Economic Analysis of Water Harvesting Technologies in Ethiopia

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Mekonnen Bekele Wakeyo

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To: Ayantu, Milki and Hildana
&
My parents

ABSTRACT

Rainfall shortage and variability constrain crop production of smallholder farmers in Ethiopia and climate change may even aggravate this problem. An attractive method to mitigate this is water harvesting. This thesis examines the economic aspects of water harvesting by exploring optimal water use and the impact of water harvesting using micro-econometric analyses of cross-section and panel data collected from Ethiopian farmers in 2005 and 2010.

In the first empirical chapter, the study estimates marginal values and elasticities of harvested water in the production of three vegetables to determine whether water allocation is economically optimal. The results are mixed, although the estimated marginal product values between onions and tomatoes show that farmers on average allocate water economically across these two crops.

The descriptive data show that the share of irrigated land is lower at larger farms. Because farm size may increase in the future, it is interesting to investigate what determines the share of irrigated land in relation to farm size. A random-effects tobit model is appropriate to estimate this relationship. The result shows that access to both credit and markets, farm-size, region, aridity, and plot distance to water source all affect the share. Encouraging water harvesting requires flexible and effective variables that will work also for larger farms.

Despite its weather-risk reducing advantage, the average disadoption rate of water harvesting technology between 2005 and 2010 was as high as 42%. To find out why farmers disadopt, binary choice models are estimated to investigate the factors that cause disadoption. Based on the estimation results, it is concluded that increasing availability of plastic sheets and labour-saving equipment (water pumps), easier market and credit access, and the cultivation of perennials can reduce disadoption.

The last empirical chapter focuses on the relation between water harvesting and fertilizer use. Due to weather risk, farmers may limit the use of purchased fertilizer, thereby continuing to grow a high share of low-risk and low-yield crops. To establish whether harvested water encourages fertilizer use, two variants of random-effect models are estimated. The results strongly support the idea that water harvesting technology induces fertilizer use, indicating that water harvesting can increase fertilizer use- and hence crop yields- in Ethiopia.

The concluding chapter discusses the results against the background of the research objective: what are the economics of water harvesting at micro level?

Keywords*: water-harvesting, micro-econometric analysis, panel data, Ethiopia*

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CHAPTER 1

INTRODUCTION

1.1 Background

Agricultural water shortage is a critical problem for Ethiopian smallholders producing crops. Crop production in Ethiopia is mainly rain-fed and rainfall shortages and variability constrain yields. This led some Ethiopian smallholders to start using water harvesting technologies including ponds, shallow-wells and river/stream (flood) diversions. The objective of using those technologies is to preserve harvested water and curb the negative effect of rainfall shortage and variability. Under normal weather conditions, rainfall provides a gross quantity of water and crops use the water remaining after evaporation. However, rainfall shortage often occurs and the shortage hinders crop growth and limits yields. The consequences of low yields are reduced income, food insecurity, and poverty (Levy et al. 2004; Fox et al. 2005; Ruttan, 2002). More severe cases of rainfall shortage or drought often lead to starvation.

Rainfall variability, which is the variation in the amount, timing and duration of rainfall, provides additional problems. While the shortage of rainfall decreases yields directly by restraining a minimum crops growing condition (de Wit, 1992), the variability influences yields by affecting the behaviour of smallholders in developing countries in two ways: through its influence on their crop choice decisions and their modern inputs use decisions. With rainfall variability, farmers who have no alternative water sources tend to grow traditional low-risk and low-value crops in order to avoid the loss of purchased inputs in cases of crop failure (Dercon, 2005, 1996; Rosenzweig and Binswanger, 1993). Studies carried out in India and Tanzania confirms the hypothesis that a lack of assets increases risk-aversion and risk-averse farmers grow relatively low-risk and low-value crops (Dercon et al. 2005). With high rainfall variability, instead of buying expensive modern inputs such as fertilizer and improved seeds with a risk of losing them due to the unpredictable rainfall, farmers prefer to keep using ‘cheaper’ traditional technologies. They continue to produce crops with their old technology because it is integrated into their years-long knowledge and perception of the rainfall variability (Dercon, 2005; 1996; Ruthenberg, 1976).

Often, the negative effects of rainfall shortage and variability can be decreased by using water storage and irrigation technologies and increasing the land under irrigation. Overcoming rainfall shortage by supplementing from irrigation relaxes the most limiting crop-production factor, i.e. water, optimizes the crop-growing conditions (de Wit, 1992) and facilitates the functioning of other inputs. Water for (supplementary) irrigation can be stored using dams, ground water reservoirs, ponds or shallow-wells. Countries with water storage systems overcame the negative effect of rainfall shortage and variability in crop production and achieved better yields than countries without these systems. Evidence shows that the average national yield achieved by several countries seems to correspond with their water storage or irrigation capacity (Grey and Sadoff, 2006).

The water harvesting technologies (WHTs) used by smallholders in Ethiopia enable water storage (capacity) for irrigation. These water stocks are expected to curb the negative effects of rainfall variability and enhance yields. There are two reasons that yields can be enhanced using WHTs. First, farmers can use the harvested water to fill the moisture shortage gap when rainfall shocks occur, for instance, when rainfall ends before the ripening of crops. Second, farmers using these technologies are also expected to use modern inputs and to produce high-value crops because of the reduced weather risk. Due to rainfall shortage and variability and lack of irrigation, however, Ethiopian farmers have low crop yields that may lead to food shortage. Food shortages have happened in other countries in the past as well. However, many countries overcame the incidence of food shortages by increasing yields. For a drought-prone country such as Ethiopia, therefore the availability of water for (supplementary) irrigation is an important condition for increasing yields. Recent figures show that Ethiopia irrigates only about 1.5% of its cultivated land (IFAD, 2009) and there is a scope for expanding WHT irrigation among the Ethiopian smallholders, who cultivate 95% of the farm land.

Even though it may seem different, water sources for irrigation in Ethiopia exist that could increase the low percentage of irrigated land. For instance, more than twelve river basins are suitable for large-scale irrigation. However, investment in large-scale irrigation has many caveats (Khan and Hanjira, 2008; FAO, 2006; 1997). For example, the landholding system is often a major restriction. If individual landholding is small and dispersed, it limits the scale of operation. Also, the number of beneficiaries per scheme is often large and the cost of maintaining a cooperation to use large-scale irrigation is relatively high. In addition, communal lands without explicitly defined property rights make investment on large-scale irrigation complex. Another constraint that contributed to the ineffectiveness of large-scale irrigation is ownership and management (Shah et al. 2002: 1-5). Most large-scale irrigation projects in Africa were financed by donors and owned and managed by governments. Government ownership and management is, however, inefficient in many respects, characterized mainly by financial shortfalls for operation and maintenance (see Shah et al

2002: 1-5; Meinzen-Dick, 1997; Meinzen-Dick et al. 1997; Rosegrant and Meinzen-Dick, 1996; Wade and Seckler, 1990; Adams, 1990). Adverse environmental impacts such as siltation and water logging cause a loss of substantial amounts of land each year; prevalence of water-related and water-borne diseases also contributed to the low performance of large-scale irrigation (Khan and Hanjira, 2008; FAO, 2006; Adams, 1991). Coupled with the lack of road infrastructure and markets, returns decreased (FAO, 2006; 1997; Adams, 1991; 1990) and due to these constraints, large-scale irrigation often failed in Africa (FAO, 2006; Morris, 1987) and could not curb the negative effect of rainfall shortage and variability as expected.

Although small-scale irrigation technologies in Africa are also not free of criticism (see Adams, 1990), the failure of large-scale irrigation and the huge resource requirement for investment have led the Ethiopian government to stimulate small-scale irrigation. Farmers in Ethiopia started adopting small-scale WHTs in the early 2000s with the aim of overcoming the risk of rainfall variability for smallholders. The rationale is that the distribution of rainfall is unpredictable and spatially uneven which urges to capture and use the run-off. Moreover, water harvesting overcomes some of the limitations of large-scale irrigation mentioned above. For instance, it is individual-farmer managed, unlike the large and medium-scale irrigation, which is often managed by cooperatives or water users associations. Ethiopian farmers have had negative experiences with the cooperative concept, which could make the sustainability of cooperative management questionable (IFAD, 2009). Since water harvesting is a private venture, it is a preferred option. In addition to the advantage of individual management, water harvesting fits with the Ethiopian smallholder land tenure system. Farmers can locate as many of those ponds and shallow-wells on their plots as they want, if they intend to increase their own scale of operation. In addition, because of the defined land-use right through land certification to individual farmers (Deininger et al. 2008) relatively few water use right conflicts arise between farmers. Up- and down-stream conflicts are rarely seen in WH irrigation. From an environmental perspective, water logging and siltation could be lower compared to the case of large-scale irrigation. Field observations show that with water harvesting, biodiversity recovers and soil moisture improves, in line with the conclusions of Vohland and Barry (2009).

Given that these WHTs are individual ventures, at the individual household (micro) level, there are a number of microeconomic aspects that are interesting to study. Mainly, individual households invest in them, use them and decide independently on water allocation unlike the communal decision-making in conventional irrigation common in developing countries. With individual ownership, farmers have an incentive to allocate water efficiently and to decrease costs through innovations. By collecting data on water harvesting technology decisions at household level, it is possible to investigate these microeconomic issues.

Water harvesting technologies are relatively new to most Ethiopian farmers, which makes it interesting to study its adoption. The theory of technology adoption suggests that potential users fail to adopt due to lack of information, risk-aversion, resource constraints, economic returns, and perceptions on the technology (Adesina and Zinnah, 1993). Rogers (1995, pp.5-35) suggests that if a technology is appropriate (the technology fulfils perceived attributes such as relative advantage, compatibility, complexity, trialability and observability), access to information determines its adoption. Similarly, risk could be another factor influencing the decision to adopt or not. For instance, farmers might avoid the risk of adopting a technology due to lack of information on labour and other complementary inputs requirements. This risk-averse behaviour typically plays an important role mainly with asset-poor farmers (Rosenzweig and Binswanger, 1993). Economic constraints such as land, labour, and capital scarcity (Suri, 2011; Sunding and Zilberman, 2001) also affect adoption. Many of the arguments from the theoretical literature on technology adoption also apply to the adoption of the risk reducing water harvesting technology. An additional issue in the case of water harvesting is the government intervention in stimulating the adoption. When the water harvesting technology was introduced, government institutions stimulated adoption by providing some incentives (e.g. subsidized plastic sheets) to farmers. This incentive may have affected the pace of adoption, i.e. faster than it would have been without intervention. Higher initial adoption rates could lead to disadoption later because farmers become disappointed in the returns and risk-reducing nature of the technology. Even though it is difficult to measure the exact degree of intervention, it is interesting to investigate these adoption-disadoption issues. Rogers (2003: 161) highlighted the role of public institutions in technology adoption but there are relatively few empirical studies on the role of public institutions.

Although individual-owned water harvesting schemes have been applied for many years in other countries, e.g. in India (Agrarwal and Narain, 1997) and China (Li et al. 2000), they are relatively new to Ethiopia and the rest of Africa. Correspondingly, only few studies focused on water-saving (Blanke, et al. 2007), yield impacts (Fox et al. 2000) and the economic feasibility (Mushtaq, 2007) of WHTs. Some of these studies indicate that WHTs are used to supplement rain-fed agriculture or to reduce risk (Rockstrom, 2000) and this lower risk encourages growing high-value crops and perennials (Marques et al. 2005).

1.2 Problem Statement

Understanding whether harvested water is economically optimally allocated among the most frequently grown crops is essential since the opportunity cost of investment for resource poor farmers is high. The labour costs are substantial; farmers have to also allocate part of their scarce land to ponds and have to buy construction materials such as plastic sheets. Therefore, generating optimal benefits per unit of water from a particular crop is required. In a water-scarce environment, maximization of yield per unit of water is a better strategy than yield maximization per unit of land, and this requires efficient water management (Ali and Talukder, 2008). To investigate whether farmers apply or manage the water so that it generates the highest marginal benefits requires estimating and comparing value marginal products(the additional output produced from one more unit of input multiplied by the output price) of water for different crops. The estimated value marginal products show whether the farmers have over- or underused the harvested water to certain crops and whether it can be reallocated to a more economical use.

The quantity of harvested water to be allocated depends on crop choice and the scale of operation for a specific crop, given a farmer's fixed landholding. Preliminary data from two survey rounds shows that few farmers allocated harvested water to all of their land. The majority of farmers allocated it on only part of their land or none of it at all. In the latter case, they use it for their livestock or for their household, or totally abandoned the system. Given that water harvesting can reduce the risk of rainfall shortage and variability, it was expected that farmers would supplementary irrigate a substantial share of their land. Interestingly, the survey data shows that the share of irrigated land declines with farm-size. A lower share of irrigated land for larger farm-size suggests that the technologies become less relevant when farm-size increases, implying that water harvesting is less attractive when the scale of agriculture increases e.g. to commercial farms. Literature suggests reasons for allocating only a portion of land to a new technology, e.g. experimenting (Foster and Rosenzweig, 1995), labour shortage (Moses and Barrett, 2006), crop choice (Moreno and Sunding, 2005) and economic viability (Suri, 2011). It is interesting to know whether these reasons could also explain the lower share of irrigated land for farms with a relatively larger size.

In crop production, the reasons for low technology adoption rates have been a constraint to yield increases. Reasons for low adoption rates have been investigated in a number of studies (Sunding and Zilberman, 2001; Feder et al. 1985). Similar to low technology adoption rates, high disadoption rates of new technologies could undermine yields. Disadoption of a technology can be defined as using a technology for some time and abandoning it later on (Wendland and Sills, 2008). The theoretical literature suggests two major causes of disadoption: replacement and disenchantment. The former refers to the replacement of an old technology with a new one, whereas the latter refers to disadoption when a technology is inappropriate to achieving perceived benefits. With regard to water harvesting in Ethiopia, disenchantment factors seem more relevant than replacement cost factors, because technologies replacing water harvesting have not been introduced recently, except in areas where rivers are available and where other irrigation methods cannot be used (e.g. irrigation using river water and motor pumps). With respect to the disenchantment factors, economic constraints (Suri, 2011) such as labour, land, financial constraints and factors affecting the availability of harvestable run-off could be responsible for disadoption. In addition to these factors the interventions of institutions that stimulate the adoption and use of water harvesting technologies (e.g. by providing expert advice, training) could also affect the dynamics of using these technologies.

Beyond serving as a mechanism to decrease water shortage in a low rainfall season, irrigation gives farmers the confidence to use modern inputs such as fertilizer (Smith, 2004; Lamb, 2003). This is because the functioning of fertilizer nutrients in crop production depends on the availability of sufficient water, in line with Von Liebig's agronomic principle of law of the minimum (de Wit, 1992). If sufficient water is available, the water dissolves the fertilizer nutrients so that roots can properly absorb the nutrients and yields increase. Variability in rainfall has a negative impact on farmers' decisions to use modern inputs (World Bank, 2006), so the use of water harvesting technology that reduces the risk of rainfall variability may also encourage the use of fertilizer. Moreover, fertilizer subsidies or policies that increase access to modern input such as fertilizer maybe ineffective in arid and semi-arid environments, since sufficient water is a precondition for fertilizer use. Therefore, investigating the impact of water harvesting irrigation on the use of other productivity-increasing inputs is very relevant. On the other hand, fertilizer use could also motivate the use of water harvesting so that scheduled application of fertilizer to plots is exercised. This is because farmers using nitrogen fertilizer try to minimize nitrogen losses by controlling the timing of fertilizer application during the crop growth period (Lisson and Cotching, 2011; Haefele et al. 2003; Shapiro and Sanders, 1998; Huang et al. 1993). This latter reason leads to see whether previous fertilizer use in turn stimulates the use of water harvesting technologies.

1.3 Objective of the thesis

The general objective of this thesis is to examine the economic aspects of water harvesting irrigation technology and its dynamics in Ethiopia. Specific objectives are to

i. Estimate the marginal value of harvested water and investigate whether harvested water is applied in an economically optimal way in three most frequently grown vegetables.
ii. Examine why the relatively larger farms show a lower share of irrigated land.
iii. Examine why some of the households prefer not to continue the use of small-scale water harvesting irrigation technologies.
iv. Examine if the use of water harvesting induces the use of fertilizer.

The first objective is selected because learning whether harvested water is optimally allocated is an issue that has to follow irrigation technology choice. Ali and Talukder (2008) underlined an important point in relation to this. They remarked that finding a technology to improve water productivity is easy but to learn whether the technologies are economical and how to improve their economic optimality is not well researched. Investigating whether water allocation is economical is therefore important from this perspective. With regard to the second objective, if WHT is expected to reduce risk, a fall in the share of irrigated land with farm-size could imply a decreasing role of WHT with commercialization. Unlike conventional irrigation, where farmers share the water and have little room to manipulate land allocation between irrigation and rain-fed, in individual-held WHT manipulation is possible. However, a falling share with farm-size could arise and investigating the causes would help establish how to increase it. The third objective looks into disadoption, a spoken issue in Ethiopia. Outsiders idly suggest that factors such as malaria cause disadoption whereas there may be several other relevant factors. Its investigation here provides lessons to learn. The findings could give insight into sustaining WHTs in the risky weather condition of Ethiopia, where conventional irrigation has many disadvantages. Finally, as a new risk- reducing technology, the potential impact of WHT motivates curiosity in the high weather- risk country. Weather risk constrains modern input use in Ethiopia and irrigation is theoretically linked to the increase of modern input-use by decreasing the risk. If the link does actually exist, increased adoption of water harvesting may increase the current low fertilizer use rate of Ethiopian smallholders.

1.4 Methodological approach and data

To achieve the objectives mentioned, microeconomic theories of production (under risk) and input demand as well as the theory of technology adoption and disadoption are used as theoretical foundations. Based on these theories, various micro-econometric techniques are used to analyse the collected cross-sectional and panel data. Micro-econometric analysis is chosen for the analysis because the economic decisions related to WHTs are farm-level decisions, the household-head being an economic decision-maker. The household head makes micro-economic decisions such as adoption of the WHT (investment), allocation of water to production, whether to continue or drop WHT, and so on.

Specifically, to meet the first objective of this thesis, it is assumed that producers are price takers and that they maximize profits given output and input prices. Profit maximization implies equating the value marginal products (VMPs) to the marginal costs of input. Based on this assumption of the microeconomic theory of production, both the standard trans-log production function (Mas-Colell et al. 1995:39-45) and the asymmetric production function (Zhengfei et al. 2006) are estimated for three most frequently grown vegetables by harvested water in Ethiopia using econometric analysis. Since each model has its own disadvantage, this makes a comparison of the outputs and the test results necessary. After estimating the production function, marginal products, VMPs and elasticities are computed for each input in each vegetable, and compared. The study uses data from 536 households collected in 2005.

To meet the second objective, decisions on the share of irrigated land are modelled by combining the Just and Pope (1978) production function and acquisition cost investment theory (e.g. Hirshleifer, 1987). The model assumes that the higher the share of land under irrigation, the lower the probability of facing weather risk. Increasing the size of land under irrigation, however, depends on the quantity of harvested water, which in turn depends on the investment on the physical structure of the schemes and on water-lifting equipment. Based on the microeconomic theory of production under risk, the Just and Pope (1978) framework that explicitly considers production risk to analyse how farmers decide on the share of irrigated land, land allocation decision making by Ethiopian smallholders is modelled in this chapter. The theoretical model captures the factors affecting the decision of three household categories- those who irrigate all, part of, and none of their lands. Then, a random effect tobit model is estimated for 400 panel households (800 obs.) to identify factors explaining the share of irrigated land. A tobit model is usedfor two reasons. First, the dependent variable is a continuous variable with its value between zero and one. Other models such as logit or probit can only be used to analyse discrete dependent variables, but not a continuous dependent variable. Second, tobit allows the use of data not only from users of water harvesting who have a certain irrigated land share but also from non-users (non-adopters & disadopters) with zero irrigated land share.

To meet the third objective of investigating why farmers disadopt water harvesting technologies, the concept of disenchantment is used to study the causes of disadoption. It suggests that disadoption occurs when a technology is inappropriate to achieve the expected benefits. The expected benefits are functions of variables that are discussed in the technology adoption literature (Suri, 2011; Sunding and Zilberman, 2001). In addition, the environmental and technology-specific factors are also discussed. In the empirical analysis, unlike several previous studies (Barrett and Moses, 2006; Neill and Lee, 2001; Cameron, 1999), this study assumes that for a household to disadopt, adopting a technology in the past is a precondition, analogous to the fact that for a divorce, a marriage in the past is a precondition. Accordingly, a household that adopted water harvesting in or before 2005 is recorded in the 2010 survey as either a continuer or a disadopter. A total of 332 panel households, of which 199 continued to use water harvesting and 133 stopped using it in 2010, are used in the empirical analysis. Based on the Hausman-Taylor panel data estimation approach (Hausman-Taylor, 1981), a linear probability model is estimated to learn why certain farmers disadopted. In addition to the Hausman-Taylor approach, a probit model using differences of time-varying variables and 2010 levels of time-invariant variables are also estimated for comparison.

To investigate whether the use of water harvesting has a causal effect on fertilizer use, first the potential endogeneity of the treatment variable, i.e. a use dummy for water harvesting, has to be tested. If the treatment variable is not found to be endogenous, then a panel probit model can be estimated to investigate whether harvested water induces fertilizer use. However, if the treatment variable is found to be endogenous, instrumenting is necessary. In addition to testing the impact of the treatment variable, the two variables might have a reverse causality that fertilizer use could in turn stimulate water harvesting. This makes it necessary to estimate a bivariate probit model. Due to the possible joint effect between the use of water harvesting and the use of fertilizer as two new technologies, a bivariate probit model can be estimated for the use of water harvesting and use of fertilizer in 2010 by including the lagged values of the two endogenous variables. The empirical analysis uses panel data of 800 observations (400 households).

1.5 Outline of the thesis

This section briefly highlights the next 6 chapters. The 2nd chapter discusses the study area and the sampling procedure used in the 2005 and 2010 surveys. The chapter also discusses the overall climatic conditions that informs why water harvesting is necessary in Ethiopia and provides an overview of the technologies. Chapters 3 to 6 are articles submitted to scientific journals for publication. Because of this, the general data description in chapter 2 could overlap with the more specific data descriptions in those chapters.

Chapter 3 deals with estimating the marginal value of harvested irrigation water in vegetable production. It involves estimating production functions and computing marginal products, value marginal products and elasticities to analyse the optimal allocation of harvested water in the three frequently grown vegetables, i.e. onion, tomato and green pepper.

Chapter 4 investigates why the share of irrigated land falls relative to farm size. To explore this, investment decisions of individual households in water harvesting is modelled. Based on the model, factors responsible for the low intensity of the use of water harvesting technologies are identified and tested.

Chapter 5 analyses why some households disadopt water harvesting despite the hypothesized economic and risk reducing benefits.

Chapter 6 explores whether water harvesting induces fertilizer use. It explores the impact of water harvesting comparing users and non-users.

Chapter 7 discusses the key conclusions, suggests areas of useful intervention for Ethiopia and other developing countries, provides a critical reflection and finally gives directions for subsequent research.

CHAPTER 2

DESCRIPTION OF THE STUDY AREA AND SURVEY DATA

2.1 Introduction

This chapter discusses the study area and its climatic conditions, the survey data used for the empirical analysis, and the sampling procedures. Section 2.2 highlights the location of the sample regions. Section 2.3 discusses the geographical and climatic conditions in the region that illustrate why water harvesting technologies are useful in Ethiopia. Section 2.4 describes the institutional and technological aspects of the water harvesting small-scale irrigation program. Section 2.5 discusses sampling procedures and the panel survey. Finally, section 2.6 provides an overview water harvesting technologies.

2.2 Location and sample regions

This study focuses on four of the nine regions of Ethiopia, namely Tigray, Amhara, Oromia and the Southern Nations, Nationalities and People's Region (SNNPR). These regions were selected because of the degree of water harvesting practices, the livelihood (dominance of crop production) and because of survey resource constraints to include all regions (Gezahegn et al. 2006). About 86% of the total population and 90% of the rural population of the country live in those regions (CSA, 2008). The area of the four regions combined accounts for 60% of the total area of the country. The four sample regions are predominantly plateaus, but topography and climate are diverse. As the country is located in the tropics (9^o01'N latitude and 38^o44'E longitude), no significant variation exists in day length and the angle of the sun throughout the year. Due to the diversity within each region, the rainfall and temperature variation is large. For instance in the largest region Oromia, in its western part substantial areas are within 2000 - 2500mm annual average rainfall whereas in its central and eastern zones, many areas are within 500 - 1000mm average annual rainfall. The variation of the amount of rainfall between the zones in other region is also substantial. In addition to the diversity in the quantity of rainfall in each region, high rainfall variability is common at national level. Rainfall variability measured by the coefficient of variation (CV) ranges from 20-62 (World Bank, 2006). In South and Eastern Oromia, Southern SNNPR and West Tigray rainfall variability is highest (CV of 30-40) and in western Oromia and Amhara it is lowest (CV of 20-25). Rainfall seasonality varies from region to region and therefore it is difficult to forecast the amount and nature of rainfall (Gissila et al. 2004).

