment is accirri

  access to |
 irrigation |
1=yes, 0=no |      Freq.     Percent        Cum.
------------+-----------------------------------
          0 |        270       46.31       46.31
          1 |        313       53.69      100.00
------------+-----------------------------------
      Total |        583      100.00

Estimation of the propensity score

note: kaadmugu != 0 predicts failure perfectly
      kaadmugu dropped and 23 obs not used

Iteration 0:   log likelihood = -384.26408
Iteration 1:   log likelihood =  -291.3439
Iteration 2:   log likelihood = -288.13425
Iteration 3:   log likelihood =  -288.0013
Iteration 4:   log likelihood = -287.99982
Iteration 5:   log likelihood = -287.99982
Logistic regression                               Number of obs   =        560
                                                  LR chi2(22)     =     192.53
                                                  Prob > chi2     =     0.0000
Log likelihood = -287.99982                       Pseudo R2       =     0.2505
```

accirri	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
hheadsex	.5026489	.2369215	2.12	0.034	.0382913	.9670064
hhage	-.0009043	.0066284	-0.14	0.891	-.0138957	.0120871
adisasta	1.654668	.744194	2.22	0.026	.1960744	3.113261
adisgonq	-.377196	.668489	-0.56	0.573	-1.68741	.9330184
adisatsig	2.567035	.8789825	2.92	0.003	.8442613	4.289809
adishante	-1.585009	.7266388	-2.18	0.029	-3.009195	-.1608229
kaka	1.762723	.6474151	2.72	0.006	.4938124	3.031633
kaadshwo	-1.85702	1.170232	-1.59	0.113	-4.150633	.4365925
kakoban	-2.607873	.8793511	-2.97	0.003	-4.33137	-.8843768
aguberki	1.479329	.6607334	2.24	0.025	.184315	2.774342
agulaelay	1.414344	.6395405	2.21	0.027	.1608672	2.66782
aguadngur	1.335759	.6508694	2.05	0.040	.0600784	2.611439
adihawkro	1.001105	.6799169	1.47	0.141	-.3315076	2.333718
adihakubaria	.7309365	.6717099	1.09	0.277	-.5855908	2.047464
adihaseqyen	1.434418	.6362181	2.25	0.024	.1874534	2.681383
adihaaditsre	.7261453	.6831756	1.06	0.288	-.6128543	2.065145
agedgulti	1.995798	.6858535	2.91	0.004	.6515503	3.340047
agedchiendog	-1.671844	.7916877	-2.11	0.035	-3.223523	-.1201644
adgedadiged	-1.19304	.6356239	-1.88	0.061	-2.438839	.0527604
mdshaareada	.7580286	.6423956	1.18	0.238	-.5010436	2.017101
mdrshakinbro	-.0450929	.632611	-0.07	0.943	-1.284988	1.194802
mdrshanadgi	-.1580476	.6284379	-0.25	0.801	-1.389763	1.073668
_cons	-.5352118	.6554222	-0.82	0.414	-1.819816	.7493921

Note: the common support option has been selected
The region of common support is [.06285968, .92433943]

Description of the estimated propensity score
in region of common support

Estimated propensity score

	Percentiles	Smallest		
1%	.0637174	.0628597		
5%	.0955438	.0630731		
10%	.1460531	.0633945	Obs	549
25%	.3495545	.0634482	Sum of Wgt.	549
50%	.664803		Mean	.5692901
		Largest	Std. Dev.	.2706705
75%	.7960953	.9237046		
90%	.8467534	.9240226	Variance	.0732625
95%	.8737244	.9242762	Skewness	-.5876221
99%	.9230006	.9243394	Kurtosis	1.90448

```
******************************************************
Step 1: Identification of the optimal number of blocks
Use option detail if you want more detailed output
******************************************************
The final number of blocks is 7

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

Inferior of block of pscore	access to irrigation 1=yes, 0=no: 0	1	Total
.0628597	43	3	46
.1428571	66	16	82
.2857143	18	8	26
.4285714	33	39	72
.5714286	34	69	103
.7142857	35	131	166
.8571429	7	47	54
Total	236	313	549

Note: the common support option has been selected

****
End of the algorithm to estimate the pscore
****

Appendix

Appendix

Summary of Questionnaire Used for Household Survey, 2005/2006[24]

Name of HH head: ______________________ HH Code: ______________________________ Tabia: __________________, Kushet/Village: ________________ Ownership of Land: Rain-fed: --------------, irrigated: --------------, both--------------------- Enumerator's Name: ___________________, Date of Interview______/____/______ (Date/Month/Year) Checked By:____________________, Date:_______/______/_______ (Date/Month/Year)

__Enumerator:__ *Please write the code in the space provided. Please do not circle on the options*

[24] The questionnaire was comprehensive and bigger than this. This shows only a summarized part of it.