On average, in these regions about 85% of the population lives in rural areas and earns their livelihood in agriculture. The livelihood is characterized by mixed farming systems i.e. crop production and livestock rearing. FAO (2009) reported that 97.6%, 99.3% and 92% of the national cereals, pulses and vegetables production respectively originate from these four regions. Water stress is a universal problem (Gezahegn et al. 2006) and rainfall shortage and variability does not only undermine crop production but also livestock rearing. As a result, food insecurity is a chronic problem. To mitigate the problem of weather shocks on crop production and indirectly on income and food security, a program to simulate the adoption of water harvesting was introduced into the four regions.

2.3 Climatic and rainfall conditions

Variations in altitude and wind directions together with amount of daylight determine rainfall, temperature, rainfall regimes and cropping seasons in Ethiopia. A rainfall regime is defined as the character of the seasonal distribution of rainfall at any place. The rainfall regime affects the surface water flows and both determine the potential for water resource management, including water harvesting (Osman and Sauerborn, 2002).The relation between these regimes and the potential for harvesting rain-water are well discussed in Admassu (2004).

Ethiopia has three rainfall regimes (UNICEF, 2004; Bekele, 1997): unimodal (single maxima), bimodal-A (quasi-double maxima) and bimodal-B (double maxima), see figure 2.1.

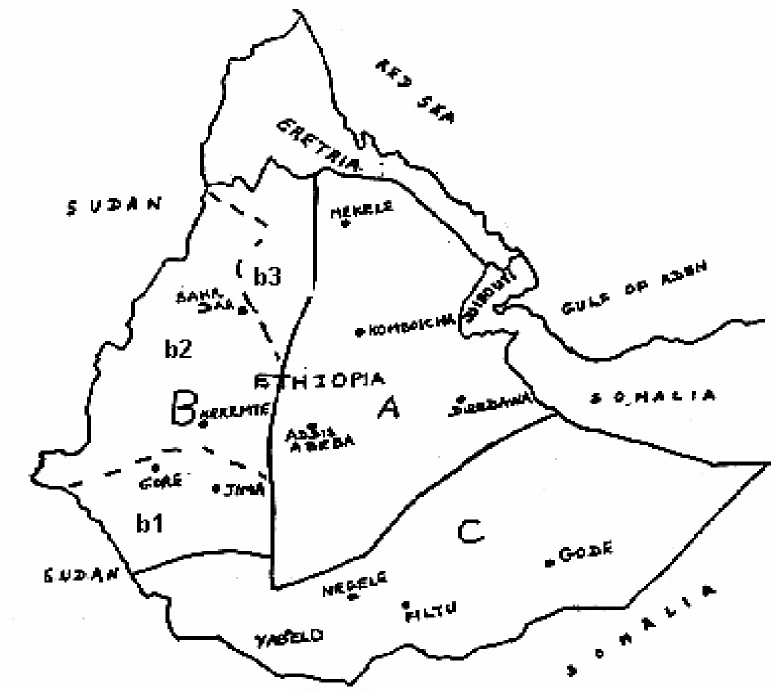

Figure 2.1 Rainfall regimes of Ethiopia (Bekele, 1997)

The unimodal (single maxima) regime, indicated as area B in figure 2.1, includes south western areas where the maximum average annual rainfall is about 2500mm. Within this regime from the Southwest to the North, rainfall declines. For instance, the maximum number of rainfall months in the Southwest is 10 but decreases to 4 as we move to the North. The peak rainfall months in this regime are shown in b1, b2 and b3, where the rainy season runs respectively from February to October, April to October and June to September (Bekele, 1997). The unimodal rainfall regime at least touches the four regions but largely extends over Oromia and Amhara. The second regime, bimodal-A (area A), has rainfall peaks in April and August, with a long winter rainfall extending from June to September and a short rainy autumn extending from February to May. The dry period is from October to January. Among the sample regions, central and east Oromia, east Amhara, north SNNPR and east Tigray fall in this regime. The third regime bimodal-B (area C) has two rainfall and two dry-periods. The sample areas fall outside this regime.

The National Meteorological Service Agency/NMSA (1996) identified three growing zones in Ethiopia related to the rainfall available for growing crops: areas with zero, one and two growing periods. Disturbances in the weather system, the direction of wind, temperature interaction around the Mediterranean, South Atlantic, Indian Ocean, African and Arabian land masses, and the Ethiopian topography determine the quantity of rainfall and the length of growing season (NMSA, 1996). One can ask what causes changes in rainfall and length of growing seasons in this region. Various researchers investigated the causes of the rainfall shocks around the Horn of Africa. Wolde-Georgis (1997) reviewed and summarized those studies concluding that the physical processes of El Niño-Southern Oscillation events thousands of kilometres away, along with sea-surface temperature in Southern Atlantic and Indian oceans, combined with human activities on the environment disturb growing seasons in Ethiopia. The disturbance of the growing season has been occurring for long time already. For instance 1618-1619 were El Niño years causing drought in Ethiopia during1618 (Webb and Von Braun, 1994). Similarly, the El Niño and their drought effect is prevalent these days with its disastrous effect of starving 3-15 million Ethiopians each year (WFP, 2004). Not only Ethiopia, but also many other African countries could not control the negative effects of weather change and as a result chronic food insecurity is a long standing problem.

The average minimum surface flows in Ethiopia occur from December to March and the peak run-off occurs from June-September. The annual run-off is estimated to be 122 billion cubic meter in 12 river basins but 97% flows to the lowlands of neighbouring countries (UNICEF, 2004).

Run-offs can be used by smallholder farmers after catching it individually in water harvesting schemes. Surprisingly, only 5% of the run-off is used so far (World Bank, 2006). Investments in such schemes capture the random and geographically unbalanced run-off. The availability of run-offs in the season combined with the drought vulnerable population in the four regions urge the use of this water. However, although run-offs are available, settlement patterns, lack of awareness about the technologies and the techniques and resource constraints often limit their use by smallholders.

In the four sample regions rainfall shocks often occur from mid-September to mid-October, which is within the major cropping season and from mid-March to May, the second cropping season. The data collected in both 2005 and 2010 indicate that farmers listed the months of March, April, May and June as major rainfall shortage months. The reason for introducing water harvesting was mainly to protect farmers from the rainfall shocks happening at the end of the first cropping months (September and October) rather than in the second growing season. However, farmers listed months of water shortage in the second growing season more than in the first. This means that instead of using the harvested water to overcome rainfall shortage in the first cropping season, they use it to grow high-value crops that can be harvested relatively quickly such as vegetables in the second growing season. The reason could be that these high-value crops grown in the second growing season help them to overcome the food shortage (either by selling them and buying food grain or using them for home consumption e.g. potato, cabbage), when they exhaust their grain stock in the winter. In a typical year, poor Ethiopian farmers often exhaust their grain stock during June to mid-August if they miss the harvests of the second season.

2.4 Institutional and technological aspects of the national water harvesting program

The major economic policy documents in Ethiopia are the Poverty Reduction Strategy Papers (PRSPs). Successive poverty reduction strategies were planned over 2002/03-2004/05 and 2005/06-2009/10 periods (MoFED, 2006) and implemented. The growth and transformation plan (GTP) that covers the period 2010/11-2014/15 is on implementation (MoFED, 2010). In all these successive strategies, five pillars of the economy are distinguished[1] and the Water Sector Development Program is one of those pillars. The Water Sector Development Program

[1]Includes agricultural development led industrialization, Education, Health and food Security.

has a 15 years implementation period and it serves the goal of poverty reduction within the *Water Resource Management Policy 2001* framework (Ministry of Water Resources, 2001). The policy gives a way to the long, medium and short-term water resource development plans. The use of water resources for irrigation is underlined as a basis to overcome weather risk and mainly water harvesting is given a priority. This means that to mitigate the risk of rainfall shortage and ensure food security, national and regional governments introduced a program that stimulates the adoption of WHTs early 2000s. The use of supplementary irrigation using harvested water was expected to fill the moisture shortage particularly during the ripening periods of food crops. Water harvesting technologies were introduced because studies confirm that weather risk is a major threat to productivity (Legesse, 2003; Dercon, 2002) and hinders modern input use.

Ethiopia has 18 diverse agro-ecologies that require diverse approaches to develop natural resources including water resource (MoARD, 2000). However, it seems that diversity is not taken into account when a program is designed. For instance, only two fertilizer types with different rates of application are used but the soil types are nineteen (MoARD, 2000). Water harvesting was introduced with similar shortcomings. It was unanimously stimulated in most of the regions without considering the geographical diversity. In addition, the way water harvesting was introduced seems to be top-down in that insufficient pilot programs and insufficient consultation with farmers was carried out. Farmers were just provided with the menu of water harvesting technologies and trainings. As a result, high disadoption rates occurred. Moreover, by and large, farmers used water harvesting to produce high-value crops instead of for cereal production as expected by policy makers. This may be because of the small quantities of water harvested and lack of capacity to collect more water or due to the better marginal returns from the high-value crops compared to other crops.

The Ministry of Agriculture and Rural Development (MoARD) was responsible for coordinating the program that introduced water harvesting. Accordingly, the Regional Bureau of Agriculture and Rural Development (BoARD) and sub-district BoARD implemented it. At local levels, sub-district *(woreda)* experts of BoARD and extension agents, in collaboration were providing assistance to farmers. Moreover, the sub-district BoARD experts trained local extension agents from peasant associations (PAs). Sub-district experts and extension agents trained farmers in harvesting water. When water harvesting was stimulated, construction materials such as plastic sheets and cement were transported to the sub-district BoARD, so that farmers could buy and use it if they choose to adopt water harvesting. The sub-district

BoARD trained farmers on how to select sites, construct schemes, etc. The objective of the program was to improve rural income and food security and therefore farmers that are found in food insecure areas were encouraged to start using water harvesting technologies. But the program did not target a specific group of farmers. Adopters of WHT, however, tend to use the water to produce vegetables and perennial high-value cash crops.

Recently, paying more attention to irrigation, the government established the Irrigation Agency at national level. Attention is paid to small-scale irrigation such as water harvesting in the growth and transformation plan (GTP) of Ethiopia (MoFED, 2010). The recent establishment of an Irrigation Agency is an institutional setup to strengthen irrigation development at national and regional levels. The establishment of this institution allows the coordination of the programs and the public good supply (e.g. R&D) which the sector lacked in the past. For instance, studies and assessments outcomes carried out suggested the need for paying attention to watershed management to improve the use of small-scale irrigation technologies and practically found to be effective.

2.5 Description of the specific study area, sampling techniques and data

The Ethiopian Development Research Institute (EDRI) carried out a survey in 2005 on the water harvesting program to answer general research questions about it (Gezahegn et al. 2006). The survey had two phases: a participatory rapid appraisal (PRA) and the main survey. The participatory rapid appraisal carried out in the four sample regions helped the research team[2] to capture the overall distribution of the water harvesting technologies and to secure qualitative information that main quantitative questionnaires cannot capture. The participatory rapid appraisal showed three predominant kinds of water harvesting technologies: ponds, shallow-wells and flood/stream diversions. In 2003, a total of 118,559 WH structures were adopted in the four sample regions. The secondary data collected from the BoARD of each region during March-April 2005 indicated that the number increased to 510,000 in 2005.

A sample was selected based on the distribution of these schemes in each region. In the 2005 survey, the team used weighted criteria to determine the regional sample sizes. Those criteria include distribution of the adopted WHTs, number of sub-districts (farm population), and number of food insecure sub-districts in a region. Of those, the number of

[2]To make the sample representative, experts from the Central Statistical Agency, the Department of Statistics (Addis Ababa University), Ethiopian Agricultural Research Organization and Ethiopian Development Research Institute designed the 2005 survey together. The team included agricultural economists, a dry-land management expert, an irrigation engineer and a statistician.

WHT structures accounted for 0.5 in the weight (Gezahegn et al. 2006). Mainly based on the distribution of adopters in the four regions, sample households were selected from 30 high and low moisture shortage sub-districts. From the 30 sub-districts, peasant associations were randomly selected depending on the number of water harvesting user peasant associations. Accordingly, EDRI selected 2082 sample households of which 1839 were adopters and 243 were non-adopters. Among the 1839 adopters, 70% use ponds and 30% use either shallow-wells or flood diversions. Nine of the sub-districts are found in Oromia with a total of 706 households (34 % of the total sample), 8 in Amhara (514 hhs.; 25%), 7 in SNNPR (562 hhs.; 27%) and 6 in Tigray (300 hhs.; 14%). Table 2.1 provides the details of the 2005 sample.

Table 2.1 Distribution of the water harvesting sample over regions, zones and sub-districts in 2005 and 2010

Region	Zone	Sub-district	Sample 2005	Sample 2010	
				N[a]	Number of PAs[b]
Tigray	Central	Adwa	80		
	Central	Doga Temben	40		
	Eastern	Atsbi wemberta	60		
	Eastern	Kilite Awlalo	41		
	Southern	Enderta	30		
	Southern	Hintalo Wajirat	49		
Amhara	Bahirdar surround.	Bahidar Zuria	4		
	Oromia	Dawa Chaffa	90		
	Oromia	Kobo	91		
	South Gondar	Dera	5		
	South Gondar	Ebnat	93		
	South Gondar	Lay-gayint	97		
	South Wollo	Meket	74		
	South Wollo	Tehuledere	60		
Oromia	Esat shoa	Adama	42	21	6
	East shao	Dugda Bora	101	55	7
	East Hararge	Goro Gutu	85	70	8
	East Hararge	Gursum	103	84	6
	South West Shoa	Alemgena	71		
	South West Shoa	Kersafi Kondaltiti	68		
	West Hararge	Chiro	87	50	6
	West Hararge	Meéso	48		
	West Hararge	Mesela	101		
SNNPR	Alaba speical	Alaba speical subd.	78	60	16
	Awasa surrounding	Shebedino	77		
	Gamogofa	Chencha	41		
	Gamogofa	West Abaya	84		
	Gurage	Mareko	71	60	8
	Wolayita	Bolososore	105		
	Wolayita	Damot Gale	106		

Total	16	30	2082	400	57

a. N: sample size b. PAs: peasant associations

Sample areas are similar in farming system i.e. both crop growing and livestock rearing are common. Farmers grow both annual and perennial crops including cereals, pulses, vegetables and fruits. The sample areas are located in the highlands, where altitude ranges from 1000 to 3200 meter above sea level. This range is within three major agro-ecologies (high, medium and low lands), which excludes the extreme cold (high altitude areas) and very hot (lowland) and heavy rainfall areas of the Southwest and the East (excludes all of area C, part of area B and part of A in figure 2.1).

The sample areas do vary in: 1) crops grown (eastern sample areas grow maize, sorghum, *chat (catha edulis)*and sweet potatoes whereas central and southern highlands grow cereals, green pepper and other vegetables); 2) soil fertility and level of aridity; 3) access to export markets (for instance, the east highlands have export opportunities to Djibouti and Somalia unlike the northern, central and southern areas which mainly use big cities as domestic market outlet); and 4) culture and languages.

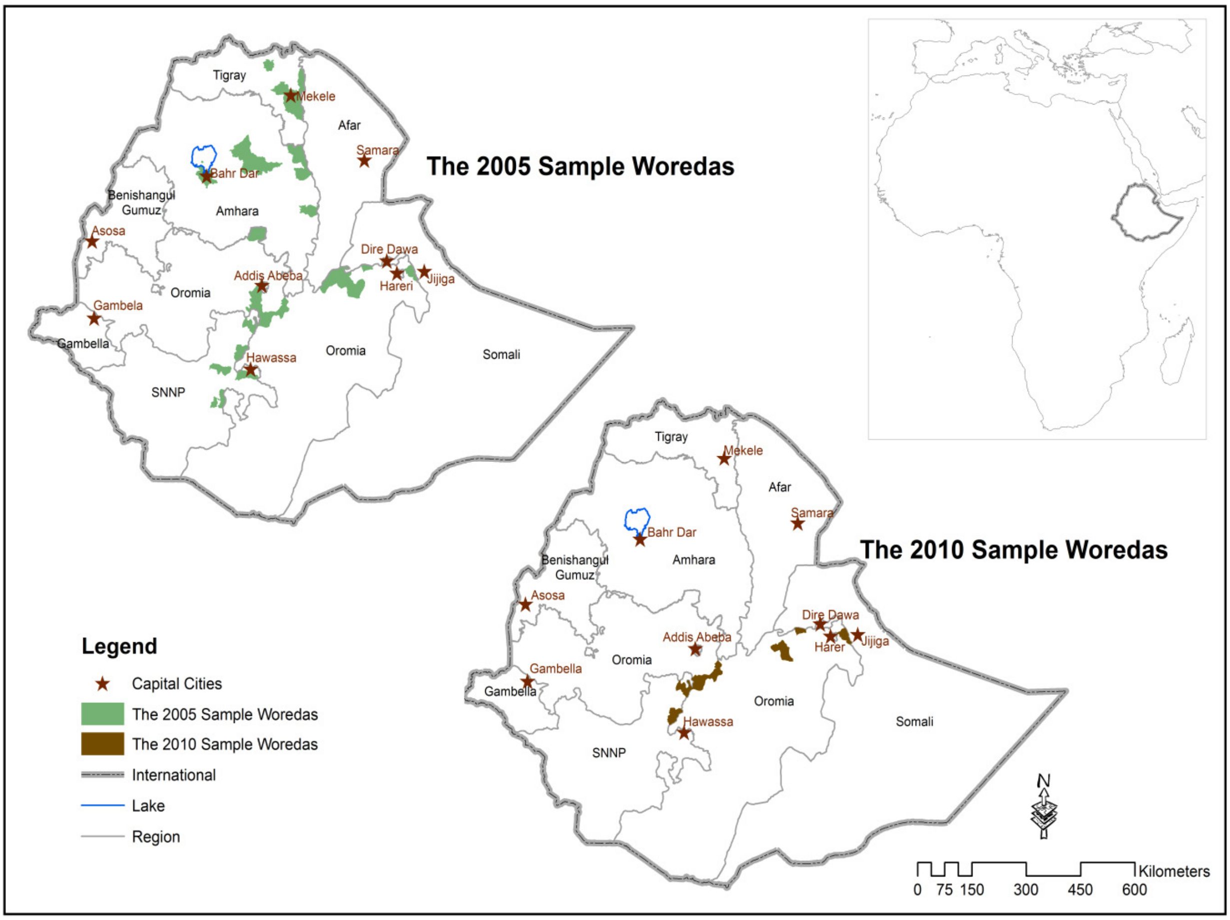

Figure 2.2 Geographical location of the sample sub-districts *(woredas)* of 2005 and 2010

In 2010, due to the limited resources, we collected data only from Oromia and SNNPR to create a two period panel data set. Although there are differences, the two regions have similarities with Tigray and Amhara in production technologies and yield. Documents also show similar food insecurity status (Famine Early Warning System Network, 2009). From 7 of the 16 sample sub-districts in the two regions, we randomly selected and interviewed 400 of the 2082 households for a second time. Before selecting sample households in 2010, we first assessed the status (whether the households continue to use, disadopt, never adopt or adopt lately) of those households interviewed in 2005. From the assessment, we noticed that some households who used water harvesting technologies in 2005 abandoned it in 2010, whereas some non-users started using it in 2010. Therefore, in selecting the 400 households for the 2010 survey, we took the status change into account and stratified the households interviewed in 2005 into users and non-users in each sub-district. Finally, 235 of the 400 households sampled in 2010 are users and the remaining 165 are non-users.

We used a structured questionnaire to collect quantitative data both in 2005 and 2010. The questionnaire focused on socio-economic variables, landholding, access to water, crop production (inputs and outputs), supplementary irrigation and rain-fed, details on the water harvesting technology used (technical and institutional aspects and constraints) and level of food security. In the 2010 survey, some variables relating to consumption expenditure, assets holding and weather and other kinds of shocks were added.

In addition to the quantitative data, the researcher collected qualitative information about rain water harvesting during assessments carried out by EDRI staffs (the researcher and other research team members) in 2005, 2007, 2009 and 2010 (before and after the surveys). These qualitative sources provide additional information about water harvesting technologies and give several insights related to the main research questions.

The Ethiopian Development Research Institute financed the 2005 survey and the Netherlands Fellowship Program NFP (Nuffic) financed the 2010 survey. The Ethiopian Development Research Institute - Ethiopian Strategy Support Program of International Food Policy Research Institute collaborative project (EDRI-ESSP-IFPRI) and the International Water Management Institute (IWMI) also supported the 2010 survey.

2.6 Overview of the water harvesting technologies

Most of the farmers who adopted WHTs in Ethiopia invested in ponds followed by shallow-wells and river/stream or flood diversions. During initial years of adoption, a pond has an average capacity of $65m^3$ but later on farmers started to modify the shapes and sizes to increase the water-holding capacity. Materials used for its construction include plastic-sheets (plastic geo-membrane) and local materials such as cement, sand, clay, mud, wood, nail, and rope. The average depth of shallow-wells varies with sub-district, ranging from 4 to 14 meters in 2005. Relatively few farmers use river/stream flood diversion and these schemes also vary in size, capacity and method of irrigation.

Basically, farmers use the harvested water for supplementary irrigation. The method of supplementary irrigation can be divided into two. The first one *(supplementary irrigation-1)* involves growing a crop using much of the required water from a harvesting scheme (almost equivalent to full irrigation) whereas the second one *(supplementary irrigation-2)* involves using much of the water from rainfall but supplement it with the harvested water. In both kinds of supplementary irrigation, the majority of the adopters of WHTs use the harvested water to grow high-value crops. Both the 2005 and 2010 data explicitly indicated this crop choice. In 2005, of the total number of plots that farmers allocated for supplementary irrigation, 91.1% were for fruits & vegetables, 6.3% for cereals &pulses and 2.6% for other perennials (e.g. *chat*, coffee, eucalyptus). The respective figures for 2010 are 80.4%, 7.1% and 12.5%, indicating a tendency to gradually increase the uses for perennials, cereals and pulses.

Documents show that water harvesting technologies are economically promising irrigation technologies in Ethiopia. For instance, Gezahegen et al. (2006) indicated that water harvesting technologies are profitable in the short run depending on the crop choice and the method of irrigation. A cost benefit analysis also indicated that they are economically viable investments in the long-run (Tesfay, 2008).

CHAPTER 3

ESTIMATING THE VALUE OF HARVESTED IRRIGATION WATER IN ETHIOPIAN VEGETABLE PRODUCTION[1]

Abstract

Water scarcity is a growing problem that impedes agricultural production in many African countries. For small-scale farmers, supplementary irrigation using individually harvested rainwater is an interesting way of mitigating it. Farmers that harvest rainwater use ponds, shallow-wells and stream diversions to collect rainwater for irrigation. This study estimates marginal values of harvested water in Ethiopian vegetable production to investigate if allocation is optimal. Marginal values for harvested water are calculated for onion, tomato, and green pepper, and for different water harvesting schemes. In the empirical analysis household data is used to estimate production functions with harvested water explicitly included as an input. Standard translog and alternative non-linear production functions that account for growth and facilitating inputs are estimated and compared on their properties and resulting elasticities. The estimation results show that the standard translog performs better than the theoretically appealing non-linear growth-facilitation production functions. Based on the translog estimates, we found that harvested water contributes positively to onion and tomato output, but not for green pepper. For onion and tomato, adding a cubic-meter of water gives eight Ethiopian Birr additional output value. The estimated value marginal products for onion and tomato do not differ much. The fact that both value marginal products are similar indicates that on average Ethiopian farmers allocate the harvested-water in an economic efficient way. Overall, farmers do seem to profit from using harvested water and non-users should therefore be encouraged to invest. Harvested water helps to reduce crop losses during drought, thereby providing a safety net against crop failure.

Keywords: water harvesting, production functions, value marginal product, Ethiopia
JEL: Q12, Q15, Q25

[1]Paper by Mekonnen B. Wakeyo and Cornelis Gardebroek submitted to *Water Policy.*

3.1 Introduction

In (semi-)arid areas water shortage due to droughts and erratic rainfall is a serious constraint to production. Moreover, besides being a crucial input itself, water (availability) also affects the decision to use other essential inputs such as fertilizer and improved seeds. Water shortage therefore may limit agricultural production growth. To overcome water shortages, some farmers have invested in small-scale water collection and irrigation technologies, often denoted as water harvesting technologies (FAO 1991). With these technologies, farmers collect and store rainwater and use it in periods with insufficient rainfall. Water harvesting technologies are thus used for supplementary irrigation. Our survey data shows that many Ethiopian farmers selectively allocate the collected water to high-value crops such as vegetables and perennials. Other farmers apply it to crops with relatively small plots so that in total not much water is required, or to crops that have a relatively short growing period. This water allocation problem has agronomic aspects but there are also interesting economic aspects. For example, it is an interesting question whether allocation of collected water to specific crops in water scarce environments is optimal from an economic point of view. Do farmers apply the water in such a way that it generates the highest marginal benefits or are they over- or under using it? Moreover, what is actually the contribution of the harvested water to the output of the most frequently chosen crops?

The need to evaluate the economic allocation of harvested water by Ethiopian smallholders is motivated by global concern regarding water scarcity. Major concerns are the continuously increasing water use in agriculture that result from population growth, rising water demand in competing non-agricultural sectors, and adverse water supply due to climate change. In the late 1990s, these factors led to the encouragement of small-scale irrigation instead of conventional irrigation with the intention of more efficient use of water in agriculture. It is assumed that poor farmers will only invest in such small-scale irrigation techniques if they expect positive returns, returns that ex post also depend on the efficiency in water use.

Previous studies conducted on the valuation of irrigation water in other countries use various methods to value irrigation water. The aim of those studies is often to identify the best water pricing method that leads to efficient water allocation and to evaluate the efficiency of irrigation water use. Young (2005:161-221) reviews different methods of water valuation in irrigated crop production. An important concept in his review is the water-crop production function. By estimating such a production function with water explicitly included as an input, value marginal products for water can be calculated and compared with the (opportunity) cost of water. Such production function studies have already been performed for conventional irrigation where farmers share irrigation water from a common irrigation scheme, but not for rainwater harvesting where farmers own irrigation technologies. Individual decision making associated with water harvesting could improve water use efficiency compared to communal irrigation, although water is not tradable in both cases (Rosegrant and Binswanger 1994). In water harvesting, water is not shared and farmers allocate water and other inputs to earn the highest return. Under the objective of maximizing returns, farmers allocate water depending on their endowment of other inputs and their crop choice. As far as inputs are scarce to individual users, they allocate them to maximize their returns so sub-optimal water allocation decreases in water harvesting. This means that the flexibility and reliability in water harvesting (e.g. in watering schedule, crop choice, input allocation) allow for maximizing returns. Shared water from conventional irrigation does not have such flexibility (Playàn and Mateos 2006; Rosegrant and Binswanger 1994). Under conventional communal irrigation, water use, crop choice and watering schedule are often fixed or rigid. In addition to the rigidity in the water share system, operation and maintenance problems of schemes often cause water use inefficiencies (Dinar et al. 1997) because they are not internalized to individual decision making (Tsur 2005).

Considering methodology, previous studies often use simple Cobb-Douglas production functions that restrict coefficients of inputs. A comparison of the elasticities of water estimated using the restrictive Cobb-Douglas production function (e.g. Sahibzada 2002) shows lower elasticities of water than under flexible specifications. Similarly, Datta et al. (1998) estimated a Cobb-Douglas function for wheat irrigation in India, but obtained water elasticities that are lower than the average value found from other studies. Another drawback of traditional functional forms like Cobb-Douglas or translog is that these specifications fail to consider the intrinsic contribution of agronomic and economic inputs to outputs. For example, water and fertilizer play a different role in production than capital or labour do. A recent study by Zhengfei et al. (2006) distinguishes inputs as growth and facilitating inputs and proposes a new functional form that takes this distinction explicitly into account in estimation. In this respect, the economic production functions correspond better with agronomic principles. The authors found that this specification explained potato production in the Netherlands better than a common translog functional form.

The objectives of this study are to assess the role of water from water harvesting sources (ponds, shallow-wells and river/stream diversion) in vegetable production in Ethiopia, and to investigate whether the water is applied in an economic efficient way. To achieve these objectives different production functions are estimated using survey data on rainwater harvesting from Ethiopia. We use two different production function specifications: a standard translog and the recently proposed framework by Zhengfei et al. (2006), where inputs are divided into growth and facilitating inputs to better capture the agronomic principles in crop production. We extend this framework of Zhengfei et al. (2006) in two directions. First, we derive expressions for elasticities for this production function specification. Second, our study proposes to use non-nested tests in comparing different models as an alternative to the simple tests suggested by Zhengfei et al. (2006).

Based on the estimated production functions, elasticities and value marginal products (VMP) of harvested water are computed for three different crops to compare optimal allocation of collected rainwater. Therefore, another contribution of this study is to provide evidence on the value of water-saving technologies (WHTs) that are privately owned by individual farm households and the economic efficiency in water use among different crops.

3.2 Conceptual framework and empirical strategy

To analyse the relation between inputs and output economists often use production functions. Marginal products and unit-free elasticities reflect the responsiveness of output to individual inputs. Moreover, assuming that producers are price takers and that they maximize profits given output and input prices, profit maximization implies that the VMP should equal the marginal costs of input use (Beattie and Taylor 1985: 137). Comparing the VMPof each input with its price or opportunity cost indicates whether the factor is optimally allocated, or whether it is under- or overused. When input prices are not available or when comparing VMPs of the same input for different outputs is intended, as is the case for harvested water, value marginal products for different crops can be compared.

In empirical applications unknown production structures are approximated using functional forms (e.g. translog, quadratic), which are polynomials of (natural logs of) inputs. Usually, these functions contain standard production factors such as labour, capital and aggregate variable inputs but ignore agronomic inputs such as nutrients and water that intrinsically contribute to plant growth. Moreover, the way inputs that have a facilitating role in crop production (e.g. labour and capital) enter into production functions is assumed to be similar to the way inputs that directly affect plant growth, like water and seeds, enter. However, in the economic literature it is recognized that inputs play different roles in production (e.g. Lichtenberg and Zilberman 1986). Based on the suggestions of earlier studies, Zhengfei et al. (2006) proposed a theoretical framework that separates inputs into growth inputs and facilitating inputs. Growth inputs are involved in the agronomic process of crop growth and land, seeds, water and nutrients are typical for this category. Facilitating inputs like labour, capital and pesticides just help to create optimal growth conditions. This distinction in inputs leads to an alternative specification of the production function:

$$y = g(x; E) \cdot f(z) \tag{1}$$

where $g(.)$ represents a growth function that depends on a vector x of growth inputs and is conditional on the growth environment E. This growth function is scaled by a facilitation function $f(.)$, which depends on the vector z of facilitating inputs and has a value between 0 and 1. When facilitating inputs are applied in such a way that they lead to optimal growth conditions, the scaling factor equals one, but when growth conditions are less optimal its value is lower than one. To ensure that the facilitation function is between zero and one, the proposed exponential specification is:

$$f(z) = \exp[-(\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i)^2] \tag{2}$$

However, the separation into growth and facilitating inputs suggests that these inputs are separable and do not interact with each other. Therefore, Zhengfei et al. (2006) suggest to test first for separability in a standard translog specification containing all inputs:

$$\begin{aligned} \ln y = \alpha_0 &+ \sum_{i=1}^{K} \alpha_i \ln x_i + \sum_{i=1}^{L} \beta_i \ln z_i + \tfrac{1}{2} \sum_{i=1}^{K} \sum_{j=1}^{K} \alpha_{ij} \ln x_i \cdot \ln x_j \\ &+ \tfrac{1}{2} \sum_{i=1}^{L} \sum_{j=1}^{L} \beta_{ij} \ln z_i \cdot \ln z_j + \sum_{i=1}^{K} \sum_{j=1}^{L} \gamma_{ij} \ln x_i \cdot \ln z_j + \varepsilon \end{aligned} \tag{3}$$

The test for separability is a test on the significance of the cross-products of ln x_i and ln z_i or testing the hypothesis that all γ_{ij} are zero. If this hypothesis is not rejected, Zhengfei et al. (2006) propose to use a production function consisting of a growth function scaled by a facilitation function as given in equation (1).

Assuming a linear specification for the growth function $g(.)$, multiplying this by the facilitating function specified in equation (2), and taking natural logarithms of the combined expression yields an equation that can be used in estimation:

$$\ln y = \alpha_0 + \sum_{i=1}^{K} \alpha_i \ln x_i + \tfrac{1}{2}\sum_{i=1}^{K}\sum_{j=1}^{K} \alpha_{ij} \ln x_i \cdot \ln x_j - (\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i)^2 + \varepsilon \qquad (4)$$

Due to the quadratic term in parentheses this model is non-linear in parameters and estimation[2] therefore requires a non-linear estimation technique such as non-linear least squares (NLS; Greene 2008: pp.285-296) or the Generalized Method of Moments (GMM). Zhengfei et al (2006) discuss the use of NLS for this model specification.

For specification (4) elasticities for growth inputs are computed in the following straightforward way:

$$\varepsilon_{x_k}^{y} = \frac{\partial y}{\partial x_k} \cdot \frac{x_k}{y} = \frac{\partial \ln y}{\partial \ln x_k} = \alpha_k + \sum_{j=1}^{K} \alpha_{kj} \ln x_j + \sum_{j=1}^{L} \gamma_{kj} \ln z_j \qquad (5)$$

where $\varepsilon_{x_k}^{y}$ is the production elasticity of input x_k. Due to the quadratic scaling part, elasticities for the facilitating inputs are calculated somewhat differently:

$$\begin{aligned}\varepsilon_{z_l}^{y} = \frac{\partial \ln y}{\partial \ln z_l} &= \beta_l + \sum_{j=1}^{L} \beta_{lj} \ln z_j + \sum_{i=1}^{K} \gamma_{il} \ln x_i - \frac{\partial \left(\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i \right)^2}{\partial \ln z_l} \\ &= \beta_l + \sum_{j=1}^{L} \beta_{lj} \ln z_j + \sum_{i=1}^{K} \gamma_{il} \ln x_i - 2\lambda_l z_l \left(\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i \right)\end{aligned} \qquad (6)$$

The last part in equation (6) follows from the fact that:

$$\frac{\partial \left(\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i \right)^2}{\partial \ln z_l} = \frac{\partial \left(\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i \right)^2}{\partial z_l / z_l} = \left(2 \cdot \lambda_l \left(\lambda_0 + \sum_{i=1}^{L} \lambda_i z_i \right) \right) \cdot z_l$$

To compute the marginal physical product (MPP) for an input, its computed elasticity is multiplied by its average product (y/x_k). Value marginal products (VMP) are calculated by multiplying the marginal physical products by their average market prices. By comparing

[2] The endogeneity of inputs in a production function is discussed in Griliches and Mairesse (1995) and Marschak and Andrews (1944). Endogeneity could also be an issue for the harvested water. Possible solutions would be to exploit panel data (not available for this paper), or to use IV techniques. But IV would be difficult to implement in the non-linear growth-facilitating function.

them to input prices the profitability of a marginal unit of the input can be assessed. For harvested water that has no market price, we compare the value marginal products of different crops to analyse whether the harvested water is allocated in an economic efficient way. Standard errors of elasticities and VMPs are obtained using the bootstrapping technique.

3.3 Data

The data for this study are obtained from a national survey on water harvesting in Ethiopia taken in 2005 by the Ethiopian Development Research Institute. This survey includes thirty sub-districts that are selected on the presence of ponds, shallow-wells and stream/river diversions. From both high and low water constrained sub-districts, peasant associations are randomly selected, and from these peasant associations 2082 households are randomly selected and interviewed. From these 2082 households, 536 households use water harvesting for supplementary irrigation in production of one or more of the three most frequently grown vegetables, viz. onions, tomatoes and green pepper. Data from these 536 households are used in this study. Since not all farmers produce all three crops, the samples size for onion, tomato and green pepper are 254, 151, and 131 observations respectively. It is also assumed that the non-users of WHT use a different production technology and so they are not included in the sample even if sufficient non-users of WHT producers of these vegetables are available to compare with that of users of harvested water.

In the production functions, one output and six inputs are considered. The dependent variable, quantity of vegetable output in kilograms, is assumed to depend on the three growth inputs land, water, and seed, and three facilitating inputs labour, capital and management. Land is measured in hectares; for seeds, some farmers gave seed quantity in number of seedlings and seedling value in Ethiopian Birr is taken to make units uniform. The quantities of water used for each vegetable crop are assessed based on the total water used in vegetable production, the respective share of each vegetable in the total crop water requirement (CWR) and the respective share of each vegetable in the total land-size of all vegetables grown by a farmer. Just et al. (1983; 1990) discussed the allocation of a total quantity of an input between crops but they do not discuss the importance of CWR in estimating the quantity of water used in crop production. Economists ignore this variable whereas agronomists pay attention to CWR in the studies of water input. This study used the CWR share of each crop along with the area share, to estimate the quantity of water used for each crop. The CWR method is also used by FAO to calculate variables including the crop water productivity, which is a variable estimating water use efficiency (e.g. Kassam and Smith, 2001). Total quantity of water used for all vegetables is the water accumulated from either pond, shallow-well or stream diversion. It is divided among all vegetables grown by the farmer based on the area share and the CWR share of each vegetable. The total quantity of water either from ponds, shallow wells, or river diversions and the total quantity of water the farmer uses is estimated by development agents in the peasant association based on the actual information from each farmer. This is because farmers have no records on the quantity of water used for each crop.

Labour is recorded in man-days of work on specific crops. Unlike labour, capital is difficult to measure. We proxied the value of capital embodied in irrigation equipment as suggested by Shani et al. (2009). The total purchasing price of this equipment is taken as a proxy to the value of capital, and the total value of capital used in production of a particular vegetable is estimated by the cost of equipment (less depreciation)weighted by the area share of that vegetable in the total horticulture area. In doing so, it is assumed that irrigation equipment is the major capital good used. Irrigation equipment ranges from buckets to treadle and motor pumps. Finally, management input is proxied by the number of years of farming experience. Since few farmers (less than 15%) use fertilizer and pesticides in production, these variables are not included as continuous variables but as dummies. Sample means of different vegetable outputs and inputs are given in table 3.1.

Table 3.1 Sample means for outputs and inputs (standard deviations in parentheses)

Variable	Unit	Onion	Tomato	Green pepper
Output (Y)	Kilogram	328.810	746.930	162.090
		(838.630)	(1662.740)	(230.230)
Land (X_1)	Hectare	0.077	0.105	0.093
		(0.140)	(0.120)	(0.130)
Water (X_2)	Cubic Meter	20.370	29.840	26.540
		(29.780)	(44.740)	(33.630)
Seed (X_3)	ETB*	53.060	27.970	11.530
		(109.180)	(49.500)	(14.850)
Labor (Z_1)	Man-days	19.820	28.170	21.040
		(14.860)	(45.510)	(20.230)
Capital (Z_2)	ETB	191.020	864.550	133.250
		(228.250)	(3200.710)	(628.630)
Management (Z_3)	Number of Years	22.490	21.290	23.300

		(10.710)	(11.400)	(11.440)
Fertilizer	Dummy (= 1 if used)	0.104	0.218	0.119
		(0.020)	(0.034)	(0.029)
Pesticides	Dummy (=1 if used)	0.021	0.122	0.071
		(0.009)	(0.027)	(0.023)

*ETB is the Ethiopian currency Birr. On average, 1 ETB was 0.115 USD in 2005

Some interesting observations can be made from the summary statistics in table 3.1. First, the standard deviations indicate there is large variation in output and in input-use within production of each vegetable. Second, the mean quantity of water used tends to increase with the mean crop water requirement of the vegetables. Accordingly, the mean water used is highest for tomato and this matches with the crop water requirement. Third, the larger the quantity of water used, the larger the quantity of labour is, probably because water use (irrigation) is a labour intensive activity. Finally, the use of capital varies substantially between different vegetables, which arise from a high mean capital equipment of tomato farmers. Tomato farmers tend to specialize in growing tomatoes and have a larger capital stock than other farmers.

Production could also be influenced by the type of water source used since they may have different labour requirements and lead to differences in water application. In our sample, 371 of the 536 selected farmers (69%) use ponds, followed by 117 users of shallow-wells (22%), 34 users of stream diversions (6%), and 14 farmers using a combination of technologies (3%). In case of ponds, the chance of accumulating water depends on rainfall availability whereas in case of shallow-wells and stream diversions it depends on underground or stream/river water availability, indirectly fed by rainfall. Since the former is more variable, farmers using ponds may grow a larger variety of crops to decrease production risks. However, table 3.2 shows that the number of crops grown does not differ much by technology type.

Table 3.2 Water harvesting technologies and number of crops grown

	Farmers Producing:				Total
Technology Type	One Vegetable only		More than one Vegetable		
	Number	%	Number	%	
Pond	78	21.0	293	79.0	371

Shallow-well	20	17.1	97	82.9	117
Stream diversions	9	26.5	25	73.5	34
Multiple technologies	3	21.4	11	78.6	14
Total	110	20.5	426	79.5	536

3.4 Estimation results and discussion

In section 3.2, two different specifications for the production function were described, i.e. the standard translog specification (equation 3) and the alternative growth-facilitation function (equation 4). Both functions are estimated for onion, tomato, green pepper separately. In this section we discuss the estimation results and the outcomes of various tests to decide what specification is most appropriate. That specification is used to calculate value marginal products in order to analyse the economic efficiency of water use.

3.4.1 Estimation results and elasticities

Since we have two specifications estimated for three crops, a large number of parameters are estimated. Instead of discussing individual parameter estimates, we prefer to discuss the quality of both models in general and to compare the calculated elasticities based on them. Tables with individual parameter estimates are given in the Appendix (tables A3.6 and A3.7). The translog production function is estimated using Ordinary Least Square (OLS), the growth-facilitation function using non-linear least squares (NLS).

For all six estimated production functions the hypothesis of all parameters jointly equal to zero is rejected at the 1% critical level in the standard F-test. R^2 values are all higher for the translog production function, ranging from 0.70 (tomato) to 0.44 (green pepper) for the translog, and 0.63 (onion) to 0.31 (green pepper) for the growth-facilitation function. Given this observation on R^2 values, it is surprising that the growth-facilitation function in all cases has more individual parameters that are significantly different from zero than the translog.

The parameters of the dummy variables for fertilizer and pesticides are in most cases not significantly different from zero. The fertilizer dummy only has a significant parameter in the growth-facilitating function for tomatoes. The parameter for the pesticide dummy is only significantly different from zero in the translog function for green pepper. In both cases the effect is positive as expected. The two dummy variables on different water harvesting techniques are more relevant in explaining production level variation among Ethiopian farmers using water harvesting technologies. For both specifications it is found that using a different technology has impact on onion and tomato production. For green pepper the result is mixed. In the translog no technology effect is found, whereas the growth-facilitation function signals a difference in output from using shallow wells, but not from using stream diversions.

To infer the effects of the six inputs on output, we calculated elasticities using equations (5) and (6). Results are given in table 3.3. Standard errors are obtained using the bootstrap procedure.

Table 3.3 Elasticities of translog and growth-facilitation function (st. errors in parentheses)

	Onion		Tomato		Green pepper	
	Translog	Growth-F.	Translog	Growth-F.	Translog	Growth-F.
Land	0.345***	1.180***	0.311**	1.120***	0.287**	1.250***
	(0.052)	(0.168)	(0.131)	(0.131)	(0.113)	(0.211)
Water	0.120***	-0.270**	0.234**	-0.228	-0.084	-0.510
	(0.044)	(0.135)	(0.100)	(0.328)	(0.098)	(0.326)
Seed	0.283***	0.072	0.203	0.160	0.249**	0.390
	(0.056)	(0.185)	(0.154)	(0.271)	(0.119	(0.304)
Labour	0.150*	0.225*	0.291**	0.020	0.327**	-0.028
	(0.083)	(0.127)	(0.120)	(0.098)	(0.151)	(0.143)
Capital	0.054	0.009	0.077	-0.003	-0.028	0.020
	(0.057)	(0.024)	(0.058)	(0.055)	(0.072)	(0.082)
Management	0.153	0.074	-0.240	-0.158	0.202	0.331
	(0.107)	(0.133)	(0.196)	(0.150)	(0.321)	(0.276)

Table 3.3 shows that the calculated elasticities are rather different for both specifications. This is most striking for land and water. For land the elasticities of the growth-facilitation function are always larger than 1, whereas in the translog they are around 0.3. For water, the growth-facilitation function has negative elasticities, which is not plausible (although it should be noted that only for onion this negative elasticity is significantly different from zero). The translog has positive and significant elasticities for water in the case of onion and tomatoes, but a negative though insignificant elasticity for green pepper. A 1% increase in water use leads to 0.12% higher onion output and a 0.23% higher tomato output; and 0.08% lower green pepper output but statistically insignificant. For the translog, elasticities for seed are positive and significantly different from zero for onion and green pepper but not for tomato. For the growth-facilitation function none of the seed elasticities is significant. Elasticities for labour

are all significant in the case of the translog, though only at a 10% critical level for onion, whereas for the growth-facilitation function only the elasticity of labour in the case of onion is significant. For both specifications, none of the capital or management experience elasticities is significantly different from zero. Overall, there are more elasticities significantly different from zero for the translog than there are for the growth-facilitation function. Additionally, values of the elasticities are more plausible for the translog. The difference between the sizes of elasticities estimated in the two models could be because of the difference in specification.

3.4.2 Specification tests for choosing between the two production functions specifications

Besides judging both production function specifications on their estimation results and elasticities, we also applied a number of specification tests to decide which specification is most appropriate given the available data. The results of these tests are summarized in table 3.4.

Table 3.4 Summary of model specification tests for onion, tomato, green pepper

Test and null hypothesis tested	Onion	Tomato	Green Pepper
Test for separability in translog	F(9;209) = 0.56	F(9;115) = 2.61	F(9;94) = 0.65
$H_0 : \gamma_{11} = \gamma_{12} = \ldots = \gamma_{33} = 0$	p-value = 0.83	p-value = 0.01	p-value = 0.75
Encompassing *J* test in translog	t-ratio = 0.61	t-ratio = 1.79	t-ratio = 5.23
$H_0 : \delta_{\hat{y}_{growthfacilitation}} = 0$	p-value = 0.54	p-value = 0.08	p-value = 0.00
Encompassing *J*test in growth-facilitation production function	t-ratio = 6.17	t-ratio = 7.21	t-ratio = 6.79
$H_0 : \delta_{\hat{y}_{translog}} = 0$	p-value = 0.00	p-value = 0.00	p-value = 0.00

An important assumption in the growth-facilitation specification is that growth and facilitating inputs are separable, which can be investigated by testing the hypothesis that all parameters γ_{ij} of the cross-products between growth and facilitating inputs are zero. The first row of table 3.4 shows that this hypothesis is not rejected for onion and green pepper, but for tomato. In other words, compared to the standard translog the growth-facilitating function is restrictive for tomato since it doesn't allow for direct interaction effects between growth and facilitation inputs.

Having estimated both translog and growth-facilitating specifications for the three crops, allows for testing which specification is preferred. Since both specifications are non-nested, we use the encompassing *J* test (Verbeek, 2008: 63-64) to test the two specifications against each other. Note that this procedure differs from Zhengfei et al. (2008) who first constructed a general hybrid model that nests both the translog and the asymmetric model and then used standard F-tests to decide whether the translog or the asymmetric model is more suitable. A drawback of that approach is that the general hybrid model is difficult to interpret since the facilitating inputs then play a double role: they interact with growth inputs but are also used in a scaling facilitating function. Our test results from the encompassing *J* test indicate two things. First, adding predicted values of the translog model in the growth-facilitating function yields a parameter that is significantly different from zero for all three crops, suggesting that the translog model is better in all three cases. Opposite, the parameter of the predicted value of the growth-facilitating function is not significantly different from zero for onion, and only at the 10% critical level for tomato. For green pepper, this parameter is significantly different from zero, suggesting that the growth facilitating function is preferred over the translog, contradicting our previous finding. Therefore, we choose translog estimates and interpreted them because they are plausible for two of the three vegetables.

3.4.3 Value marginal products of harvested water

Based on the estimation results and the specification tests we decided to use the elasticities based on the translog specification to calculate and compare the (value) marginal products of a cubic-meter of water for different crops. In the estimated translog production function, the elasticity of green pepper is not significantly different from zero. To be consistent, we decide to compare the values for onion and tomatoes based on the estimated translog production function.

The average physical marginal product of onion is 1.93 kg per m^3 water, whereas for tomatoes it is 5.85 kg/m^3. However, since the market prices of these crops differ, it is more useful to compare value marginal products (VMP) that are obtained by multiplying the physical marginal products by the average[3] market prices per kg in 2005, ETB 4.33 and ETB 1.35, respectively. Table 3.5 gives value marginal products for onion and tomato, also for different subgroups of water harvesting technologies used by households.

[3] This price is an average market price computed from average price that each household sold its vegetable.

Table 3.5 Value marginal products of water for onion and tomato in Ethiopian Birr (st. dev. in parentheses)

	Onion	*Tomato*
Average	8.34 (1.06)	7.90 (0.81)
Pond	5.52 (1.14)	6.23 (1.12)
Shallow-well	22.50 (2.78)	8.28 (1.35)
Stream diversions	5.02 (2.48)	13.63 (1.91)

Although the average value marginal product for onion (ETB 8.34) is slightly higher than it is for tomato (ETB 7.9), the difference is not significantly different from zero. In other words, at the average level Ethiopian farmers divide their water over both crops in an economic efficient way. If the value marginal products would be significantly different, it would be profitable to apply more water to the crop with the higher value marginal product. Roughly speaking, applying a marginal cubic meter of water for supplementary irrigation, pays off about 8 Ethiopian Birr for both crops.