Part One: Household characteristics

[Interviewer: Write members in this order: a) Head first b) Spouse(s) c) Son/daughter d) other]

I.D. code	Name	Relationship to head (code a)	Sex Male----1 Female--0	Current Residence (code b)	Is [NAME] a member of the household Yes ….1 No…...0	Age (Years)	Marital Status Code (c)
01							
02							
03							

Code a: Relationship to Head
1=Head, 2=Wife/husband, 3=Son/daughter, 4=other relatives living in the HH.
Code b: Current residence
1=Here and present, 2=Here but temporarily absent, 3=Lives elsewhere, 4=other, specify
Code c: Marital Status
1=Married, 2=Single, 4=Divorced/separated, 5=Widowed, 6= not applicable (for under age)

Part One: (cont…)

I.D. Code	Can [name] read a letter Yes … No ….0	Can [name] write a letter Yes … 1 No . 0	Does [Name] have the adult literacy program certificate Yes …….1 No ……. 0	Has [Name] ever attended or is he/she attending school? Attending school…1 Has attended in the past… 0 No…3 (next person)	Does name has specific training/qualification? 1=Yes, 2=No
01					
02					

1. Do you own land? -----------------------

Type of land	1=Yes	2=No
Irrigated		
Rain-fed		
Homestead		
Other, specify		

2. How do you get the land? ------------------
Code: 1=through land distribution, 2=family inheritance, 3=fixed rent, 4=Share cropping, 5=others, Specify------

Part Two: Plot level Data

Part Two: Land ownership and land quality

Plot name	Type of plot Code (a)	Plot size in tsimad	Ownership Code (b)	Soil type Code (c)	Soil depth Code (d)	Slope Code (e)	Land quality Code (f)	Susceptibility to erosion Code (g)	Degree of soil degradation Code (h)

Codes: a) Type of plot: 1=Irrigated, 2=Rain-fed

b) Ownership: 1=owner operated, 2=rented in (fixed), 3=sharecropped in, 4=other, specify

c) Soil Type: 1=Baekel, 2= Walka, 3= Hutsa 4= Mekeyih, 5= Other, Specify…………

d) Soil Depth: 1=Shallow, 2=Medium, 3=Deep, 4=Other, Specify………..

e) Slope: 1=Meda (plain), 2=Tedafat (foothill), 3=Daget (midhil), 4=Gedel (Steep Hill), 5=others Specify----

f) Land Quality: 1=Poor, 2=Medium, 3=Good, 4=Other, Specify…………

g) Susceptibility to Erosion: 1=High, 2=Medium, 3=Low, 4=None

h) Degree of Degradation: 1=Highly Degraded, 2=Degraded, 3=Moderately Degraded, 4=Not Degraded

Part Two: (cont…): Amount of hired labor in 1997 E.C

Plot Name	Type of plot Code (a)	Walking distance from home in hours/minuets (one way only)	Rental arrangement (in or out) Code (b	Total hired labor	Total hired/shared oxen (oxen days)

Codes:
a) Type of plot: 1=Irrigated, 2=Rain-fed:
b) Rental arrangement: 1=Owner operated, 2=Rented in (fixed), 3=sharecropped in

Part Two: (cont…): **Input used in 1997 E.C (Rain-Fed)**

Plot name	Belg (short rain season)						Keremti (Main rain season)					
	Fertilizer	Manure	Seed	Labor	Oxen	Other(specify)	Fertilizer	Manure	Seed	Labor	Oxen	Other (specify)

Part Two: (cont…): **Amount of production in 1997 E.C (Rain-fed)**

Plot name	Belg (short rain season)		Main season	
	Unit	Amount	unit	Amount

Part Two: (cont…): Input used during last year, 1997 E.C (Irrigation)

Plot name	First harvest						Second harvest					
	Fertilizer	Manure	Seed	Labor	Oxen	Other(specify)	Fertilizer	Manure	Seed	Labor	Oxen	Other (specify)

Part Two: (cont…): Amount of production in 1997 E.C (Irrigation)