However, looking at the value marginal products for the different water harvesting technologies shows there is substantial heterogeneity in values. For onion, the 41 farmers that collect water from shallow-wells have a substantially higher value marginal product. This signals underuse of water, which is confirmed by looking at the average quantities of water applied. For onion, farmers collecting water from shallow wells on average use 14.23 m^3 of water, which is lower than the average use of water by farmers using ponds (18.79 m^3) or steam diversions (35.25 m^3). However, this reasoning does not hold for tomato. For this crop the highest average value marginal product is observed for farmers using water from stream diversions who also are the ones who use most water (44.85 m^3 against 20.53 m^3 and 37.83 m^3 for users of ponds and shallow-wells, respectively). Of course, a number of caveats apply in this comparison. First, as shown in table 2 some farmers specialize in growing only one or two crops so that they do not equalize VMPs in water applications. Second, the numbers are average values over farmers in various regions with varying water availability. Third, value marginal products are calculated on the basis of average market prices, whereas in reality farmers receive different prices for their crops (Jaleta and Gardebroek, 2007).

The difference in the estimated VMPs for onion and tomato with the water sources is challenging to theoretically justify but may require further econometric analysis. Theoretically, there should be no difference in the VMP with water sources. However, differences could be caused by reliability and flexibility in the water source (Playan and

Mateos, 2006), ease of management of schemes (Playan and Mateos 2006; Oweis and Hachum, 2006), seed type or genetic variety (Oweis and Hachum, 2006; Cia and Rosegrant, 2003), and soil fertility (Ahmadi et al. 2010). For instance, Playan and Mateos (2006) indicate that crop yields obtained with groundwater irrigation are up to 50% higher than crop yields obtained with other sources of water due to the greater water supply flexibility and reliability from groundwater sources. Ahmadi et al. (2010) attribute the difference in potato yield between unlimited and limited water resource conditions and different soil types. In addition, farm management experience could play a role. Irrigation experiences matters in water use, design, management and maintenance of schemes (Clemmens and Dedrick, 1994). In this study there are some additional explanations for the different VMP values in addition to those suggested in the studies mentioned above. First, the farming experience in years may not proxy well for the experience in irrigation, so that differences in WHT management are not properly accounted for. Differences in agro-ecology, water quality and soil moisture can also cause yield differences with similar water sources in the sample areas. For instance, in the case of shallow-wells in central Ethiopia, farmers find ground water at a shallow-depth. This means that the plots where shallow-well water is used by itself has some moisture which requires less additional water to earn better yield with equal quantity of water. Finally, often the size of ponds is larger and in construction ponds occupy more land (space) on the fields than shallow-wells and stream diversions. The surface occupied by ponds could cause output differences between ponds and the other two irrigation water sources because farmers report output and land-size without deducting the space occupied by a pond.

3.4.4 Comparison of estimated VMPs with values from other studies

The difference between this study and many previous studies on irrigation is the type of irrigation and the volume of water used in production. In most previous studies, the type of irrigation is conventional full irrigation where the volume of water used for production is close to 100%. In water harvesting irrigation, however, the average volume of water used is low because farmers use it as supplementary irrigation. Due to this relatively low quantity of water used, the VMP will be higher compared to studies on conventional irrigation.

A summary of literature on the value of irrigation water is available in Conradie and Hoag (2004). They review 17 studies that apply mathematical programming models to estimate irrigation water values and summarize the range of value of water in both developed and developing countries. This range is between USD $0.0042/m^3$ and USD $0.1899/m^3$. Similarly, Hussain et al. (2007) reviewed literature and stated that the estimated price of irrigation water varies widely across countries and regions and falls within the range of USD 0.001/m^3 and USD 0.74/m^3. This range is also the African irrigation water price range. Pazvakawambwa and Van der Zaag (2000) used field experiments to determine the value of irrigation water in maize production from a supplemental irrigation scheme in Zimbabwe. They found a marginal value of 0.15USD/m^3.Their conclusion is that the value of water in supplemental irrigation for cereals is high compared to the conventional irrigation.

Using the exchange rate given in table 3.1, we also converted our value marginal products to USD values. For onion the VMP is then USD 0.96/m^3 and for tomatoes it is USD 0.91/m^3. As expected, these values are higher than the values from studies on conventional irrigation. However, the values are also higher than the ones found by the comparable study of Pazvakawambwa and Van der Zaag (2000). However, one should take into account that production and market conditions vary widely in different countries, so that care should be taken in such comparisons.

3.5 Conclusions and discussion

In this study we investigated the value of irrigation water collected from water harvesting technologies in Ethiopia. Translog and growth-facilitating specifications were estimated for three major cash crops, viz. onion, tomato and green pepper.

Although theoretically the growth-facilitation production function that separates inputs into growth and facilitating inputs is more plausible, specification tests favoured the classic translog specification. Moreover, the calculated elasticities from the translog are more plausible. From this we can conclude that in this application the polynomial approximation of the translog function is better than the growth-facilitating specification, which may have been too rigid. A drawback of the growth-facilitating specification is also that it requires a non-linear estimation technique.

Based on the translog estimates, we found that the supplementary harvested water contributes positively to onion and tomato output, but there is no statistically significant impact on green pepper production. One per cent more water added gives 0.12% more onion output and 0.23% more tomato output. Interestingly, the value marginal products of both crops are similar. For both crops adding one cubic meter of water gives 8 Ethiopian Birr additional output value. The fact that both value marginal products are similar indicates that on average Ethiopian farmers allocate their water in an economically efficient way for selected vegetables. A difference would have indicated that there would be potential gains by allocating more water to the crop with the highest value marginal product. The fact that we did not find a significant impact for green pepper may indicate that water applied to that crop could have been more optimally applied to onion or tomatoes. One needs to remember, however, that the presented values are averages and that farmers do not always grow all three crops, so that shifting water supply to other vegetables is not always possible. Moreover, the quantity of water for each vegetable is estimated based on the total quantity of water that they used for all vegetables, because farmers have no records of the quantity of water they used for each vegetable. Additionally, results indicated also that there were major differences in value marginal products for different water harvesting technologies.

For onions and tomatoes, we can say that farmers profit from using harvested water as indicated by the positive and significant value marginal products. However, for green pepper we did find negative values of marginal products, although not significantly different from zero. Harvested water provides a safety net against crop failure at least for some crops.

Appendix

Table A3.6 Translog parameter estimates for onion, tomato and green pepper

Parameter	*Onion*	*Tomato*	*Green Pepper*
Intercept	-0.363 (2.874)	-5.958 (2.651)**	0.144 (3.560)
lx_1	-0.520 (0.433)	-2.785 (0.647)***	-0.653 (0.707)
lx_2	0.549 (0.326)*	0.867 (0.552)	-0.263 (0.695)
lx_3	0.474 (0.420)	0.358 (0.466)	-1.039 (0.884)
lz_1	1.317 (0.816)	1.164 (0.832)	1.300 (1.308)
lz_2	0.388 (0.390)	1.101 (0.340)***	0.887 (0.548)
lz_3	0.265 (0.801)	0.822 (0.607)	0.791 (0.856)
lx_1lx_1	-0.063 (0.025)**	-0.185 (0.047)***	-0.074 (0.043)*
lx_1lx_2	0.048 (0.041)	0.123 (0.054)**	0.012 (0.066)
lx_1lx_3	0.029 (0.034)	0.015 (0.054)	-0.047 (0.098)
lx_2lx_2	-0.097 (0.030)***	-0.091 (0.046)**	-0.112 (0.051)***
lx_2lx_3	0.003 (0.041)	0.098 (0.064)	0.136 (0.094)
lx_3lx_3	0.002 (0.030)	0.006 (0.052)	0.112 (0.087)
lz_1lz_1	0.053 (0.100)	0.019 (0.109)	-0.016 (0.125)
lz_1lz_2	0.004 (0.070)	-0.098 (0.050)*	-0.123 (0.096)
lz_1lz_3	-0.385 (0.160)**	0.074 (0.183)	-0.203 (0.317)
lz_2lz_2	-0.014 (0.019)	-0.017 (0.019)	0.000 (0.027)
lz_2lz_3	-0.034 (0.063)	-0.035 (0.062)	-0.103 (0.130)
lz_3lz_3	0.147 (0.082)*	-0.094 (0.099)	-0.010 (0.140)
lx_1lz_1	0.069 (0.076)	0.241 (0.092)***	0.007 (0.112)
lx_1lz_2	0.025 (0.035)	0.132 (0.040)***	0.070 (0.060)
lx_1lz_3	-0.016 (0.074)	0.176 (0.114)	0.098 (0.152)
lx_2lz_1	-0.019 (0.069)	0.119 (0.110)	-0.020 (0.120)
lx_2lz_2	0.047 (0.031)	-0.058 (0.040)	0.043 (0.052)
lx_2lz_3	0.027 (0.066)	-0.067 (0.131)	0.143 (0.173)
lx_3lz_1	-0.015 (0.092)	-0.179 (0.112)	0.033 (0.165)
lx_3lz_2	-0.052 (0.037)	0.008 (0.048)	-0.056 (0.079)
lx_3lz_3	0.021 (0.075)	0.036 (0.120)	0.163 (0.154)
d_shallow well	0.566 (0.169)***	0.452 (0.210)**	-0.038 (0.299)
d_stream diversion	-0.396 (0.184)**	0.709 (0.343)**	0.124 (0.502)

d_fertiliser	-0.216 (0.204)	0.262 (0.256)	-0.269 (0.458)
d_pesticides	1.406 (0.442)	-0.025 (0.386)	1.375 (0.616)**
N	241	147	126
R^2	0.69	0.70	0.44
F-test	15.18 ***	8.55 ***	2.36 ***

Note: Numbers in parentheses are standard errors. ***, ** and * indicate that the parameter is significantly different from zero at the 1%, 5% and 10% level, respectively.

Table A3.7 Growth-facilitation function parameter estimates for three crops

Parameter	***Onion***	***Tomato***	***Green Pepper***
Intercept	1.063 (0.168)***	0.436 (2.247)*	-1.174 (0.213)***
lx_1	-1.270 (0.153)***	-1.777 (0.181)***	-1.699 (0.200)***
lx_2	1.441 (0.207)***	1.310 (0.259)***	1.109 (0.288)***
lx_3	1.213 (0.203)***	0.468 (0.247)*	0.884 (0.452)*
lx_1lx_1	-0.229 (0.039)***	-0.351 (0.058)***	-0.355 (0.062)***
lx_1lx_2	0.163 (0.030)***	0.226 (0.045)***	0.162 (0.049)***
lx_1lx_3	0.124 (0.024)***	0.063 (0.048)	0.120 (0.079)
lx_2lx_2	-0.223 (0.055)***	-0.230 (0.087)***	-0.227 (0.089)**
lx_2lx_3	-0.054 (0.035)	0.130 (0.055)**	-0.001 (0.077)
lx_3lx_3	-0.094 (0.054)*	-0.089 (0.088)	-0.026 (0.145)
d_fertiliser	-0.075 (0.201)	0.494 (0.260)*	0.143 (0.387)
z_1	-0.007 (0.004)*	-0.001 (0.004)	-0.002 (0.004)
z_2	$-3.2*10^{-5}$ ($7.7*10^{-5}$)	$5.2*10^{-6}$ ($5.1*10^{-5}$)	$2.7*10^{-4}$ ($9.3*10^{-5}$)***
z_3	-0.002 (0.003)	0.011 (0.007)	0.025 (0.010)**
d_shallow well	-0.460 (0.241)*	-0.670 (0.546)*	1.130 (0.542)**
d_stream diversion	0.224 (0.099)**	-1.038 (0.425)**	0.778 (0.585)
d_pesticides	-0.456 (0.447)	0.357 (0.397)	0.239 (0.356)
N	241	147	126
R^2	0.63	0.59	0.31
F-test	92.03 ***	171.64 ***	79.37 ***

Note: Numbers in parentheses are standard errors. ***, ** and * indicate that the parameter is significantly different from zero at the 1%, 5% and 10% level, respectively.

CHAPTER 4

FARM SIZE AND THE SHARE OF IRRIGATED LAND IN WATER-HARVESTING IRRIGATION IN ETHIOPIA[1]

Abstract

Rainfall shortage constrains production in small-holder agriculture in developing countries and with on-going climate change these shortages may increase. Rainwater harvesting irrigation is an interesting technology that decreases this risk. Therefore, one would expect an increasing use of this technology in drought-prone areas. However, data collected in Ethiopia shows that the share of irrigated land in total landholding declines with farm size in a particular year. This study investigates why the share declines with farm size using panel data collected in 2005 and in 2010. A random effects tobit model is estimated for the share of irrigated land as a function of variables affecting returns, market prices, source of finance and expectation formation. The findings show that credit per hectare, distance to market, ease of selling output, landholding, regional differences, aridity and distance of plots from natural water sources significantly affect the share of irrigated land. By safeguarding the availability of credit and improving local infrastructure farmers may extend the share of land irrigated by harvested water.

Keywords: water harvesting, farm size, random effects tobit, Ethiopia

[1] Paper by Mekonnen B. Wakeyo and Cornelis Gardebroek to be submitted to a Journal.

4.1 Introduction

Rainfall shortage constrains production in smallholder agriculture in developing countries. Farmers face a risk of rainfall shortage especially during ripening periods. The use of collected and stored rainwater (harvested water) at the ripening stage decreases this kind of production risk. Additionally, at lower risk farmers are more inclined to use modern inputs such as fertilizer and improved seeds. Chemical fertilizer and improved seeds require sufficient water to effectively increase yields. Thus, water harvesting technologies (WHTs) increase yield and sustain income by reducing production risk. These technologies may become even more important in the future since drought spells are expected to become more frequent and severe in Ethiopia and other countries due to climate change (Deressa et al. 2009; Boelee et al. 2012). Given their benefits, one would expect an increasing use of water harvesting technologies.

Despite these benefits, the survey data collected from Ethiopia in 2005 and 2010 show that the share of irrigated land by water harvesting declines with farm size. This suggests that when farms get larger, they increase the area of irrigated land less than proportionately. In some areas, limited rainfall could constrain expansion of the area irrigated by collected rainwater. However, in our survey only 10% of the farmers indicated that limited rainfall is a constraint in the adoption of WHTs. In several areas, farmers using the technologies earn high returns, and despite various constraints, in some areas the number of farmers adopting is increasing (Gezahegn et al.2006). Nevertheless, if farm size increases the share of irrigated land decreases.

A declining share of irrigated land suggests that irrigation based on harvested water becomes less relevant when farm size increases, which may imply that water harvesting has no future when the scale of agriculture increases and farms get more commercial. However, before concluding that the technologies become unfit with increasing farm size, it is worth investigating what the causes are for the declining share. For example, farmers may face credit constraints, which could limit the financial capacity to buy plastic, clay and cement for pond construction. Shortage of credit may also constrain buying water lifting equipment such as treadle and motor pumps. Another constraint of investment is labour. Labour shortage could constrain larger farmers severely because irrigation is a labour intensive activity and if larger farmers are short of labour they can only use irrigation on a small portion of their land.

Theoretical literature suggests farm size may negatively relate to intensity because farmers may try to learn the outcome of new technologies by applying them on a portion of their farm (Feder et al. 1985) instead of fully adopting them. However, this argument only holds in the first few years of adoption. Other studies found other factors than size determining intensity of technology use (Benin et al. 2004). Suggested explanations for the declining intensity of water harvesting use for irrigation are use of water for livestock instead of irrigation (Tulu, 2006), crop choice (Moreno and Sunding, 2005), other income sources (e.g. Feder et al. 1985), low investment (Pender and Kerr, 1998) and socio-economic factors (e.g. Foster and Rosenzweig, 2010).Whether these factors are also relevant in explaining adoption of water harvesting and the observed declining share is an open empirical question.

This study investigates that the share of irrigated land in total landholding of farmers using water harvesting decreases with farm size among the surveyed Ethiopian farmers. This is important to understand since for subsistence farmers water harvesting may be a promising way of coping with droughts that may occur more frequently in the future due to climate change. In this study a theoretical model is developed that shows investment in water harvesting technology is beneficial for two reasons. First, the harvested water increases output levels and second, it reduces output variability. Besides investment costs there may also be other factors that impede farmers from investing in WHTs such as lack of credit, lack of market access and customers to sell outputs, and natural conditions (environmental and geographical). In the empirical analysis of this study a panel tobit model is used to investigate which factors explain the share of land irrigated by harvested water. This model is estimated using two-period panel data on 400 Ethiopian households.

The study is organized as follows. Section 4.2 discusses the theoretical framework of decision making on the share of irrigated land considering both the output increasing and risk-reducing effects of harvested water. Section 4.3 discusses the tobit model and data used in the empirical analysis. Section 4.4 presents the estimation results. In the final section 4.5, conclusions are drawn and policy implications are given.

4.2 Theoretical framework explaining the share of land irrigated by harvested water

This section discusses a theoretical framework explaining the share of land irrigated by harvested water on individual farms. It starts with existing conditions related to WH in Ethiopia, and finally shows how farmers decide on the share of land to be irrigated.

Though they may have other objectives, farmers mainly invest in water harvesting to decrease production risk. Investment in WHTs for supplementary irrigation is different from participation in large and medium-scale irrigation, where ownership is usually communal and where using the water from a dam beyond a certain distance is costly. In that case the distance of plots from a dam determines the share of irrigated land (Amacher et al. 2004; Dumagay, 1984). In WH, however, farmers can locate the water collection schemes near their plots.

Two kinds of investment are common in water harvesting in Ethiopia. The first is the investment in the physical structure of the schemes. It includes digging (a pond, shallow-well or canal), permanently sealing the floor of ponds (with plastic, cement or clay), installing filtering canals and various mechanisms to increase water flowing in (e.g. installing silt-trap, growing grasses and planting trees). The second is investment in water lifting equipment, including manual and motorized irrigation equipment such as water-cans, buckets, treadle pumps and motor pumps. The second kind of investment complements the first investment by creating the capacity to catch, to preserve (Oweis and Hachum, 2006) and to distribute water (Takeshima et al.2009). Both investments together determine the area of land that can be irrigated.

To model how farmers decide on the share of irrigated land using water harvesting, the assumption is that this supplementary irrigation reduces production risk. Just and Pope (1978) suggested a production function that explicitly considers production risk and we will use this as a starting point in our analysis of investment in water harvesting technologies:

$$y = f(x, L, A_I, A_{NI}) + \varepsilon \cdot h(x, L, A_I, A_{NI}) \qquad (1)$$

where y is output, x are variable inputs, L is labour, A_I is irrigated land, A_{NI} is non-irrigated land. The function $f(.)$ gives the mean output level and $\varepsilon \cdot h(.)$ reflects the variation in output, where ε is a random term that reflects the risk in production (e.g. due to drought) and where $h(.)$ indicates how inputs and other variables relate to these production risks. Some inputs may reduce the effects of these risks, whereas others may increase it. Important assumptions are that output $f(.)$ is increasing in A_I at a decreasing rate ($\partial f(.)/\partial A_I > 0, \partial^2 f(.)/\partial A_I^2 < 0$), and that irrigated land is risk-reducing ($\partial h(.)/\partial A_I < 0, \partial^2 h(.)/\partial A_I^2 < 0$).

The one-period benefit of an additional unit of irrigated land is given by the value marginal product (*VMP*), which is the combined value of the marginal increase in output and the marginal decrease in output risk due to an additional unit of irrigated land:

$$p \cdot \partial y/\partial A_I = p\left[\partial f(.)/\partial A_I + \varepsilon \cdot \partial h(.)/\partial A_I\right] , \qquad (2)$$

where *p* is output price. In investment decisions, farmers usually have a longer time horizon than one period (Gardebroek, 2004). The relevant time horizon *T* depends on the expected number of years the invested water harvesting system lasts, which to a large extent depends on the kind of construction material used, i.e. plastic, cement or clay (Gezahegn et al. 2006). The expected discounted sum of the yearly VMPs (dynamic value marginal product, DVMP) is a function of A_I, and is used to assess the long-run benefits of investment:

$$DVMP(A_I) = E\left[\sum_{t=0}^{T} p \left[\partial f(.)/\partial A_I + \varepsilon \cdot \partial h(.)/\partial A_I\right] \Big/ (1+r)^t\right] \tag{3}$$

where *E* is the expectation formation operator and *r* is the discount rate. These expected long-run benefits are compared with the acquisition costs of water harvesting technology (Johnson and Pasour, 1981). Acquisition costs depend on the labour and material costs to construct a water harvesting scheme, which are related to the irrigated area A_I, and on the possibility and amount of loans. Farmers require a financial resource to buy the investment inputs such as plastic and cement. The source of finance could be either own savings or a loan. Poor farmers often lack own savings and therefore may use credit at some cost of borrowing. Farmers who use savings do not incur borrowing costs and their acquisition cost may be lower than those who borrow at some cost. Recognizing that both benefits and costs are a function of A_I, the optimal size of irrigated land A_I^* can be determined. If expected benefits are higher than the acquisition costs, A_I^* is positive, else it is zero. Acquisition cost C_0 incurred at t=0 is a function of credit *B*, income saved from various sources (e.g. off-farm income *S*), family labour *L*, and the area of land to be irrigated A_I:

$$A_I = \begin{cases} A_I^* & if \quad E\left[\sum_{t=0}^{T} p\left[\partial f(.)/\partial A_I + \varepsilon \cdot \partial h(.)/\partial A_I\right] / (1+r)^t\right] - C_o(B,S,L,A_I) > 0 \\ 0 & otherwise \end{cases} \tag{4}$$

Optimal land allocated to irrigation in water harvesting is thus a function of variables affecting long-run returns and initial costs of investment. The long-run expected return in turn encompasses a series of short-run (annual) returns from production, including risk reduction.

The change in mean output due to the change in irrigated land $\partial f(.)/\partial A_I$ depends on many factors. Among those soil fertility is one (Sunding and Zilberman, 2001) because soil fertility intrinsically determines output. Soil fertility varies with respect to nutrients, moisture, slope, etc. In addition to soil fertility, labour, fertilizer, and improved seed use affect output. Farmers with sufficient family-labour can use that labour for production on the irrigated land.

Farm management, training and education also affect productivity of a plot because they influence the timing of farm activities and how properly inputs (including water) are applied. Farmers that are educated or took training may have better skills in selecting sites for water harvesting and maximizing water collected from a catchment. They may also be better in selecting appropriate crops and saving water by reducing evaporation, siltation, cleaning and maintaining, etc. compared to farmers who did not take training.

These three human capital variables affect not only production, but also determine expectation formation in investment decisions. Farmers with equal resources may decide differently on investment due to the difference in expectations. Expectation formation also depends on the information farmers collect (Saha et al.1994) on water harvesting and its profitability. Information access in turn depends on household characteristics such as education, gender and experience (Foster and Rosenzweig, 2010). Better educated and experienced farmers access information better than illiterate ones.

The theoretical model also indicates that market prices *p* affect the value marginal product. In developing countries, markets are often imperfect due to high transaction costs from limited transport infrastructure and imperfect market information. Differences among farmers with respect to those variables cause price differences between farmers. The difference in prices makes returns vary among farmers, caused by the difference in the ease of selling, distance to markets, and membership in marketing cooperatives.

Importantly, the expected benefits of water harvesting also depend on the reduction in output variability ($\varepsilon \cdot \partial h(.)/\partial A_I$). Output variability depends on environmental, geographical, and of course technical factors. Aridity, a situation of low rainfall and high temperature, is one of these factors. In arid regions, a limited number of rainfall days decrease the rainwater available to harvest. Aridity also increases evaporation and speeds up finishing the harvested water. Those issues increase variability of output. In addition to the aridity effect, weather conditions matter in vulnerability to pests and crop diseases, which also affects output variability. In addition, distance of plots from natural water resources also may add to output variability. If plots are close to natural water sources such as river and lakes, they preserve moisture and require less harvested water and are relatively less susceptible to output variability than far away plots.

4.3 Empirical model and data

4.3.1 Empirical Model

As indicated in the introduction, an important objective of this study is to investigate why the share of irrigated land decreases with farm size. Since farmers usually decide on the acres to be irrigated, the theoretical model described in the previous section explains the level of irrigated land rather than the share. However, in the econometric analysis we will use the share of irrigated land as the dependent variable. It is important to realize that explanatory variables may have a different impact on irrigated area and share of irrigated land. A large farmer may have more irrigated acres than a small farmer, but still may have a lower share. To solve this problem, we included several explanatory variables such as credit, labour, and off-farm income on a per hectare basis.

The dependent variable share of irrigated land is a continuous variable ranging from zero to one. Given the double-censored nature of the dependent variable and the fact that we have two years of data available on all households, a panel tobit model is most appropriate to estimate. Depending on how to treat the farm-specific effects, a fixed or random effects panel tobit model has to be chosen. However, with short panels fixed effects tobit models are problematic to estimate[2]. Due to the non-linear character of the panel tobit model, fixed farm effects cannot be differenced out as in linear fixed effects models ('incidental parameter problem', (see e.g. Cameron and Trivedi, 2005: 800), and estimation therefore would yield inconsistent estimates. Therefore, in this study a random distribution of the farm-specific effects is assumed and based on this assumption a random effects (RE) tobit model is estimated. The random effects tobit model assumes a strong condition of zero correlation between the two error components and the explanatory variables. Despite, the RE tobit has two advantages. First, it captures both between and within variation in the data. Second, compared to a pooled model a random effects model explicitly considers the unobserved heterogeneity that has impact on the dependent variable. The households in sub-districts vary

[2] However, with Generalized Method of Moments (Honore, 1992) , there is a possibility to estimate the FE tobit with two years panel data as suggested by one of the examiners of the thesis committee members. This can be used to improve the paper.

in farming practices, culture, institutional support, how easily farmers share information, etc. It is reasonable to assume that those unobserved variables are randomly distributed.

From equation (4), we can draw the share of irrigated land S_{it} by dividing the irrigated land A_{Ii} of each farmer with a total landholding L_i of each famer i at time t:

$$S_{it} = \frac{A_{Iit}}{L_{it}} \tag{5}$$

The standard random effects tobit model follows from equation (5). Let S_{it} be the share of irrigated land of farmer i at time t. In terms of latent variable S_{it}^*:

$$\begin{aligned} S_{it}^* &= X_{it}^{'}\beta + \alpha_i + \varepsilon_{it} \qquad i = 1, 2, ..., N \\ S_{it} &= \begin{cases} 1 & if \quad X_{it}^{'}\beta + \alpha_i + \varepsilon_{it} \geq 1 \\ S_{it}^* & if \quad 0 < X_{it}^{'}\beta + \alpha_i + \varepsilon_{it} < 1 \\ 0 & if \quad X_{it}^{'}\beta + \alpha_i + \varepsilon_{it} \leq 0 \end{cases} \end{aligned} \tag{6}$$

where $X_{it}^{'}$ is vector of explanatory variables; α_i and ε_{it} are identically, independently distributed error terms with mean 0 and variances σ_α^2 and σ_ε^2 respectively. In the random effects model, α_i captures the unobserved time invariant household specific effects while ε_{it} is the stochastic disturbance or the residual. The random effect tobit model uses weighted maximum likelihood, which is based on weighted random components of the model to obtain unbiased, consistent and efficient estimates of parameters β_i. The weighted random component is based on the combined distribution of α_i and ε_{it}. The error components α_i and ε_{it} can be combined as $\xi_{it} = \alpha_i + \varepsilon_{it}$ where $\xi_{iT} \sim N(0, \Lambda)$, with $\Lambda = \begin{bmatrix} \sigma_\alpha^2 & \sigma_\alpha \sigma_\varepsilon \\ \sigma_\varepsilon \sigma_\sigma & \sigma_\varepsilon^2 \end{bmatrix}$.The joint error component ξ_{it} is normally distributed with mean 0 and variance 1, while both of its components are distributed with mean 0 and their variances adding up to 1. The assumption of constant variances allows estimation of the random effects tobit by maximum likelihood.

Based on the theoretical model and related literature, we use the following explanatory variables to explain the share of irrigated land:

Credit per hectare. a technology that entails paying up-front costs requires that farmers have prior funds (Foster and Rosenzweig, 2010). Many other studies underline credit as a major constraint in technology adoption. Farmers often lack sufficient savings to fund investments and therefore rely on credit. Creditshortage decreases adoption or delays adoption (Sunding et al. 2001). Farmers with access to credit can invest on water schemes and water-lifting equipment, and this investment increases the quantity of water available for irrigation. When more water is available for irrigation, more land can be irrigated.

Off-farm income per hectare. can be an alternative source for financing investment. However, if this income is attractive, farmers could spend more time off-farm than on farm, affecting the way they operate their farm and their decisions using water harvesting technologies. Various studies found a negative relationship between off-farm participation and investment on new technology (Amachur et al. 2004). Other studies refined this and concluded that it depends who among the household members is the source of off-farm income and what the farm size is (Fernandez-Cornejo and Hendricks, 2003). Since in our data it is not known who earns the off-farm income, this study tests the effect of off-farm income regardless of who earned it.

Labour per hectare. Irrigation is a labour intensive activity. For instance, the 2005 data shows that farmers using water-harvesting on average spent 34% more time on farming than non-users. Thus farmers who have sufficient labour can irrigate more land compared to farmers with labour shortage (Feder et al. 1985). Labour is a decisive input not only in production but also in marketing because when there is no transport or when transport cost is high, farmers have to carry to sell to local markets. Thus, more family labour is expected to increase the share of irrigated land.

Soil fertility. Some kinds of soils hold little moisture and the use of water harvesting could improve the moisture holding capacity or fertility. This means that farmers with many less-fertile plots could use water harvesting on more of their plots. Other farmers might maximize output from existing fertile soil by water harvesting. Those two possibilities indicate soil fertility can take either sign depending on the fertility of the plots available and chosen for irrigation.

Landholding size. Water harvesting systems also require land for its construction. Think of ponds or basins for water storage. If a farmer has relatively much land, then he/she has more options to select sites and to construct many schemes in proportion to the total landholding compared to a farmer owning less land. So, when a farmer is land constrained, he may either not invest in water harvesting, or choose an investment that does not require much land.

Management experience. Experienced farmers increase production by their skills and knowledge relating to input use, water-requirement and timing in farm activities. Their knowledge of climate conditions most likely leads them to increase investment in water harvesting. They also use marketing experience in crop choices. Those experiences are also likely to increase the irrigated area. A problem in estimation is how to measure experience. In the literatures it is often suggested to use the number of years engaged in farming as a proxy for experience (Weinberg, 2005).

Education. Better educated farmers are often early adopters (Pender and Kerr, 1998) and perceive scale-effects with learning (Foltz and Chang, 2002). They tend to maximize their profit by investing more on new technologies. In water harvesting, more educated farmers may have learned better how to construct the schemes, to select the type of technology appropriate for their environment and how to use it to reduce the risk of weather shocks compared to their uneducated colleagues. So, it is expected that the share of irrigated land increases with more years of schooling.

Ease of getting buyers. If farmers know they can sell their high-value crops easily, then they tend to focus more on these crops that often require irrigation. A number of farmers have customers who buy their vegetables at the farm gate rather than at a market center, so that distance to market matters less. A positive sign is expected if farmers have such opportunities.

Distance to market. With short distance to a market, transport costs decline. Farmers can also access market information, and buyers visit farms more often. These opportunities tend to increase benefits of irrigated high-value crops and therefore there is a tendency to irrigate more land with less distance to market. A negative relationship is expected between distance to market and irrigated land.

Membership in marketing cooperatives. Cooperatives improve market access and provide market information on marketable output and give members bargaining power. They also enable group credit for transporting marketable outputs. Members have better opportunities to safeguard their (future) returns on cash crops than non-members and therefore are more likely to expand irrigated land.

Training. Farmers who participated in training programs on water harvesting better use and manage water harvesting based on what they learnt and therefore a positive sign is expected.

Aridity index. In the data, a high aridity index represents a low aridity i.e. more humidity or less rainfall shortage. In a locality, if rainfall is high but variable like in some cases in highland Ethiopia, then water-harvesting is essential. Under this low aridity condition farmers can collect sufficient water to use it during rainfall shortage. Compared to high arid areas, sufficient water is available in low arid (of high aridity index) areas to collect more water, thereby increasing the possibility to irrigate more land. In this case, the expected sign is positive because the availability of water and less evaporation increases the irrigated land.

Distance of plots from the natural water source. Farmlands near natural water sources such as rivers, lakes or wetlands have a high water table and have better moisture than far away farmlands (Tzialla et al. 2006). Farmers with their lands close to those natural water sources might not invest in water harvesting because the land has good natural moisture. Under this condition, being close to natural water sources decreases investment. However, if farmers who are relatively close to a natural water source invest on water-harvesting to maximize output from these plots, they use relatively little water per plot and irrigate a relatively larger area compared to the case of farmers whose plots are far away, suggesting a positive sign. Therefore, it is difficult to predetermine the sign.

4.3.2 Data

In 2005 the Ethiopian Development Research Institute conducted a national survey and interviewed 2082 randomly selected households from 30 sub-districts. In 2010, out of those 2082 households, 400 are randomly selected from 7 of the sub-districts and interviewed for a second time. This study uses a balanced two-years panel based on the 400 households that were interviewed in both years. Of course it is possible to include all the 2082 observations after testing (in non-linear models) for a difference between households.

The dependent variable, share of irrigated land, is computed as the share of irrigated land to total land. Total land is the sum of crop land, homestead, fallow and unused lands. Users of water harvesting technologies can use water on those lands to grow crops. Excluding non-crop land in computing the share of irrigated land would exaggerate the scarcity of land and therefore is included. Defined in this way, the overall average share of irrigated land for users of water harvesting is 0.177 (table 4.1). Table 4.1 shows that the share of irrigated land declines from quartile 1 to 4 in both years: from 0.374 to 0.088 in 2005 and from 0.298 to 0.146 in 2010. The table indicates also despite the declining share, the average area of irrigated land increases with farm size, except for quartile 3 and 4 in 2005.

Table 4.1 Averages for total land, irrigated land and shares for water harvesting users

Quartiles of Land- holding	*Mean Landholding (hectare)*	*Mean Irrigated-Land and Mean Share (Std. dev. in parenthesis)*	
		Mean Irrigated Land	*Mean Share*
2005			
1	0.621 (0.15)	0.232 (0.23)	0.374 (0.27)
2	1.084 (0.13)	0.274 (0.21)	0.253 (0.19)
3	1.807 (0.28)	0.377 (0.35)	0.209 (0.20)
4	3.880 (1.39)	0.343 (0.53)	0.088 (0.18)
Mean 2005	1.848(1.40)	0.307 (0.37)	0.166 (0.22)
2010			
1	0.601 (0.14)	0.179 (0.11)	0.298 (0.20)
2	1.090 (0.13)	0.319 (0.27)	0.293 (0.24)
3	1.903 (0.30)	0.382 (0.34)	0.201 (0.22)
4	4.042 (1.92)	0.576 (1.15)	0.146 (0.16)
Mean 2010	1.909 (1.51)	0.367 (0.57)	0.203 (0.22)
Overall Mean	1.879(1.45)	0.337 (0.46)	0.177 (0.22)

With respect to the explanatory variables, table 4.2 shows that the average per hectare values of credit, off-farm income, and labour also decrease for higher quartiles. The descriptive statistics thus suggest these variables have a positive correlation to the share of irrigated land.

Table 4.2 Means of variables for different land quartiles for WHT users (2005 and 2010)

Variables	*Quartile Mean*			
	Quartile 1	Quartile 2	Quartile 3	Quartile 4
Total land in hectare (a)	0.61	1.09	1.83	3.96
Share of irrigated land (b)	0.32	0.26	0.20	0.10
Total irrigated land (= a x b)	0.19	0.29	0.35	0.34
Capacity investment per ha (‘000 ETB)	0.43	0.87	0.70	0.75
Credit per ha (‘000 ETB)	0.57	0.64	0.58	0.44
Off-farm income per ha (‘000 ETB)	0.85	0.98	0.61	1.19
Labour per ha (in adult equivalent)	6.71	3.74	2.39	1.45

*Note: ETB is the Ethiopian currency Birr. 1 ETB was 0.0741 USD in June 2010

A summary of the descriptive statistics of variables included in econometric estimation is given in Table 4.3.

Table 4.3 Descriptive statistics of variables used in estimation (all farmers)

Variables	*Mean*	*Std. Dev.*	*Min*	*Max*
Dependent Variable				
Share of irrigated land	0.16	0.21	0.00	1.00
Explanatory Variables				
Education dummy (0= with no year of schooling)	0.35	0.48	0	1
Experience independent of parents (years)	21.17	11.30	0.00	59.00
Training on water harvesting?(yes=1)	0.66	0.47	0	1
Gender(1= male)	0.93	0.24	0	1
Total land(hectare ha)	1.92	1.69	0.13	13.75
Credit per ha ('000 ETB)	0.46	0.97	0.00	9.36
Off-farm Income per ha ('000 ETB)	0.79	1.82	0.00	20.91
Labour per ha (in adult equivalent)	3.55	3.04	0.23	36.80
Distance to market (hour)	1.39	0.94	0.00	3.67
Do you get buyers easily? (yes = 1)	0.68	0.47	0	1
Membership in cooperative? (yes = 1)	0.24	0.43	0	1
Soil fertility index	12.69	12.55	0.25	97.25
Plot distance to natural water source (hours)	0.46	0.71	0.00	6.00
Aridity index	0.67	0.27	0.11	1.12
Region dummy (1 = Oromia)	0.70	0.46	0	1

Table 4.3 shows the mean and standard deviations of the dependent and explanatory variables for all farmers, users and non-users of water harvesting technologies. The aridity index measures water deficiency of a location and it is defined as $AI=P/PET$, where P is the mean annual precipitation and PET is evapo-transpiration. The higher the aridity index the less arid a region is.

4.4 Results

Equation (6) was estimated as a random effects tobit model. This section first interprets the coefficients of the estimated model. The parameter estimates of the random-effects tobit are summarized in table 4.4. At the end of the section, we discuss the estimation method used and some general specification tests.

The empirical model that is based on the concept of risk-reducing effect (Just and Pope, 1978) of water harvesting captured the expected variables determining the share of irrigated land. Table 4.4 indicates credit per hectare received and the ease of selling output increase the share of irrigated land, in line with our expectation. Credit enables farmers to buy construction materials such as plastics, cement and clay, or water-lifting equipment such as motor pumps, allowing for more capacity to collect and store water and therefore a larger area that can be irrigated. The coefficient shows a thousand ETB increase in credit received per hectare increases the share of irrigated land on average by 0.029, which is modest. Similarly, farmers who are confident in selling their outputs grow marketable crops by harvested water more often than farmers who worry about getting their crops sold. Farmers that can easily sell their crops have a share of irrigated land that is on average 0.048 higher. This finding is in line with the negative and significant parameter for distance to markets. Lack of rural transport and high transport-costs increase the time to access markets. Especially in east Ethiopia, the hilly-terrain exacerbates the problem. Farmers that need less time to reach a market have a higher share of land irrigated by harvested water. This can also be explained from the fact that these farmers grow more marketable crops that are sold on the nearby market. Water harvesting reduces the risk of crop failure for these commercial crops. The estimated coefficient indicates an additional hour of travel time to the market center decreases the share of irrigated land by 0.03. Significance of parameters for ease of selling and distance to market points out that market access strongly affects the share of irrigated land.

The results also show that distance to a natural water source, and a high aridity index (low aridity) increase the share of land irrigated by harvested water. Unlike farmers whose plots are close to lakes, rivers or marshy wet-lands, farmers who are far away face higher weather risk and tend invest on water harvesting to increase their land under irrigation. Plots far away from the natural water sources tend to have relatively less moisture than plots close to natural water sources. In other words, farmers whose plots are close to those sources may not even feel weather risk as a problem and so they tend to invest less. The estimated coefficient of plot distance from natural water sources shows an hour increase in the time to reach a natural water source increases the share of irrigated land by 0.027.

From a water availability perspective, the effect of aridity is contrary to the effect of distance to natural water source. It is discussed that being far away from natural water sources increases the share of irrigated land, showing the need for water harvesting in areas where other water sources are distant. Contrary to this, a high aridity index (low aridity) increases the share of irrigated land. In less arid areas, farmers have more rainfall to catch, save and use than farmers in more arid areas, so that the former can irrigate a larger share of their farmland. This is because low aridity implies more rainfall to harvest and lower evaporation to save the harvested-water than high aridity. The estimated coefficient also shows with a rise in aridity index by one (lower aridity), the share of irrigated land increases by 0.117. The larger coefficient compared to other variables' coefficients shows availability of rainfall in water harvesting is essential.

Table 4.4 Estimates explaining the share of irrigated land

Variable	*Description*	*Random Effects Tobit*[a]
Constant		0.197***
		(0.076)
Total Landholding	hectare	-0.027***
		(0.011)
Credit per hectare	'000 ETB	0.029**
		(0.015)
Off-farm income per hectare	'000 ETB	-0.007
		(0.007)
Labour per hectare	Number	-0.005
		(0.004)
Cooperative	Dummy	0.0001
		(0.029)
Ease of selling	Dummy	0.047**
		(0.025)
Distance to market	hours	-0.034***
		(0.011)
Experience	Years	-0.003***
		(0.001)
Training	Dummy	-0.037**
		(0.020)
Soil Fertility index	Index	-0.001
		(0.002)
Plot distance to natural water source	hours	0.027**
		(0.016)
Aridity Index	Index	0.117***
		(0.034)
Oromia	Dummy	0.086***
		(0.025)
Education	Dummy	0.014
		(0.026)
Gender	Dummy	-0.076
		(0.061)
σ_α	Sigma α_i	0.085***
		(0.032)
σ_ε	Sigma ε_i	0.254***
		(0.011)
ρ	rho	0.101
		(0.072)
Likelihood Ratio Test of σ_u		3.080 (p-value: 0.04)
Log -likelihood		-253.964

Wald Test: χ^2 (15)	132.660
N= 787	left censored: 257, uncensored:530[c]

a. Numbers in parentheses are standard errors; *** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$.

b. Missing values of some variables caused a loss of 13 observations, and this reduced N from800 to 787.

c. The number of observations with the share of irrigated land zero, between zero and one, and one are 257, 523 and 7 respectively. The estimation of RE tobit model with or without right-censored seven observations has only negligible difference on coefficient signs and significance.

On the other hand, total landholding, the experience of the farmer after becoming independent of parents, and training have a statistically significant negative effect on the share of irrigated land. The effect of total landholding is in line with our expectation. With more land, the share of irrigated land falls. This is in line with the common observation that was stated earlier and that is central in this study. However, it is contrary to the hypothesis that land shortage constrains size and number of water harvesting schemes.

The signs of parameters for management experience after becoming independent of parents, and for taking training on water harvesting are not in line with our expectation. The result indicates that more management experience lowers the share of irrigated land. Experience, measured by the number of years is collinear with age. Older farmers may stick more to traditional production practices, which may be an explanation for the negative sign. Similarly, taking training on water harvesting decreases the share of irrigated land. An explanation for this finding is found in the descriptive statistics that shows 73% of the farmers who do not use water harvesting nevertheless participated in training for using water harvesting technology. Of course, this is a remarkable finding questioning the relevance of these training programs.

The result also indicates that in Oromia (compared to SNNP region) the share of irrigated land on average is 0.087 higher. A recent census indicates in Oromia, the number of farmers using motor-pumps by far exceeds those in SNNP region and this may cause the difference. Other explanations may be geographical or ecological differences between the regions, or simply a difference in unobserved farm structure in both regions.

Off-farm income, cooperative membership, gender and education do not significantly affect the share of irrigated land. Interestingly, labour also has an insignificant effect on the share of irrigated land, contrary to our expectations. Our expectation was that irrigation is a labour intensive activity and it affects the share of irrigated land. The descriptive analysis of the data shows that the mean labour per hectare of non-users of WHT and their per hectare labour in each land-size quartile group is higher than that of users. These indicate the estimated coefficient sign is consistent. This indicates other reasons are possible and a possible reason for the insignificance of labour is that use of equipment such as motor pumps, capital good and plastic-sheet could be more important in irrigating more proportion of farm-land than labour.

Finally, the results show that the unobserved farm-specific effects have a significant effect on the share of irrigated land because σ_α is significant at 1% level. Unobserved farm specific characteristics such as institutional support and attention paid to water harvesting irrigation, religious, culture (e.g. staple food-crop), etc. factors not observed by the researcher have a significant influence the share of irrigated land.

Various tests are carried out to check the quality of estimation. Before estimating the random effect (RE) tobit model, we expected the landholding variable to be endogenous, however the Hausman-test does not show that it is endogenous. In addition, the log likelihood ratio test rejected the pooled tobit in favour of the random effect tobit at 5% significance level (p-value = 0.040). These tests show that the RE tobit is superior to both pooled tobit and IV-tobit. Estimations are carried out with bootstrapped standard errors and coefficients in all three tobit models have no big differences in magnitude and sign.

4.5 Conclusions and Implications

In countries where agricultural production is risky due to unpredictable rainfall, harvested water can be used for supplementary irrigation to decrease production risk. In those areas, the more land of a smallholder that is irrigated the more a farmer could control production risk arising from rainfall shortage. In recent years, Ethiopian farmers have invested in water harvesting technologies to collect rainwater and use it for supplementary irrigation. However, in the data it is observed that the share of irrigated land decreases with farm size. This lower share of irrigated land suggests that for large commercial-farms the importance of water harvesting is smaller. This study investigates why the share of irrigated land falls with farm size. Using two-period panel data the factors behind the declining share are analysed.

As a basis for the empirical analysis, the study developed a theoretical framework for analysing investment decisions on risk-reducing technologies such as water harvesting. In this framework the assumption is that farmers choose a certain area to be irrigated, based on their investment possibilities. In the formulated theoretical framework, benefits of irrigated acres are compared to cost of investment and potential constraints, such as lack of credit or labour. This theoretical framework gives a foundation to identify variables presumed to affect investment and the share of irrigated land.

To test the effect of potential influential variables, a random effect tobit model is estimated using panel data collected in 2005 and in 2010. Observed farm-specific factors such as credit per hectare, ease of selling output, aridity index and differences between Oromia and SNNP have positive and significant effects whereas landholding, distance to market, management experience, and training on water harvesting have negative effects. When large farmers face a credit shortage, they invest on a limited number of schemes, insufficient to irrigate a large proportion of their land. Similarly, if farmers are market-constrained, they irrigate a smaller portion of their land. The finding that the geographical and environmental variables determine the share is also reasonable. Water harvesting technology uses rainfall, accumulated in ponds, and shallow-wells or obtained from stream or flood diversions, indicating that some rainfall is a basic condition for water harvesting. Highly arid regions are characterized by low rainfall, not highly variable rainfall. Therefore, farmers in these regions cannot collect sufficient rainfall if they invest in water harvesting. In addition, evaporation of harvested water is high. These conditions decrease the attractiveness of WHT.

The findings also show that unobserved farm-specific factors cause diversity among households. Households are diverse in culture, the local institutional support they receive (e.g. with the supply of investment inputs, and post investment advices) and cultural variations. For instance, in some sub-districts local development agents give continuous advice, and arrange availability of inputs such as plastics and improved seed varieties. This kind of institutional support is not uniformly available to households across sub-districts and this could cause differences in behaviour.

So, what do these results imply? The results show the importance of credit and of the connection to markets to sell their output as important positive drivers for increasing the share of land irrigated by harvested water. Improving infrastructure enables farmers to reach markets in a better way and this may encourage them to invest in these risk-reducing systems and have a higher share of land that is irrigated by collected water. So, large farms may also extend the area irrigated by water harvesting if both credit and good infrastructure are present. The results also show that not all farmers have an interest in these systems. If there is another source of water close by, e.g. a lake, farmers are less inclined to invest in these structures. Therefore, farmers that are further away from alternative water sources, but that are also close to markets to sell their products, should be targeted by extension agents. Based on the finding, in this study extension agents can also improve the target farmers for training by carrying out training demand assessment rather than enrolling all farmers.

CHAPTER 5

EMPTY PONDS AND POCKETS: DISADOPTION OF SMALL-SCALE WATER HARVESTING IRRIGATION TECHNOLOGIES IN ETHIOPIA[1]

Abstract

Both low rates of adoption and high rates of disadoption of new irrigation technologies undermine yield in developing countries. This study analyses disadoption of small-scale water harvesting irrigation technologies in Ethiopia where the average disadoption rate in the sample areas is as high as 42%. Given that Ethiopia is a drought-prone country with 95% of its crop production being rain-fed, such a high disadoption rate for irrigation technologies is surprising and urges investigation. Using panel data collected from Ethiopia in 2005 and 2010, for 332 of the households we estimate two binary choice models to identify factors underlying disadoption. We find household, farm, environmental, and technology-specific factors that are responsible for disadoption. Mainly, the number of rainfall shortage months, labour shortage, age, education, and shortage of plastic-sheet increase disadoption, whereas experience with water harvesting (learning-by-doing), ease of selling output, farm profit, credit access, training and growing perennial crops decrease the probability of disadoption. There is no evidence that malaria has a significant effect on disadoption. Based on these findings, paying attention to the supply of plastic sheet, encouraging the import of motorized water-pumps and their distribution, providing training, advising farmers on crop choices and giving credit and market accesses could all contribute to decreasing disadoption of WHTs. These activities require the engagement of the private sector wherever it is optimal to engage in.