Plot name	First harvest		Second harvest	
	Unit	Amount	unit	Amount

Part Three: Land Rental Market and Contract

Part Three: Land rental Market and Contract

Type of land rental contract	Have you performed any of these contract types during last year (1997 E.C)? 1=Yes, 2=No	Was it simple to make land rental contracts? 1=Yes, 2=No
Fixed rent in		
Fixed rent out		
Sharecropped in		
Sharecropped out		
Other, specify		

Part Three: (cont…): Land rent out (Landlord)

Plot name	Type of land Code (a)	Who was your partner? (Name)	Tabia	Kushet	What is your relationship with the tenant? Code (b)	Why did you rent out land? Code (c)	Do you have land which was not rented out? 1=Yes, 2=No	As a land lord, did you have many tenants to choose from? 1=Yes, 2=No

Part Three: (cont…): Land contract out

Plot name	Type of land Code (a)	How many tenants have contacted you?	Have you adopted the type of rent you preferred? 1=Yes, 2=No	Why you preferred this type of contract? Code (d)	How did you make the contract agreement? Code (e)	Have you faced any problem in enforcing the contract? 1=yes, 2=No

Part Three: (cont…): Land contract out

Plot name	Type of land Code (a)	What conditions matter for the renewal of contract to the same tenant? Code (f)	If the rental arrangement is share cropping, do you think that the tenant shrinks (deliberately avoid to work hard) 1=Yes, 2=No	If your answer to is yes, what mechanisms do you use to motivate the tenant? Code (g)

Code (a): Type of land: 1=Irrigated, 2=Rain-fed
Code (b): 1=Relative, 2=Neighbor, 3=Friend, 4=other, specify-------------------
Code (c) Code: 1=Shortage of labor, 2=having excess land, 3=Personal problem (e.g., illness, aged, etc), 4=Renting out is more profitable than own cultivation, 5=Shortage of oxen, 6=Seed problem, 7=lack of credit/cash, 8=credit obligations, 9=other, specify---
Codes (d): 1=reduce risk when crop fails, 2=it enables me to share input costs, 3=it gives incentive for the tenant to work hard,4=other
Code (e): 1=oral contract, 2=Written contract, 3=Use neighbor as witness, 4=report contract to tabia/village leaders
Code (f):1=amount of output, 2=Skill/ability/resource rich, 3=the tenant is relative, 4=the tenant is neighbor, 5=Land conservation, 6=other,
Code (g): 1=Quit the contract for the following season, 2=Increase the share of the tenant, 3=supervise the tenant closely, 4=other

Part Three: Land contract in (Tenant)

Plot name	Type of land code(a)	From whom did you rent in land? (Name)*	Tabia	Kushet	2 What is your relationship with the land lord? Code (b)	3 Why did you rent in land? Code (c)	4 Did you have your own land? 1=Yes, 2=No	5 As a tenant, did you have many landlords to choose from? 1=Yes, 2=No

Part Three: (cont…): Land contract in (Tenant)

Plot name	Type of land Code (a)	How many Landlords have you contacted?	Have you adopted the type of contract you preferred? 1=Yes, 2=No	What is the advantage of such type of contract? Code (e)	How did you make the contract agreement? Code (f)	Have you faced any problem in securing the contract the contract? 1=yes, 2=No

Code (a): Type of land: 1=Irrigated, 2=Rain-fed
Code (b): 1=Relative, 2=Neighbor, 3=Friend, 4=other
Code (c) 1=have more labor, 2=have more oxen, 3=have more finance and other resources, 4=have less land, 5=other
Code (d): 1=Fixed rental contract, 2=Sharecropping, 3=Wage contract, 4=Cost sharing, 5=other, specify
Codes (e): 1=Reduce risk when crop fails, 2=It enables me to share input costs, 3=It gives me incentive to produce more, 4=other, specify
Code (f): 1=oral contract, 2=Written contract, 3=Use neighbor as witness, 4=report contract to tabia/village leaders

Part Four: Irrigation and Irrigation technology

Plot Nam	Plot size	What is the source of irrigation water? Code(a)	How is water conveyed from the source to your plot Code(b)	Which one of these infrastructures do you prefer? Code(b)	Why do you prefer this infrastructure Code (c)	How do you lift water from the source? Code (d)	Where is the location of your plot from the water source		How long does it take to irrigate your plot (hours/minutes)
							Code(e)	Distance in meter	

Code (a): 1=Dam, 2=River diversion, 4=Drip/sprinkler, 5=Shallow well
Code (b): 1=Concrete canal, 2=Earthen canal (not concrete), 3=Flood, 4=Plastic covered canal, 5=Drip/sprinkler.
Code (c): 1=It saves water, 2=It saves time, 3=Irrigates more land, 4=Discharge more water at a time
Code (d): 1=Motorized pump, 2=Hand pump, 3=Foot pump (estihena), 4=pipe, 7=other, specify
Code (e): 1=Head tail, 2=Middle, 3=end tail