Keywords: disadoption, water-harvesting, panel data, Ethiopia
JEL: O33, Q16

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[1] Paper by Mekonnen B. Wakeyo and Cornelis Gardebroek, to be submitted to a journal.

5.1 Introduction

Low adoption rates of new agricultural technologies thwart crop yield increases in developing countries. These low adoption rates have been a research topic in many studies (e.g. Foster and Rosenzweig, 2010; Sunding and Zilberman, 2001; Feder et al. 1985) including adoption studies on soil and water conservation technologies (He et al. 2007; Mushtaq et al. 2006; Sidibe, 2005; Caswell and Zilberman, 1985). Recently, the issue of disadoption of new technologies has also attracted the attention of researchers. Similar to low technology adoption rates, high disadoption rates could undermine structural increases in agricultural yields. It is important to investigate potential drivers of yield increases in developing countries since productivity growth in these countries is often low, while at the same time many experience rapid population growth. Due to low yields and low yield growth, food shortages are often prevalent and many developing countries remain food-aid dependent.

Many technologies adopted recently in developing countries originate from the green revolution technology packages. One of the major preconditions for the successful replication of these technologies in other countries (e.g. India, Mexico) is water availability. Gollin et al. (2005) note that high-yield varieties were successfully replicated in some regions because they were applied either in water-intensive or irrigated conditions. In Africa, these green revolution technology packages could often not be replicated due to water shortages (Collier and Gunning, 1999; Moris, 1987). Shortage or variable availability of water not only directly affects plant growth, but it may also prevent farmers from using costly inputs such as fertilizer and improved seeds.

Although African countries did invest in irrigation, these were often investments in large-scale irrigation that frequently failed due to a number of constraints associated with them (see Adams, 1990; Moris, 1987). Cognizant of these failures, researchers suggested a “blue revolution” for Africa (Movik et al. 2005) to complement the yield-increasing inputs and technologies such as fertilizer and improved seeds. Due to the many failures of large-scale irrigation, it was suggested that this *blue revolution* could better be achieved by stimulating adoption of small-scale irrigation. Moreover, studies underlined that food shortages in African countries is due to low yields that are not caused by absolute water scarcity but by recurring spells of drought (Ngigi et al. 2005), which supports the use of supplementary irrigation from small-scale irrigation schemes (Oweis and Hachum, 2006; Rockström, 2000). With this in mind, water harvesting technologies (WHT) for small-scale irrigation were promoted during the early 2000s in Ethiopia, a country with variable and often insufficient rainfall. The data collected in 2005, the first year of our survey, indicated that adopters on average invested 1832 Ethiopian Birr (226 USD) on water harvesting technologies.

Preliminary analysis of our data shows that farmers using those technologies seem to be better off. For instance, WHT users had fewer months of food shortage than non-users. IFAD (2009) indicated that this is because yields in Ethiopian small-scale irrigation increased 75-100%, whereas yields on rain-fed farms only increased 25-40%; the average quantity of permanent and liquid assets was higher for users compared to non-adopters and disadopters[2]. In addition, similar to the findings of Huang et al. (2005), farmers who own motor pumps earned income from renting and share-cropping agreements that they entered into with the farmers who have no motor pumps. Furthermore, because of the use of WHTs, diversification of income, e.g. from keeping poultry or new high-value crops (e.g. apples), became possible (van Koppen et al. 2009) and consequently income increased and vulnerability to shocks declined. The technologies seem to have decreased yield variability, similar to observations in other countries (Andersson et al. 2011). Despite the suggested benefits, WHT disadoption, defined as using a technology for some time and abandoning it later (Wendland and Sills, 2008), is substantial. For instance, during 2005 - 2010, the average disadoption rate of WHT in our sample was 42%, varying among sub-districts from 3% to 71%. Such a high disadoption rate of WHTs is remarkable for a country with 95% of its crop production being rain-fed and therefore prone to uncertain water availability (World Bank, 2006).

Water harvesting technologies are relatively cheap, technically simple, and able to mitigate dry spells in rain-fed production by providing supplementary water at the critical stage of crop growth (Oweis and Hachum, 2006; Rockström, 2000; Reij et al. 1988). Why this substantial disadoption occurred[3] has not been investigated. It is relevant to investigate disadoption since without water harvesting farmers may be more prone to water shortage, leading to lower and more variable production. Moreover, the previous benefits from WHT could dissipate. Unless the causes of disadoption are adequately investigated, water harvesting can be erroneously perceived as not very useful by policy makers, contrary to its proven usefulness in countries with diverse weather conditions such as India and China. The use of water harvesting is dependent on household characteristics including socio-economic factors (e.g. education, labour, and market access), natural environmental conditions and weather risk (e.g. rainfall, number of months of water shortage), investment material supplies (e.g. plastic

[2]Of course this simple inspection of the data does not provide causal evidence for the benefits of WHT but it is a first quick indication.

[3] This happened without the presence of an improved substitute technology (Rogers, 2003:190-192).

sheet), learning-by-doing and regional differences. One would expect that changes in these variables may lead to disadoption of WHT. The objective of this study is therefore to investigate the factors that explain disadoption of WHT. Insight into these determinants may help in taking action to resolve constraints in WHT use and to formulate better strategies for promoting water harvesting technologies (Rockström et al. 2010).

In the economic literature there are a number of studies that provide explanations for disadoption. Gedikoglu (2010) used replacement cost in relation to farm-size to explain technology disadoption and concluded that farm-size decreases disadoption, whereas uncertainty on the profitability of the technology tends to increase it. Rogers (2003:190-192) suggested replacement of an old technology by a new one, and disenchantment with a technology as reasons for disadoption. Related to disenchantment are lack of knowledge causing misuse of a technology, and financial constraints for maintenance. With experience in WHTs, farmers could sustain the technology rather than dropping it. Moreover, in water harvesting, the quantity of rainfall (run-off) captured is also affected by the length of rainfall shortage months (which captures the uncertainty), altitude and distance from water sources. So, besides various socio-economic variables, factors influencing the use of WHT such as environmental and geographical factors may also have induced disadoption.

Lack of technical knowledge (e.g. construction and design, site selection) is often a problem for farmers when they start using WHTs (Makurira et al. 2011; Ngigi et al. 2005). However, gradually farmers improve this knowledge through learning-by-doing and sharing experience (Foster and Rosenzweig, 2010) which could decrease disadoption. Disadoption is often due to changes over time in variables that are key in water harvesting. For instance, the routine activities of WHT irrigation are dependent on family labour. Over time, shortage of family labour may happen, e.g. due to family members' marriage, participation in education, aging, sickness, or off-farm activities. Maintenance cost is also substantial. The 2010 data shows 2% - 11% per annum maintenance cost of total investment and financial constraint could therefore also cause disadoption. Farmers' perceptions about health risks such as malaria may also change, decreasing the interest of farmers in water harvesting. Moreover, poor infrastructure may increase disadoption due to a lack of market opportunities. So, in addition to technical factors related to construction and maintenance, it is vital to closely examine socio-economic factors to understand the abandonment of WHTs.

Several studies on water harvesting examined adoption (He et al. 2007; Mushtaq et al. 2006; Sidibe, 2005), up scaling of the technologies (Tumbo et al. 2011), their productivity in supplementary irrigation (Karrou and Oweis, 2012; Moges et al. 2011) and their advantages as agricultural water technologies (Ngigi et al. 2005). Despite their large contributions, those studies examined the static aspects of WHTs. A study on the dynamic aspect of WHTs such as disadoption further increases our understanding of these technologies.

Previous studies on disadoption of other agricultural technologies give insight into potential factors underlying the disadoption of water harvesting. Gedikoglu and McCann (2009), Boys et al. (2007), Rahim et al. (2008), Moser and Barrett (2003), Neill and Lee (2001), Cameron (1999) and Carletto et al. (1996) suggest that farm-size, the lifespan of the physical components of the technology, labour shortage, wealth, education and age affect the decision to disadopt. As those findings show, the effect of farm-size, wealth and education is mixed; the effect of labour shortage, age and short lifespan of the components of a technology increase disadoption. For instance, Adegbola (2010) concluded from the study on the disadoption of maize storage technology in Benin that those farmers who face labour shortage, who do not participate in on-farm demonstration after adoption and who live in a village with low-market-access disadopt storage technologies more than other farmers. The period between adoption and observed disadoption as well as the type of technology and the local circumstances may also play important roles. Some of these factors are also used in explaining disadoption of WHTs in this study.

A drawback of many of the above-mentioned studies excluding Adegbola (2010) is that they used cross-section or recall data (e.g. Rahim et al. 2008; Boys et al. 2007; Neill and Lee, 2001) to investigate disadoption. A contribution of our study is the use of panel data in analysing the underlying causes for disadoption. Panel data allows for using changes in explanatory variables in explaining disadoption (e.g. changed labour supply) whereas cross-section data only provides levels of variables. Moreover, panel data estimation techniques allow for dealing with unobserved heterogeneity in the sample.

The text is organized as follows. Section 5.2 briefly discusses the conceptual framework and empirical model. Section 5.3 describes the data and the data collection process. Estimation results are presented in section 5.4. Finally, section 5.5 provides conclusions and implications.

5.2 Conceptual framework and empirical model

Disadoption is observed only for farmers who adopted a technology sometime in the past. This means that the relevant population and sample to analyse disadoption consist of former adopters. Whether farmers continue to use or abandon WHT is assumed to affect the income of farmers. The availability of harvested water for supplementary irrigation may raise production levels and reduce crop failure. However, the choice between continued use or abandonment of WHT also depends on the experience that farmers have with these technologies, their need for it, i.e. frequency of periods with insufficient rainfall (e.g. to fill the ponds), and constraints experienced in using them (e.g. shortage of construction materials and their maintenance). Because of these latter factors, we assume that farmers decide to disadopt a technology when the expected utility from continuing to use a technology is lower than the expected utility from discontinuing the use of the technology. Utility is assumed to depend on income, but also takes into account other factors such as ease of use, perceived effectiveness, availability of materials, etc.

Assuming that farmers maximize utility, the decision by household i in year $t$on whether to continue to use water harvesting technology ($WHT_{it} = 1$) or to disadopt ($WHT_{it} = 0$) is based on a comparison of expected utilities of both situations. Using the difference in expected utilities gives the following decision rule:

$$WHT_{it} = \begin{cases} 1 & if \;\; E[U_{it}^{1} - U_{it}^{0} | X_{it}] > 0 \\ 0 & if \;\; E[U_{it}^{1} - U_{it}^{0} | X_{it}] \leq 0 \end{cases} \qquad (1)$$

where E is the expectation operator, U_{it}^{1}denotes the utility of continuing to use WHT and U_{it}^{0} is the utility of disadoption. Farmers differ in the way they form expectations on the utility levels of both choices. These differences are due to characteristics of the farmer (e.g. age, education level, and experience with the technology). The vector X_{it} accounts for the different variables (observed and unobserved) that are assumed to have an impact on the utilities of both choices and the way expectations are formed on these utilities.

Equation (1) provides the basis for a binary choice model to analyse disadoption choices. Given the availability of two-period panel data in our study, a panel binary choice model could be estimated. However, when we have a panel with only a limited number of observations per household (in our case only two), a fixed-effect probit or logit specification is plagued by the incidental parameter problem (Wooldridge, 2002: 484). The non-linear nature of the probit and logit model prevents a within or first-difference transformation to eliminate the household-specific effects (Verbeek, 2008: 394; Greene, 2002). In addition, the fixed effect logit estimator only exploits data where a change is observed (0 to 1) or (1 to 0) leaving many observations out (loss of information). Even if we could estimate a fixed-effect probit or logit model, we would also have problems in dealing with endogenous explanatory variables in our model. Unobserved farm effects may capture wealth and attitude towards new technology, for example, which correlate with the explanatory variables such as credit. The covariance between the residuals of the disadoption equation and explanatory variables such as credit could be non-zero, which leads to biased estimates of the adoption equation. So the potential endogeneity in some explanatory variables including credit, farm profit, off-farm income and training creates another barrier in estimation since instrumenting is difficult in a panel probit model (Wooldridge, 2002: 490; Greene, 2002). Omitted variables influencing these potentially endogenous variables (number of lenders in a locality) could correlate with the error term and bias the estimate.

To overcome these two problems we follow a suggestion by Angrist (2001) and estimate a Linear Probability Model (LPM) using panel data estimation techniques. This linear model allows for a within or first-difference transformation to remove the household-specific effects and allows dealing with correlation between regressors and household-specific effects. To deal with the latter problem, a standard fixed effects (FE) approach is often used. However, since we also include some time-invariant explanatory variables that would be dropped in an FE approach, we used the Hausman-Taylor (HT; 1981) estimation approach. The advantages of HT as an alternative panel data estimator are discussed in Verbeek (2008: 371). By using the Hausman specification test, it is possible to compare the estimates of the Hausman-Taylor-based LPM with the estimates of the standard FE-LPM model.

The Hausman-Taylor-based linear probability model is specified as:

$$P(\mathrm{WHT_{it}} = 1) = \alpha_i + \sum_{\mathrm{k=1}}^{\mathrm{K}} \beta_{1k} X_{1kit} + \sum_{\mathrm{l=1}}^{\mathrm{L}} \beta_{2l} X_{2lit} + \sum_{\mathrm{m=1}}^{\mathrm{M}} \gamma_{1m} Z_{1mi} + \sum_{\mathrm{p=1}}^{\mathrm{P}} \gamma_{2p} Z_{2pi} \qquad (2)$$

$$\mathrm{i} = 1, \ldots, \mathrm{N}, \quad \mathrm{t} = 2005, 2010$$

where $P(\mathrm{WHT_{it}} = 1)$is the probability that a farmer uses WHT in 2005 or 2010. Farmers that disadopted WHT in 2010 have an observed value of zero for this dependent variable. Furthermore, X_{1kit} are exogenous time-varying regressors and X_{2lit} are endogenous time-varying regressors; Z_{1mi} are exogenous time-invariant regressors and Z_{2pi} are endogenous time-invariant regressors; $\beta_{1\mathrm{k}}$, $\beta_{2\mathrm{l}}$, γ_{1m}, and γ_{2p} are slope parameters to be estimated and α_i are household-specific effects. In equation (2), we included three time-invariant variables: a region dummy, average distance from plots to natural water source, and altitude.

In addition to the Hausman-Taylor LPM, a probit model is estimated for disadoption of WHT in 2010 using differences from 2005 to 2010 in the values of time-varying explanatory variables and 2010 levels of time-invariant variables. The dependent variable in this model is a discrete variable that indicates whether farmers continued to use or abandoned WHT in 2010. Only data from households that had adopted WHT in 2005 is used in estimation. Differencing the time-varying variables creates a single observation for each household. The observations of the dependent and the explanatory variables for each household allows the estimation of a probit model for 2010 (apparently cross-sectional), although the differenced explanatory variables are computed from the panel data. This model explicitly focuses on the effect of changes in time-varying variables (e.g. labour availability, funds for maintenance), and levels of time-invariant variables (e.g. education level) on disadoption. The differencing also decreases the correlation of some potentially endogenous explanatory variables with omitted variables[4]. We expect similar signs for the coefficients of the explanatory variables in this model compared to those of the Hausman-Taylor based LPM, but not an equal size of the coefficients. The expected signs are similar because the dependent variable is not changed. This probit model is specified as follows:

$$P\left(\mathrm{WHT}_{\mathrm{i},2010} = 1\right) = \Phi\left(\beta_0 + \sum_{\mathrm{k}=1}^{\mathrm{k}} \beta_k \Delta X_{ki} + \sum_{\mathrm{j}=1}^{\mathrm{J}} \gamma_j Z_{ji}\right) \quad i = 1, \ldots., N \qquad (3)$$

where ΔX_{ki} $(= X_{ki,2010} - X_{ki\,,2005})$ are changes in the value of k time-variant variables from 2005 to 2010; β_k are their coefficients; Z_j are j time-invariant variables with coefficientsγ_j; β_0 is a constant term; and Φ is the cumulative distribution function for the standard normal distribution.

In the introduction a number of theoretical and empirical studies on disadoption were discussed. These studies suggest various factors that influence the utility from disadoption, including household, farm characteristics and technology-specific variables. Included household characteristics are education level, age and gender of the household head, and off-farm income. Farm characteristics include availability of labour, livestock, landholding, distance to market, ease of selling output, credit access, farm profit, growing perennial crops, and soil fertility. Technology-specific factors include skills, material and natural conditions determining the suitability of the technology: learning-by-doing, training, plastic shortage, perception of the technology (e.g. as a cause of malaria), and geographical and environmental variables such as plot distance to water sources, months of rainfall shortage (severity) and altitude. Below we discuss and hypothesize their relation to the disadoption of WHTs.

[4] Estimating the probit model with the dependent and the explanatory variables at levels lacks this advantage in a model where some variables (e.g. credit, off-farm income) are potentially endogenous.

- *Education.* Even though education is often believed to stimulate adoption of a new technology, findings on the influence of education on disadoption are mixed. For instance, Gedikoglu and McCann (2009) concluded that more educated farmers tend to disadopt a new technology of injecting manure in United States. On the other hand, Foster and Rosenzweig (2010) concluded that more educated farmers tend to acquire and process information about a new technology and then achieve better returns compared to less educated farmers, so that more educated farmers disadopt new technologies less often. These conclusions indicate that it is difficult to predetermine the effect of education on technology disadoption.

- *Age.* Often, older farmers tend to be more risk-averse (Feder et al. 1985) than younger farmers consequently adopt technologies slowly. Several studies found that older farmers disadopt technologies more frequently (Rahim et al. 2008; Moses and Barrett, 2006). Similarly, in this study we expect a negative sign.

-*Gender.* The effect of gender on disadoption is difficult to predetermine. This is because on the one hand, female-headed households could be interested in WHTs if they can manage the routine farm activity by themselves or have children who handle it. On the other hand, female-headed households tend to consider sharecropping rather than managing their farm by themselves. After the sharecropping arrangement, often female-headed households tend to engage in non-farm activities such as petty trade rather than engaging in irrigation which requires much time.

-*Labour.* Irrigation activities are labour-intensive and water harvesting irrigation is no exception (He et al. 2007). The data from the 2005 survey shows that farms using water harvesting required 34% more labour than rain-fed farms. Unless a household has sufficient family labour the routine irrigation activities could discourage the use of the technology. From field assessments, we observed that females and children often engage in WH irrigation activities in the case of labour shortage. Disadopters often mention labour shortage as one of the factors for their disadopting. Consequently, labour shortage created a demand for water lifting equipment (nearly 34% of the users stressed the need for water lifting equipment as one of the major constraints see Fig.5.1) and based on this, the government exempted motor pumps from import taxes. Farmers who have sufficient labour or motor pumps tend to maintain using WHT whereas farmers who face labour shortage most likely disadopt. Therefore we expect a positive sign on the quantity of farm labour available.

- *Off-farm income.* Some of the sources of off-farm income in Ethiopia include employment in urban centres, food-for-work (productive safety-net program) and petty trade activities. These off-farm activities often compete with irrigation for labour time. If off-farm income is high, farmers could spend more time off-farm than on-farm, which affects the way they operate their irrigated farm. This could lead to disadoption of water harvesting. Therefore, a positive relation is expected between disadoption and off-farm income. Some empirical studies confirm that off-farm income increases disadoption (Rahim et al. 2008; Moser and Barrett, 2003).

- *Livestock size.* Livestock size could influence the probability of disadoption in two ways in the highlands of Ethiopia (our study does not include pastoralists in the lowlands). On the one hand, users of water harvesting might use the water from WHT for their livestock. In relation to this point, the survey data shows that on average WHT users allocate 9.8% of the harvested water for their livestock in 2005, which increased to 19.6% in 2010. Similarly, the number and proportion of users of the water for livestock also increased from 145 (43.6%) in 2005 to 187 (94%) in 2010. On the other hand, farmers in the highlands (where mixed farming is practised) who own large livestock could drop WHT if they generate most of their income from livestock. The findings of Rahim et al. (2008) support the idea that income from livestock could have a disincentive effect. In the former case, livestock motivates to maintain WHT, but in the latter case, it motivates disadoption. Therefore, it is difficult to predetermine the coefficient sign.

- *Landholding.* Small landholding could limit the space the size of ponds and their number. Small landholding could also limit expansion. In such cases, a farmer may not adjust ponds to the required scale-level he wants. The limited scale of operation may discourage these farmers to continue with water harvesting. Similarly, if a farmer has a relatively small plot and is risk-averse, he tends not to invest in high-value crops but rather prefers to grow low-risk low-value crops to secure food for the household and there is low tendency to adopt/continue to use WHT. A related study Gedikoglu (2010) found that smallholders with larger landholding abandon technologies less often than smallholders with little landholding, whereas Wendland and Sills (2008) found the reverse for farmers in Togo and Benin.

- *Distance to market.* With distant markets, the cost of marketing increases. A rise in marketing costs decreases the expected returns from investing on water harvesting. If farmers have already invested in WHT and markets are distant, the probability of disadoption may increase due to high marketing costs. Infrastructure and institutions (Diao and Nin Pratt, 2007; Oskam et al. 2004) could contribute to the ease of accessing markets. Overall, farmers with good market access tend to produce high-value marketable crops and therefore continue to use the technologies.

- *Ease of selling output.* Customers influence the demand for farm outputs in local and international markets. Some of the outputs are sold locally and others (e.g. fruit, vegetables, *chat/*catha edulis) are exported and wholesalers collect them directly from farmers. In the local markets, where smallholder farmers sell most of their output, customer relationship, brokerage, and social capital play a role in selling outputs (see Gabre-Madhin, 2001). The ease of getting customers for those outputs may have a positive effect on the use of WHT.
- *Credit access*. Farmers need funds to buy water lifting equipment, to repair and maintain their water harvesting systems, to substitute exhausted plastic sheets, to hire labour and to buy inputs, etc. Shortage of funds constrains poor farmers with limited financial resources and discourages the use of water harvesting. Consequently, credit access is expected to decrease disadoption.
- *Farm profit.* Returns drive technology adoption and losses cause disadoption (Suri, 2011). In this study we test the effect of farm profit. Farmers with a positive farm return could sustain the use of a new technology because they have the motive of a positive return. In addition, profit income could be a resource to finance maintenance, water lifting equipment and other operational costs to run WHTs. However, profit could also create a disincentive to continue to use the labour-intensive activity of irrigation if most profit is earned from rain-fed agriculture. Therefore, it is difficult to predetermine the effect of profit on the disadoption of WHTs. Other studies found that farm revenue from other perennial crops decreases disadoption (Rahim et al. 2008).
- *Perennial dummy*. Crop choice could affect disadoption of WHT. If a crop is perennial, often it requires less water (Bathgate and Pannell, 2002) because its roots grow deep and extract ground water. Farmers growing some kinds of perennials (e.g. coffee, eucalyptus, mango) use the water from WHT in the early growth stages. This means that once the perennials have grown and start extracting water from the soil, farmers disadopt WHT. However, for other perennials this can be different. For instance, perennials such as *chat* and some species of cabbage found in Ethiopia are leafy and they require a relatively low quantity of water to give leaves multiple times per annum with a small but critical amount of water. Water harvesting may provide these required small but critical water quantities, which is confirmed by the success of WHT in east Ethiopia. So, farmers tend to continue to use WHT if they use it for perennials such as *chat* and in this case a positive relationship is expected between perennials and disadoption.
- *Soil fertility.* Soil fertility affects the water input per unit of land. Sandy soils have low water storage capacity and a high infiltration rate. They require more water than the fertile loam, silt

and clay soils to give the same yield, which means that low soil-fertility could increase disadoption. Reij et al. (1988) and Ngigi et al. (2005) underlined that soil fertility critically affects the success in the use of WHT. In the data, a higher soil fertility index indicates a higher soil fertility, so we expect a positive sign.

- *Learning-by-doing*. Irrigation is a technology that few Ethiopian farmers were familiar with. For instance, only 1.5% of the irrigable land (IFAD, 2009) and only 0.5% of the total agricultural land was irrigated in Ethiopia in 2007 (World Bank, 2006) showing the limited experience of Ethiopian farmers in irrigation, due to which they are unaware of the potential profitability ex ante. Experience with WHT will result in them being better able to assess its profitability (Foster and Rosenzweig, 2010). Moreover, field observations on water harvesting in Ethiopia showed that farmers gradually learned to use WHT. The gradual learning includes controlling evaporation and seepage, managing the watering time and choosing appropriate crops. For instance, farmers learned to use algae and petroleum-ash to decrease evaporation, and to save water by adjusting the time of watering. Because of these experiences, some farmers increased their returns. The positive returns in turn encouraged them to continue to use WH instead of disadopting. The number of years a farmer used WHT proxies learning-by-doing similar to the proxy that Neill and Lee (2001) used. We expect a positive coefficient.

- *Training***.**Training provides skills and experience to construct ponds and other water harvesting technologies, and for site selection, silt-trapping, crop choice, etc. Moreover, trained farmers could excel untrained farmers in economizing on water use. Several studies found that training increases the adoption of rain water harvesting technologies (e.g. Tumbo et al. 2011; He et al. 2007; Sidibe, 2004).Thus we expect farmers who did not take training to be more likely to disadopt.

- *Lack of plastic sheet.* Plastic sheets are often used in constructing ponds for water harvesting. Sufficient supplies of plastic sheets discourages disadoption, however, plastic sheets are not always available because they are not constantly imported. This may be because of lack of interest by the private sector in importing them due to foreign currency shortages, distribution costs, and risks. As a result, there is often a shortage of plastic sheets at local and central markets (e.g. Addis Ababa market). Farmers underlined plastic shortage as a severe constraint not only in maintaining the use of WHT but also in initially adopting it. For instance, in 2010, 43% of both users and disadopters indicated shortage of plastic-sheet as a constraint to using ponds (Fig.5.1). Consequently, some of them disadopted, others could not expand, and still others did not adopt water harvesting. So, the shortage increases disadoption and we expect a negative sign.

- *Perceived malaria problems.* Ponds can be a place for mosquitoes to multiply if they are not frequently cleaned. Farmers could perceive malaria as a health risk to their family because of the use of water harvesting and they may want to avoid this health risk by disadopting water harvesting. Therefore, the perception that the use of WHT causes malaria could increase disadoption.

- *Average distance from plots to natural water sources (NWSs).*Plots close to natural water sources such as rivers, lakes and marshy areas often have a better soil-moisture. This means that if farmers invest in ponds close to a natural water source, they tend to disadopt when they realize that the plots do not need water from the ponds. These farmers may initially have adopted because of their expectations about the return from the technologies or other incentives provided by public institutes to encourage adoption. On the other hand, schemes constructed close to natural water sources could replenish water and seepage, which has a negative impact on adoption and sustenance of WHTs in those areas could also be low (e.g. Ngigi et al. 2005). This means that an increase in plot distance from natural sources decreases disadoption of WHTs.

- *Number of months of rainfall shortage (severity of rainfall shortage).*Investment in ponds is feasible if sufficient rainfall or run-off is available to accumulate. This means that more months of rainfall shortage could trigger disadoption because of no available rainfall to accumulate. However, if the number of months of rainfall-shortage is high and farmers have no option (or it is uneconomical) to use other irrigation methods such as ground water, farmers critically collect the available rainfall (run-off), accumulate and use it for crops. Therefore, it is difficult to predetermine the sign of rainfall shortage.

- *Altitude*. For users of water harvesting in Ethiopia, given sufficient rainfall it is expected that they will harvest sufficient run-off and continue to use it. This increases the probability to continue with water harvesting. Contrarily, steep-slope areas often face soil erosion and siltation and this could destroy the structure of water harvesting technologies. In this case, farmers may disadopt water harvesting. Therefore, altitude could increase or decrease the probability of disadoption.

- *Region.* Differences may exist among regions in the support that they provide in the use of WHTs and the attention paid to small-scale irrigation. Regional differences could also include cultural, social and environmental difference. Studies indicate that these factors are often responsible for the success of irrigation in Africa (You et al. 2011). For instance one region could assign more extension agents than the other, which causes a difference in disadoption. The role of extension agents is an important driving factor in adopting new irrigation technologies in scarce water environments (Blanke et al. 2007). It is difficult to predict the sign of region dummy because of many kinds of variations between regions.

5.3 Study area and data

The Ethiopian Development Research Institute (EDRI) conducted a national survey in 2005 and interviewed 2082 randomly selected households from 30 sub-districts. In 2010, out of these households, 400 were randomly selected from 7 sub-districts that are found in two regions (Oromia and Southern Nations, Nationalities and Peoples/SNNPR) and interviewed for a second time. Of the 400 panel households, for this study we used 332 households who adopted a water harvesting technology in 2005 because adoption is a precondition for disadoption in 2010. Out of these 332 households, 133 of them disadopted WHT between the 2005 and 2010 survey, whereas 199 continued to use it. In addition to quantitative data, we collected qualitative information from field assessments in 2005, 2007, 2009 and 2010. The qualitative information helps to understand disadoption.

Figure 5.1 shows major constraints in using water harvesting listed by both continuing users and disadopters in 2010. Farmers could mention more than one constraint. Shortage of plastic sheets, financial restrictions, shortage of rainfall, seepage and evaporation, and collapse of water schemes are major constraints mentioned. Other reasons include lack of market availability, and shortage of labour and land.

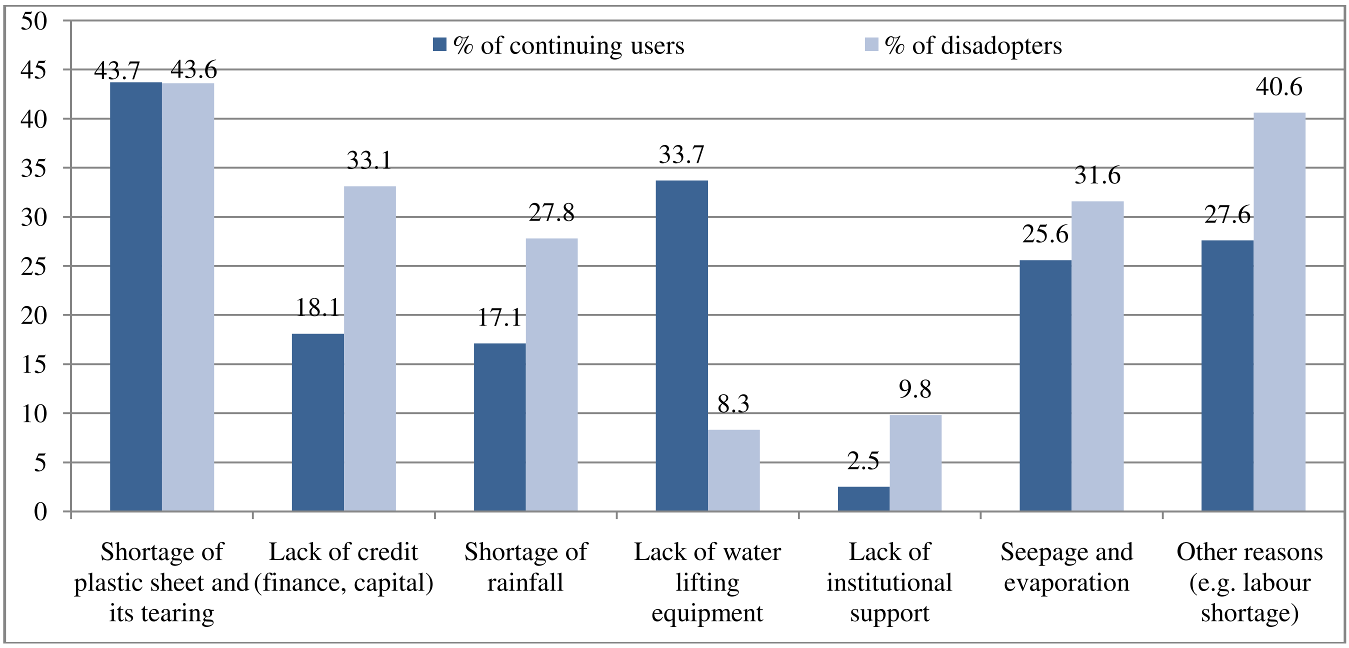

Figure 5.1 Constraints listed by continuing users and disadopters of WHT in the 2010 survey

In the empirical models for disadoption, the dependent variable is whether a farmer continued to use or stopped using (disadopted) WHT in 2010. If the farmer continued to use WHT in 2010, the dependent variable is assigned a value of 1 whereas if the farmer disadopted it is assigned 0.

The data used in estimation is two-period panel data (2005 and 2010) with years missing between the 2005 survey and the 2010 survey. The mean values of the dependent and explanatory variables are summarized in table 5.1.

Table 5.1 Mean of variables[a] used in estimation for continuers and disadopters

Variables	Users N=398	Disadopters N=266
Users-disadopters dummy, 0 = disadopters *(dependent Variable)*	1.00 (0.00)	0.50 (0.50)
Education dummy, 1 if attended school	0.70 (0.46)	0.69 (0.46)
Age of household head	41.30 (11.20)	47.40 (12.1)
Dummy gender of household head, 1 = male [b]	0.93 (0.25)	0.98 (0.14)
Off-farm income, 1000 ETB	1.06 (4.01)	0.87 (2.99)
Labour, in adult equivalent	4.28 (2.12)	4.75 (2.13)
Livestock asset owned, in TLU	7.08 (6.31)	8.65 (9.30)
Total land holding, hectare	1.85 (1.41)	2.44 (2.10)
Distance to market centre, hour	1.23 (0.90)	1.59 (1.01)
Dummy, easy to sell output? 1 = yes	0.73 (0.44)	0.71 (0.45)
Credit accessed, 1000 ETB [c]	0.55 (0.79)	0.30 (0.74)
Farm profit[d], 1000 ETB	5.95 (9.66)	3.04 (5.92)
Dummy, used WH to grow perennials? 1= yes	0.57 (0.50)	0.06 (0.24)
Soil fertility index (higher values show higher fertility)	12.35 (11.10)	16.4 (14.32)
Learning-by-doing (experience in WH, years)	4.83 (3.15)	3.58 (1.91)
Dummy, did you take training on WH? 1= yes	0.74 (0.44)	0.80 (0.40)
Dummy, is plastic sheet a constraint in WHT? 1=yes	0.39 (0.49)	0.39 (0.49)
Dummy, is malaria a health problem? 1=yes	0.25 (0.43)	0.12 (0.33)
Average plot distance from natural water sources, hour	0.67 (0.76)	0.26 (0.60)
Number of months of rainfall shortage listed	3.79 (1.28)	3.91 (1.19)
Altitude above sea level, 1000 meters	1.92 (0.39)	1.92 (0.38)

Region dummy, 1= Oromia	0.66 (0.47)	0.60 (0.49)

a. Standard deviations in parentheses.

b. Gender of household-head changed in 5 of the households from 2005 to 2010: 3 of them to female and 2 to male, possibly due to marriage, divorce and/or death.

c. Note that ETB is the Ethiopian currency Birr. One ETB was 0.0741 USD in June 2010.

d. Farm profit is the sum of rain-fed profit and irrigated farm profit i.e. sum of the gross revenue minus input costs of oxen-days, seed, labour, fertilizer, pesticide expenditures from each farming system.

Table 5.1 indicates that disadopters and continuers have clear differences in the mean values of certain variables. Figures 5.2 and 5.3 show the difference of some of these variables for 2005 and 2010 for continuing users (Fig.5.2) and disadopters (Fig. 5.3). For instance, for continuing users (continuers) the number of farmers growing perennial crops increased whereas for disadopters the number of perennial growers decreased. Interestingly, the opportunity to sell outputs increased and the average distance to markets decreased respectively for both groups. Those variables indicate growing market opportunities, which could contribute to maintain the use of WHTs and produce cash crops.

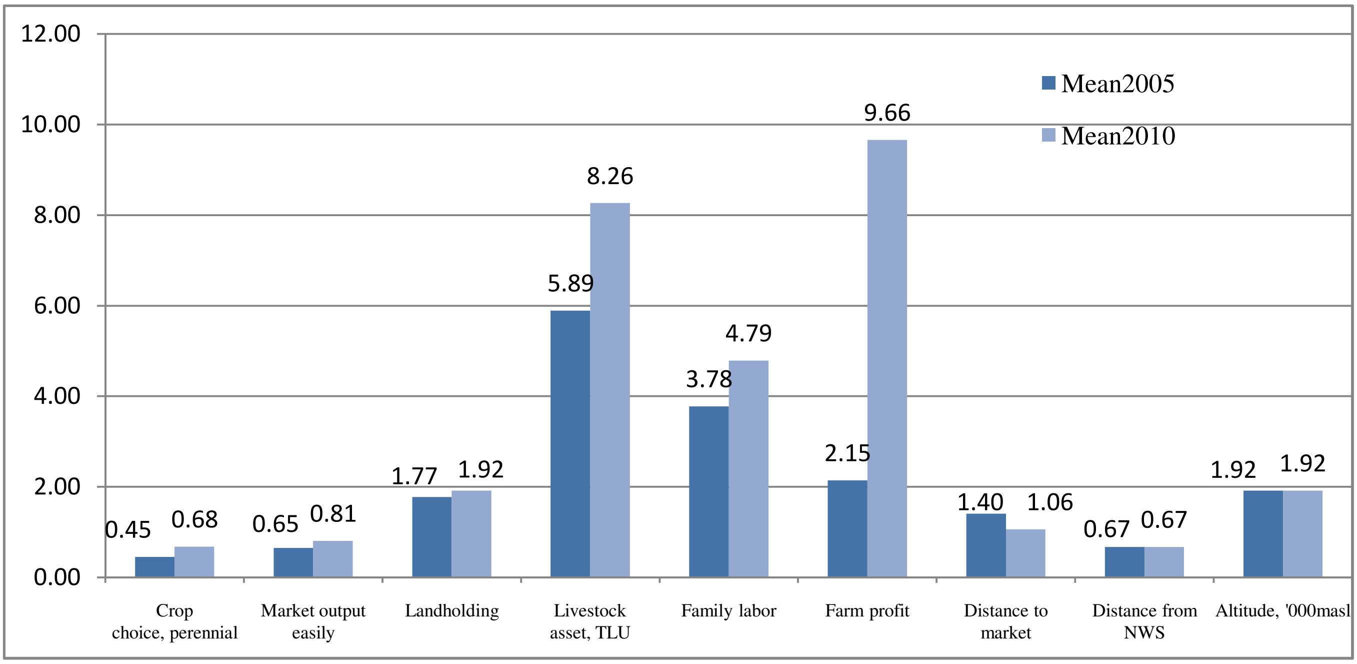

Figure 5.2 Differences in mean of selected explanatory variables in 2005 and 2010, continuers

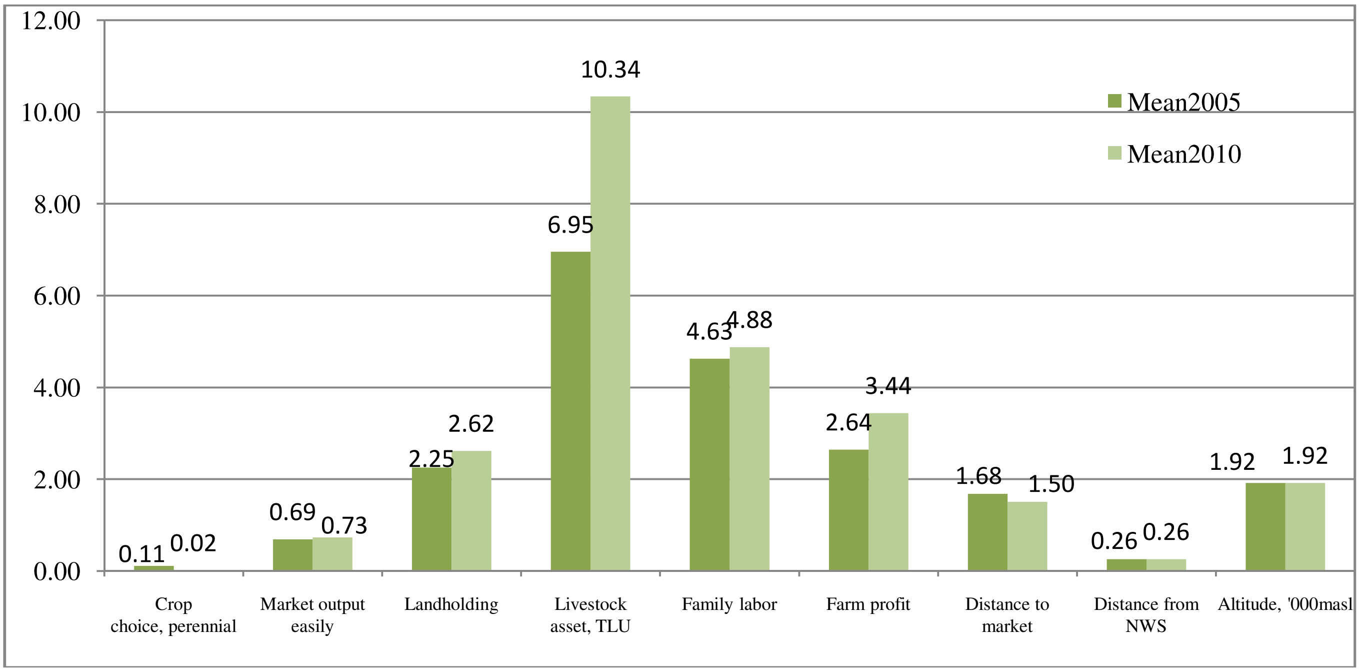

Figure 5.3 Differences in mean of selected explanatory variables in 2005 and 2010, disadopters

Finally, it is interesting to look at the WH technology that the farmers were using before disadoption. Ponds were the dominant WHT adopted in 2005. In 2005, 284 of the 332 households (85.6%) used a pond as WHT; 26 (7.8%) used shallow-wells, 12 (3.6%) used stream diversions and 10 (3.0%) used multiple WHT. The 2010 data shows the overwhelming majority of water harvesting systems disadopted were ponds i.e. for 128 (96%) of the 133 disadopters.

5.4 Results

In this section, the estimation results of the Hausman-Taylor LPM (equation 2) and the probit model using 2010 data (equation 3) are discussed. The Hausman-Taylor LPM is compared to a standard FE-LPM model and specification tests and robustness checks are discussed.

The Hausman-Taylor LPM estimation results are summarized in table 5.2. Variables increasing (decreasing) disadoption have negative (positive) coefficients. Education level, age, off-farm income, the number of rainfall shortage months, shortage of plastic sheets, livestock, soil fertility, and altitude have a negative and significant sign and therefore are associated with higher disadoption. On the other hand, landholding, size of family labour, learning-by-doing (experience in WHT), ease of selling output, farm profit, growing perennial crops, access to credit and participation in training have a significant positive sign and therefore farmers with higher values for these variables have a lower probability of disadopting WHT. The signs of most coefficients are as expected.

Table 5.2 Estimates of disadoption of water harvesting technology in two models [a]

Variable	Hausman-Taylor LPM[b]	Probit [c,d]
Constant	5.171***	-5.017***
	(0.678)	(2.043)
Education	-0.297***	0.336
	(0.056)	(0.244)
Age	-0.072***	-0.209
	(0.006)	(0.208)
Gender	-0.106	-0.831*
	(0.124)	(0.498)
Off-farm income	-0.007*	0.007
	(0.004)	(0.014)
Labour	0.029***	0.171***
	(0.010)	(0.064)
Livestock holding	-0.017***	-0.009
	(0.004)	(0.027)
Landholding	0.037**	0.116
	(0.017)	(0.105)
Distance to market	0.012	-0.058
	(0.021)	(0.147)
Ease of selling output	0.065*	0.937***
	(0.034)	(0.343)
Credit access	0.078***	0.178
	(0.020)	(0.157)
Farm profit	0.007***	0.040***
	(0.002)	(0.015)
Perennials	0.163***	1.415***
	(0.038)	(0.517)
Soil fertility index	-0.004**	-0.009
	(0.002)	(0.012)
Learning-by-doing (experience in	0.026***	1.324***
WHT)	(0.008)	(0.341)
Training	0.090*	-0.016
	(0.056)	(0.335)
Plastic sheet constraint	-0.075***	-0.802**
	(0.027)	(0.327)
Malaria considered as problem	-0.021	0.155
	(0.036)	(0.289)
Average plot distance from	0.048	0.744***
natural water source (NWSs)[e]	(0.127)	(0.224)

Number of water shortage months	-0.020*	-0.100
	(0.011)	(0.094)
Altitude	-0.515**	-0.218
	(0.259)	(0.307)
Oromia	-0.283	0.530*
	(0.205)	(0.291)
Wald (χ^2) or F-tests	χ^2(21): 566.5***	χ^2(21): 60.9***
Count $R^{2, f}$	99.8%	92.7%
Number of observations, N^e	646	315
Number of households	331	315

a. Numbers in parentheses are standard errors; *** p < 0.01, ** p < 0.05 and * p < 0.1

b. Variables including off-farm income, credit access, farm-profit, learning-by-doing, training and growing perennial dummy (crop-choice) are suspected to be endogenous variables and they are instrumented.

c. Probit model estimated on change in time-variant variables and time-invariant variables (at levels) for disadoption in 2010.

d. Missing values for some variables caused a loss of up to 18 observations, and this reduced N from 664 to 645 and from 332 to 315 in the first and the second models respectively.

e. Altitude and average plot distance from natural water sources are time invariant variables.

f. Even without any model, it is possible to correctly predict 82% of the 646 observations and 60% of the 315 observations.

Next, we discuss the factors that significantly affect disadoption in the Hausman-Taylor LPM in more detail. All four household variables have a negative effect, of which three parameters are significantly different from zero. Older farmers have a higher probability of disadopting the water harvesting technologies. Surprisingly, educated farmers have a higher probability of discontinuing the use of water harvesting by 0.30. This result is in line with Foster and Rosenzweig (2010), i.e. educated farmers may realize that water harvesting is uneconomical and therefore disadopt. It could also be that educated farmers have other activities that conflict with time needed for irrigation.

Similar to the finding of Gedikoglu and McCann (2009) and Neill and Lee (2001), we find that off-farm income increases disadoption. Irrigation is a labour intensive activity and this result suggests that off-farm income earners have less time for irrigation activities. This corresponds with the finding that a rise in adult equivalent labour by one unit increases the probability of continued use by 0.029, as expected. Also, our field observations during the survey and the informal discussions with farmers indicated that the shortage of labour resulted in the disadoption of WHT.

Farmers having a large number of livestock tend to disadopt water harvesting. A rise in livestock asset by one TLU ceteris paribus increases the probability of disadoption by 0.017. This shows a positive relationship between disadoption and livestock holding. A possible explanation is that livestock asset owners have other options to diversify their income to decrease the effect of weather risk instead of using water harvesting. This corresponds to the findings of Wendland and Sills (2008) and Rahim et al. (2008). This diversification argument for disadoption of WHT is plausible for mixed farming systems as practiced in highland Ethiopia.

Similarly, owning land decreases the probability of disadoption, and this is expected since the more land farmers have, the more space they have to locate water harvesting systems and they may also have a bigger need for harvested water to reduce rainfall shortage risks. With a hectare increase in landholding, the probability of disadoption decreases by 0.037.

Whereas the distance to the market has no significant impact on disadoption, the coefficient of the ease of selling is positive and significant at 10% critical level. This indicates that when selling output is considered easy the probability of disadoption is on average 0.065 lower than when farmers consider it difficult to sell their output. A lack of market opportunities and price risk may prevent farmers from selling their output that is irrigated by harvested water, and this eventually may lead to disadoption. Difficulties in selling output may also lead to shortage of funds necessary for maintenance and replacement of WHT systems. The increasing popularity of mobile phones could have a positive impact on the marketing of high-value crops. For instance, in the 2005 sample, none of the farmers owned a mobile (cell phone) but in the 2010 survey nearly 12.5% of them used a mobile (cell phone). Such devices enhance the selling of output at a reasonable price thus contributing to continued use of water harvesting.

The coefficient of access to credit is positive, as expected. When the amount of credit taken increases by 1000 ETB the probability of disadoption decreases by 0.078. The positive sign of credit is in line with the descriptive analysis that 33% of the disadopters and 18% of the adopters indicated shortage of finance as a constraint for using WHT. The descriptive statistics showed that farmers lack financial resources to buy water-lifting equipment (to ease labour shortage) and plastic sheets. Also farm profits may serve as a source of funding. The parameter of this variable is also significant, which is in line with Suri (2011), but the marginal effect is much smaller compared to credit. A 1000 ETB increase in profits only decreases the probability of disadoption by 0.007. This relatively low importance of profits suggests that farmers rely more on credit to finance the maintenance of WHT than farm profits. This is plausible since in Ethiopia credit often can only be used for investment in farm equipment (Berhane and Gardebroek, 2011; Berhane et al. 2009), whereas farm profits can be used for household consumption, savings, purchase of inputs, or investment. The significant farm profit variable also indicates that farmers with a more profitable farm tend to continue with water harvesting as opposed to farmers who are less profitable, which is in line with Suri (2011) that returns lead to continuing the use of a technology. The finding that profit has a positive coefficient indicates also that profit income does not have a disincentive effect on water harvesting, which is different from that of Rahim et al. (2008) for farm revenue. Farmers with more profit income could finance equipment and maintenance costs better than farmers with less profit income.