Part Five: Income and Asset Ownership

Part 5.1: Household Income

1. What do you think about your status of living? (Subjective view)
   Code: 1=rich, 2=medium, 3=poor, 4=others, specify----------

2. Can you please tell us the source and amount of your income during last year (1997 E.C)?

Part 5.1 (cont…): Household Income

Source of income	1997 E.C		
	Unit	Amount	Value(Birr)
Rain-Fed Agriculture			
Irrigated Agriculture			
Other Agricultural Activities			
Off-farm employment			
Transfers			
Self employment			

Part 5.2: Asset ownership (Productive and domestic assets)

Part 5.2.1: Durable Asset ownership

No.	Type	Amount (number owned)	Value (Birr)
	Farm implements(Tools)		
	Domestic Assets		
	Other		

Part 5.2.2: Livestock ownership in the last 12 months

Type of livestock	number owned beginning of last year(in 1997 September)	Number of sold	Number of died	Number of slaughtered	Number of Bought	Number of Owned at this time	Estimated Value (Birr)
Oxen							
Milk cows							
Goat/sheep							
Poultry							
Beehives							

Part Six: Food Security, Coping Mechanism and Access to Credit

Part 6.1: Availability of Food during each month of last year (1997 E.C)

1. during which month of last year (1997 E.C growing season) did your household had enough or shortage of food? (enough or not enough)

	Enough	Not enough
January		
February		
March		
April		
May		
June		
July		
August		
September		
October		
November		
December		

Part 6.2: Coping Mechanisms

2. Which of the following can you say was true for your household at any point in time during last year as a coping strategy of food shortage?)

	Yes	No
Sold productive assets		
Consume seed stock		
Eat food normally we do not eat (wild food)		
Eat less preferred food		
Sought daily work outside farm		
Migrated to find work		
Borrowed cash or grain		
Eat fewer meals per day		
Reduced quantity of food per meal		
Sold cultural items		
Sold animals		
Sold household effects (utensils, etc)		
Sold firewood		
Made and sold of charcoal		
Rented out land		
Withdrew children from school		
Sold safety items		
Distressed migration		
Looking for relief		

Part 6.3: Credit and Saving

1. Do you have access to different types of credit sources? Please give the details in the following table

Source/Type of credit	Access	
	Yes	No
Dedebit Credit and saving institution(DECSI)		
State bank		
Private bank		
Farmer association		
Cooperative		
Other, specify		

Part 7: Community Level Data

1. Average annual rainfall
2. Agro-ecology
3. Altitude
4. Population

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The thesis consists of an introduction and four independent papers. It investigates the role of production risk and irrigation investment on farm households' production decisions, efficiency, and income. Paper I analyses whether land rental contract choice depends on poverty, capital constraints, production risk and random shocks. It shows that poor households experiencing random shocks are more likely to choose fixed rent contracts as a distress response to shocks implying that fixed rent contracts may be used to meet immediate needs. It also revealed that fixed rent contracts are preferred when production risk is low (such as in irrigated land), while sharecropping is more likely when production risk is high. Paper II examines how production risk, access to irrigation, and food deficits affect households' fertilizer adoption. A positive and significant synergy exists between irrigation and fertilizer use, while a negative relationship exists between risk and fertilizer adoption. A higher probability of households being food self-sufficient was negatively associated with the probability of fertilizer use. Similarly, food deficit households predicted to be so were less likely to use fertilizer. However, the food deficit households who decided to use fertilizer, used significantly higher amount of fertilizer than households that did not face food deficit. Paper III assesses the technical efficiency of farmers on irrigated and rain-fed land. It also assesses whether irrigation expands the smallholders' production frontier, and whether there is a room to increase agricultural production given the current input use and technology. Results indicate that irrigation has expanded the production frontier, but farmers are more efficient on their rain-fed plots than irrigated plots suggesting that that there is huge untapped potential in irrigated agriculture. Paper IV assesses the income effects of irrigation investments and finds that irrigation investment has significantly improved household income and reduced poverty. Groundwater-based irrigation projects have higher income effect than micro-dam and river diversion suggesting that the use of water-saving technologies (such as pressurized tube irrigation and manually operated shallow-well) may reduce water losses due to run-off and excess percolation.

Professor Stein Holden was Gebrehaweria's advisor.

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