Growing perennial crops also has a positive and statistically significant impact on sustained use of WHT. This is true in the sample sub-districts because the farmers there predominantly use WHT to grow high-value and profitable perennial crops such as *chat*, coffee and fruits. Crop choice often improves water use efficiency (Karrou and Oweis, 2012). Therefore crop choice matters in disadopting WHT. Soil fertility increases the probability of disadoption (marginal effect 0.004, see table 5.3). Possibly, farmers allocate fertile soils for growing cereals, which is a source of food and which relies less on WHT. One of the characteristics of fertile soil is its capacity to preserve soil moisture.

The importance of training and learning for maintained use of WHT technologies is underlined by the positive and statistically significant parameters of these variables. Farmers' capacity to accumulate experience varies. The findings show that those farmers who accumulated more experience maintained the use of WHT, whereas others who accumulated less experience disadopted it, in line with the suggestion that learning-by-doing affects adoption (Foster and Rosenzweig, 2010). The finding is similar to the findings of Wendland and Sills (2008) for soybeans, Moser and Barrett (2006) for rice, and Neill and Lee (2001) for maize technologies, but contrary to the finding of Gedikoglu and McCann (2009). Also, Carletto et al. (1996) found that earlier adoption delayed withdrawal due to the effect of learning-by-doing. Similar to learning-by-doing, the positive and significant coefficient of training indicates that if a farmer takes training, the probability to disadopt decreases by 0.088, showing that training is important in decreasing disadoption. Both these findings are in line with our expectations.

Turning to variables that reflect problems experienced by farmers in maintaining WHT, we see mixed results. Limited availability of plastic sheets significantly increases disadoption (marginal effect of 0.07 in LPM). The plastic sheet was imported and fixed for use in the fixing centres found in each region (e.g. shashemene centre for Oromia and SNNPR) and then distributed to sub-districts for sale to farmers. The discussions with sub-district agricultural bureau staffs indicate farmers who want to adopt plastic ponds were often provided no more than one because of the limited availability. Importantly, the lifespan of plastic used for WHT is estimated at ten years. After ten years, farmers could sustain WHT if they are able to replace worn-out plastic with new. This illustrates that with a limited supply of plastic, farmers have a higher probability to disadopt WHT. This finding is in line with disadoption found at the end of the lifespan of a storage technology in Senegal (Boys et al. 2007).

Fear of malaria is however not a reason for disadoption. This finding is in line with the descriptive statistics that only 22% of the 332 households interviewed in 2005 and 18% of them in 2010 (a declining proportion of farmers) responded by saying that malaria is their concern as a health problem.

Interestingly, the estimation results also indicate that one more month with rainfall shortage increases the probability of disadoption by 0.020. When the number of rainfall shortage months increases, the probability that ponds run dry increases, which may lead farmers to disadopt because of insufficient rainwater to harvest. This finding is similar to the remark of Moges et al. (2011) and is expected because the availability of rainfall is a precondition to harvest rainwater. Apparently this effect is stronger than the need for having WHT due to rainfall shortage. Distance from plot to nearest water source is not found to have an impact on disadoption. The final significant effect is found for altitude. A 1000 meters rise in altitude increases the probability of disadoption by 0.51. At higher altitudes, aridity is expected to fall and the importance of water harvesting seems to be lower.

Finally, we have to remark that the estimated Hausman-Taylor LPM is statistically significant, indicating the rejection of the null hypothesis that the estimated coefficients are jointly zero.

Another model estimated is the probit model[5] using differences of time-varying variables between 2005 and 2010 and 2010 levels of time-invariant variables (equation 3). Its parameter estimates are given in the second column of table 5.2. We found similarities and differences between the Hausman-Taylor and probit estimates. First, the significant variables

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[5] For comparison, a standard FE-LPM is estimated (not depicted here). The FE-LPM is found to be less efficient compared to the HT-LPM estimates and the former considers only a within variation whereas the latter exploits both the within and between variations. On the other hand, both HT-LPM and FE-LPM correctly predicted almost all observations, i.e. 99.8% of the variation in the dependent variable when the unit-specific error-component method is used (Angrist and Krueger, 2001). Without the unit-specific error-component method, HT-LPM and FE-LPM correctly predicted only 72.7% and 82.8% respectively. Nevertheless, the signs of the FE-LPM estimates are similar to that of HT estimates. The difference between their coefficients is in the level of significance and marginal effects.

in HT (labour, ease of selling output, farm profit, perennial crops, learning, and plastic sheet shortage) have similar signs and are also significant in the probit estimates. Second, many significant coefficients in the HT estimates are not significant in the probit, but most of the signs are similar (age, off-farm income, livestock, credit, soil fertility, training, water shortage months, and altitude). This shows that the probit estimates are less efficient. Third, the sizes of the coefficients of the two estimates are different and this is expected. This is because the two models have different functional forms, use different estimation techniques and the probit model uses fewer observations. Finally, no significant variable carried opposite and significant signs in the two models (no controversial sign that makes interpreting difficult).

In the estimated probit model, plot distance from natural water sources, the region dummy for Oromia, and gender had statistically significant parameters, in contrast to the HT model. The former two are associated with lower disadoption whereas gender increases disadoption. Male household heads have a probability of disadoption that is 0.83 higher compared to females, which is surprising and opposite to what we expected. However, we have to be careful in interpreting this result given the small number of female household heads in the sample. The estimated marginal effects in probit (see column 3 in table 5.3) indicate that a change in average plot distance from natural water sources by an hour decreases the probability of disadoption ceteris paribus by 0.29. This means that the further the plots are from natural water sources the lower the tendency to disadopt, indicating that to farmers with their plots far from natural water sources water is scarce and scarcity of water urges the use of WH. This is consistent with the suggestion of Tzialla et al. (2006). Similarly, the time-invariant region dummy is statistically significant and has the expected sign. The positive coefficient of the regional dummy indicates disadoption was significantly lower in the Oromia region. The regional variation may be due to environmental, institutional and cultural factors. For instance, the descriptive data computed for 2010 (not depicted here) indicates that the average extension visit per month is 2.9 in Oromia whereas it is 2.3 in SNNPR, pointing to the difference in the level of institutional support. On the other hand, the fact that WHT was stimulated in rainfall-abundant and rainfall-scarce regions equally could also stimulate disadoption. In our 2005 and 2007 field assessments in the four regions, interviewed officials of the Regional Agricultural Bureaus indicated that WHTs should not be uniformly stimulated in both rainfall-abundant and rainfall-shortage areas.

Interestingly, the probit model estimates on the changes in time-variant explanatory variables correctly predicted 92.7% of the dependent variable, exceeding the prediction of both HT and FE-LPM, but the prediction of the latter is based on 315 observations. On the other hand, the HT model including unit-specific error-component predicted disadoption almost 99.8% because the unit-specific error-component scales the equation.

Table 5.3 Estimates of marginal effects in two models

Variables	Marginal effect (HT-LPM) (dy/dx)[a]	Standard errors	Marginal effect Probit (dy/dx)[a,b]	Standard errors
Education	-0.297***	0.056	0.13	0.09
Age	-0.072***	0.006	-0.08	0.08
Gender	-0.106	0.124	-0.28**	0.13
Off-farm income	-0.007*	0.004	0.003	0.01
Labour	0.029***	0.010	0.17***	0.06
Livestock holding	-0.017***	0.004	-0.001	0.01
Landholding	0.037**	0.018	0.05	0.04
Distance to market	0.012	0.021	-0.02	0.06
Ease of selling output	0.065**	0.034	0.36***	0.12
Credit access	0.078***	0.020	0.07	0.06
Farm profit	0.007***	0.002	0.02***	0.01
Perennials	0.163***	0.038	0.49***	0.13
Soil fertility index	-0.004*	0.002	-0.004	0.004
Learning-by-doing (experience in WHT)	0.026***	0.008	0.52***	0.15
Training	0.090*	0.050	-0.01	0.13
Plastic sheet constraint	-0.075**	0.027	-0.30***	0.12
Malaria considered as problem	-0.021	0.036	0.06	0.11
Average plot distance from natural water sources	0.048	0.127	0.29***	0.09
Number of water shortage months	-0.020*	0.011	-0.04	0.04
Altitude	-0.515**	0.259	-0.09	0.12
Oromia	-0.283	0.205	0.21*	0.11

a. *** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$

b. Marginal effects (ME) of a continuous variables indicates the change in the probability of disadoption with a change in an explanatory variable by a unit (but precise for instantaneous change) holding other variables at their mean whereas ME of a dummy indicates change in the probability of the disadoption for a move from 0 to 1, holding other variables at their means.

5.5 Conclusions and implications

Documents indicate that low water intensity and lack of irrigation have constrained crop yields and kept productivity low in Africa. In several African countries there were various attempts to redress this problem. Recently introduced water-harvesting irrigation technologies in Ethiopia are one of those attempts. In addition to the benefits that farmers can earn due to improved yields and reduced risk of water scarcity, these irrigation technologies are attractive for smallholders due to the relatively low investment outlays they require, the fact that they fit to the land tenure system, and that they can easily be extended. But despite the benefits and attractive properties high disadoption rates, varying from 3% to 72%, with an average of 42% are witnessed in our sample areas. In this study we investigated the causes of disadoption of water harvesting technologies. For this purpose, two binary choice models are estimated using two-period panel data collected from Ethiopia in 2005 and 2010. The first model is a Linear Probability Model that is estimated using the Hausman-Taylor panel data estimator. The second model is a probit model that explains disadoption in 2010 based on changes in time-varying variables between 2005 and 2010 and levels of time-invariant variables in 2010.

The estimation results suggest that a variety of factors exist that relate to disadoption. As expected, some of these factors correspond with the reasons farmers reported for their disadoption during interviews such as shortage and tearing of plastic sheet, labour shortage, lack of credit (e.g. to buy a motor pump), and rainfall shortage. Other factors that were found to be significantly related to disadoption but not reported by farmers are often in line with the scant economic literature on disadoption. These include learning-by-doing, training, and negative income effects e.g. due to owning livestock. However, in the quantitative analysis, this study could not capture how the top-down approach of stimulating water harvesting may have contributed to disadoption. Farmers' views were hardly considered when the technology was introduced. The qualitative information indicates that this contributed to disadoption.

Some recommendations can be given for decreasing and stopping disadoption of water harvesting systems. Variables strongly affecting disadoption, such as labour shortage, lack of credit, non-participation in training, and plastic sheet shortage should be given attention by extension agents and policy makers. The measure taken to decrease the import tariff on motor pumps to encourage their use could ease labour shortage. Motor pumps ease labour shortage because they ease both lifting water from the sources and support water transport. Those activities are time -consuming and tiresome if they have to be done manually. A problem related to the motor pumps is the low financial capacity of farmers to purchase them. For poor farmers, even subsidized motor pumps are often still too expensive. Therefore, subsidizing the motor-pumps is not a final solution unless farmers are supported through access to credit.

Farmers indicate the shortage of plastic sheets as a major constraint to the use of water harvesting. The parameter estimates also confirmed that the shortage of plastic sheets causes disadoption. In addition, local institutes confirm plastic sheets shortage as a serious bottleneck in water harvesting. The estimated maximum lifespan of plastic sheets is 10 years, and if not supplied in time farmers could disadopt water harvesting via ponds. The shortage not only affects farmers already using ponds for water harvesting but also farmers that aim to adopt it and those who are faced with torn plastic-sheet ponds, cracked cement and clay ponds and who want to replace them with plastic sheets, similar to the case in China (Li et al. 2000). Therefore it is critical to ensure the supply of plastic sheets to decrease disadoption. The shortage of plastic sheets also signifies the role of institutions in stimulating technologies in developing countries. Plastic was imported and supplied with the support of public institutions initially. Later on, public institutes withdrew from supporting the supply of plastics, and this was not continued by traders or other private parties, leading to shortages. This shows that the success of a newly introduced technology also depends on whether private market parties can take over (some of) the initial role of public institutes. For the supply of plastics, this seems not to have happened in a proper way, which is a lesson for institutional intervention in stimulating new technologies.

Training farmers also proved to be important in decreasing disadoption. Training on technical skills helps farmers maintain schemes and maximize the quantity of harvested water. Training on water harvesting focuses on site selection, water saving, crop choice, water use efficiency, and returns. In addition, training helps experts to disseminate best practices of water harvesting. The role of extension agents is also essential in reducing disadoption. The findings indicate that there is less disadoption in Oromia compared to SNNPR. One source of regional difference could be the level of institutional support such as extension advice. Extension agents (and the government) could evaluate and re-evaluate farmers' performance in water harvesting and introduce farmers to best practices, facilitate information exchanges and local input supplies. Extension agents could also play a role in stimulating informed crop choice decisions by farmers. The results also showed that farmers who grow perennial crops disadopt less. Advice by extension agents on crop choice is necessary. This advice should not only focus on crop water requirement but also on market availability and other costs.

CHAPTER 6

DOES WATER HARVESTING INDUCE FERTILIZER USE AMONG SMALLHOLDERS? EVIDENCE FROM ETHIOPIA[1]

Abstract

Rainfall shortage is a major production risk for smallholder farmers. Due to rainfall shortage, smallholders limit the use of modern inputs such as fertilizer and improved seeds. This study investigates if water harvesting technologies (WHT) induce fertilizer use and whether there is joint adoption of fertilizer and water harvesting technologies. Using panel data collected from Ethiopian farmers in two regions in 2005 and 2010, a random effects probit model and a bivariate probit model are estimated to investigate these two issues. Both models include variables that are hypothesized to affect fertilizer and WHT use. The findings indicate that: 1) water harvesting increases the probability of using fertilizer; 2) past WHT use positively affects the probability of current fertilizer use but past fertilizer use does not affect current WHT use;3) total landholding, farm capital, and education significantly increase the probability of fertilizer use whereas the price of fertilizer, distance to market decrease the probability of fertilizer use; 4) there are significant regional and yearly differences in fertilizer use; 5) growing perennial crops and distance from natural water sources increase the probability of using water harvesting in 2010 whereas distance from markets, age and altitude decreases it. These results imply that measures encouraging water harvesting can also lift low fertilizer use in Ethiopia among Ethiopian smallholders.

Keywords: water harvesting, fertilizer, panel data, Ethiopia

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6.1 Introduction

Rainfall shortage is a major production risk for smallholder farmers. Due to rainfall shortages smallholders limit the use of modern inputs such as improved seeds and fertilizer (Alem et al. 2010). Especially in developing countries, limited use of modern inputs has prevented farmers from reaching high yields (Ruttan, 2002). Therefore, limited and irregular rainfall leads to low production directly and indirectly (via low fertilizer use), and consequently to food insecurity and occasional famines in developing countries such as Ethiopia. The World Bank (2011) stresses that already in Ethiopia in 2011 five to seven million people suffered from chronic food insecurity due to recurring rainfall shortage and low output.

Ethiopia implemented several water and soil conservation programs to ensure food security since the severe droughts of the mid-1970s. Communities carried out soil and water conservation activities throughout the country. Additionally, public institutions invested substantial resources in R&D to stimulate innovations that increase productivity (e.g. improved seed varieties). Although these programs had positive contributions (Gebremedhin et al. 2009; Gemeda et al. 2001; Shiferaw and Holden, 1999), their success in increasing productivity is often constrained by water shortages. Due to low investment in water supply mechanisms such as irrigation, farmers do not apply productivity increasing innovations sufficiently.

Recently, in an attempt to reduce risks for smallholders, there is a policy shift to encourage farmers to invest in risk reducing technologies on their land. Whereas Ethiopian farmers in the past had little incentive to invest on their land due to lack of property rights, the land certification that started in some of the regions in 2003 and that safeguards tenure security (Deininger et al. 2008) has changed this. Among these risk-reducing investments are small-scale water-saving technologies that are often denoted as water harvesting technologies (WHT).

Water harvesting technologies include ponds, shallow-wells and stream/river diversions. These technologies help to accumulate rainfall water or water from floods that can be used if rainfall shortages occur in the future. Ponds are the dominant WHT used in Ethiopia, accounting for 65% of the constructed WHTs. The surface of ponds is often sealed with plastic, cement or clay so that they can hold water for a relatively long time. Average capacity is about $65m^3$ and the catchment area varies from 0.4 to 2.5 hectares. Run-off from natural catchments or from roads, natural water courses, foot paths and cattle-tracks (Ngigi et al. 2005) is used to fill ponds. Some ponds are covered to protect evaporation. The second type of WHT (20%) is shallow-well. Farmers dig them in areas of accumulated flood or in areas with high groundwater levels. The remaining 15% of WHTs are stream/small river diversions. Some farmers divert the run-offs to their plots to increase soil moisture. In this study we do not distinguish between these three types of WHT.

In Ethiopia, WHT are introduced and encouraged on a large scale since early 2000s. Since this period a large number of Ethiopian farmers adopted WHT, although they were used before in some regions of Ethiopia. Farmers that invested in these technologies are expected to use fertilizer due to the reduced risk of water shortage. This is because the functioning of fertilizer nutrients in crop production depends on the availability of sufficient water, in line with Von Liebig's agronomic principle of law of the minimum (de Wit, 1992; Paris, 1992). If sufficient water is available, it dissolves the fertilizer nutrients so that roots can properly absorb the nutrients. In contrast, if there is a shortage of water, the chemical fertilizer would dehydrate the roots and damage the crop. This indicates that to use purchased fertilizer, a farmer has to have confidence in the quantity of rainfall (water). If the water from rainfall happens to be insufficient, the farmer may use an alternative source of water, e.g. water collected in WHT. So, WHT could have a positive impact on fertilizer use. However, even though the availability of water is a precondition for effective use of fertilizer, its demand is not only conditioned by the availability of water but also by other factors that affect supply and demand of fertilizer. Dercon and Hill (2009) reported that fertilizer use by small farmers in 2007/08 was only on 39% of cultivated area. Zerfu and Larson (2011) investigated the functioning of fertilizer markets in Ethiopia and focused on factors that determine fertilizer demand without looking into the interaction between water availability and fertilizer use.

A preliminary analysis of the data used in this study indeed shows that farmers who use WHT apply fertilizer more often than those who do not use WHT. However, such a casual glance is not sufficient to conclude that differences in fertilizer use are due to WHT. It could be that farmers who have better financial means are better able to both invest in WHT and purchase fertilizer. Moreover, there can be regional factors that encourage both the use of WHT and fertilizer. For instance, in regions with strong emphasis on promoting WHT, extension agents may also emphasize the benefits of using fertilizer in conjunction with WHT. In regions that pay more attention to rain-fed farming there may be less attention for promoting fertilizer. This may lead to a situation of joint technology adoption, i.e. farmers adopting both technologies simultaneously. In this case it is not only WHT that stimulates fertilizer use via its risk-reducing effect, but use of fertilizer may in turn spur investment in WHT. In other words, one question is whether WHT has a causal effect on fertilizer use, but another question is whether this causal effect also is the other way around. To assess the presence and direction of these causal effects between WHT and fertilizer use a more rigorous analysis is required.

Empirical literature shows that modern inputs are used more in irrigated farming than rain-fed farming and as a result productivity is higher in the former. For instance, Gollin et al. (2005) underlined that the green revolution had the highest impact in irrigated cereals. Similarly, Byerlee and Siddiq (1994) reported that the increased use of fertilizer was substantially higher in irrigated areas compared to rain-fed areas. Lamb (2003) and Smith (2004) suggested that the use of irrigation increases fertilizer demand. Additionally, some studies showed that because of water shortage the use and effectiveness of fertilizers may be limited. Olwande et al. (2009) and Jayne et al. (2003) concluded that production risk and low returns cause low fertilizer application in Africa. To see how the quantity of water affects the effect of fertilizer, Li et al. (2004) conducted a field experiment in a Chinese semi-arid area and found that the highest quantity of water from water harvesting (400 mm) gives a maximum wheat yield from fertilizer compared to the yield from fertilizer on successive lower quantities of water. In related studies focusing on Ethiopia, agronomists conducted studies focusing on optimal fertilizer in various soil types (e.g. Kebede and Yamoah, 2009; Abegaz, 2008) and in various water supply conditions (Bekele and Tilahun, 2007), and the effect of supplementary irrigation on yield (Bello, 2008).

The objective of this study is to investigate the causal relation between water harvesting and fertilizer use in Ethiopia. We first focus on a potential causal effect of WHT on fertilizer use. Second, we consider the possibility of joint technology adoption of WHT and fertilizer. To analyze these issues we exploit two-period panel data collected from Ethiopian farmers in two regions in 2005 and 2010 and estimate two binary choice models. The use of panel data in our analysis has a number of advantages compared to cross-sectional data, which is often used in technology adoption studies. First, panel data allows for dealing with unobserved heterogeneity among farmers and across time. Unobserved differences in attitudes towards technology, farm management, risk and time preferences, and environmental conditions are relevant in our context and can be accounted for. The same holds for unobserved year effects. This reduces omitted variable and selection bias problems increasing the reliability of parameter estimates. Second, panel data provides both variation between farms and variation within farms (over time), leading to better parameter estimates. Third, it allows for investigating the changes in WHT and fertilizer use over time, which can be exploited to investigate whether WHT preceded fertilizer use or vice versa. This feature of panel data has proven valuable in other impact assessment studies (e.g. Berhane and Gardebroek, 2011).

The use of farm panel data to analyze the relation between WHT and fertilizer is one of the contributions of this study to the literature. Other studies that focus on the effect of WHT or irrigation on fertilizer use are often based on cross-section data (e.g. Gebregziabher and Holden, 2011) or data from research stations (Fox et al. 2005). Another contribution of this study is to analyze the direction of causality between WHT and fertilizer use. Fox et al. (2005) and Gebregziabher and Holden (2011) consider the importance of supplementary irrigation on fertilizer use, but do not investigate whether fertilizer use could also spur investment in WHT, although Fox et al. (2005) do suggest the importance of joint adoption. Compared to other studies that specifically focus on fertilizer use decisions (e.g. Alem et al. 2010; Jayne et al. 2003; Olwande et al. 2009) our study adds WHT, which reduces soil moisture stress, as an important factor in explaining fertilizer use.

The paper is organized as follows. Section 6.2 describes the conceptual framework and section 6.3 describes the available data and the variables used in estimation. Section 6.4 presents the empirical models and the estimation procedures. Estimation results are presented in section 6.5. Conclusion and implications are given in section 6.6.

6.2 Conceptual Framework

6.2.1 Factors affecting fertilizer use

Fertilizer is added to soil to provide nutrients that are deficient in the soil. Plants absorb these nutrients if soil moisture and other soil characteristics are favorable, which may lead to yield improvement. Numerous studies exist that investigate yield changes due to fertilizer use under various conditions (e.g. Gandorfer et al. 2011; Fox et al. 2005; Rötter and van Keulen, 1997). However, agronomic conditions such as soil moisture and soil quality are not the only factors that determine fertilizer use. In developing countries fertilizer is often a scarce input that involves economic decisions by farmers in buying and using it. Demand for fertilizer is explained by micro-economic production theory, which states that input demand is a function of input and output prices and the level of quasi-fixed inputs such as labour, capital (proxied by the number of oxen owned) and land. Other variables affecting the use of fertilizer include ease of accessing inputs (representing transaction costs proxied by distance to market) and availability of complementary inputs (Duflo et al. 2008). Moreover, in developing countries household characteristics such as education, age, gender and household size affect demand for inputs such as fertilizer (Sadoulet and de Janvry, 1995: 162). As argued already in the introduction, water harvesting is expected to stimulate fertilizer use because it prevents shortages of water, which is necessary for the absorption of fertilizer nutrients. Moreover, water harvesting is expected to reduce the risk of crop failure due to drought, which reduces the risk of wasting applied fertilizer.

In this study we focus on explaining whether farmers' fertilizer use decisions instead of explaining applied fertilizer quantities, since reported quantities turned out to be unreliable in our dataset. Based on the discussion above and relevant literature, the following variables are assumed to affect fertilizer use:

- *Water harvesting*. A key hypothesis in this study is that WHT increase the use of fertilizer. Soil moisture is a precondition for the functioning of inorganic nutrients so that roots can absorb the nutrients through diffusion. Diffusion of nutrients is weak when there is insufficient water. Farmers can use the water from WHT to overcome water shortages. Therefore, a positive relationship is expected between WHT and fertilizer use.

- *Price of fertilizer.* In microeconomic production theory, input demand is a function of all prices assuming perfect market conditions. Although we recognize that these perfect market conditions are not met in the Ethiopian context, nevertheless we expect that prices are important drivers in fertilizer demand. Studies mention that high fertilizer prices hamper fertilizer application in Africa (e.g. Olwande et al. 2009). However, rather than absolute prices, relative prices would be more appropriate because farmers compare input cost with the return from output. However, getting accurate data on relative fertilizer prices is difficult and therefore we choose to include the absolute fertilizer price. In our dataset the absolute price of fertilizer varies among farmers. There are two reasons for this: (1) the transport cost per kg of fertilizer from the port of Djibouti to different locations in Ethiopia is different and this transport cost is added to the fertilizer price. Jayne et al. (2003) discussed the effect of port distance on fertilizer price in Kenya, Ethiopia and Zambia in detail; (2) some farmers buy small quantities of fertilizer from other farmers at a slightly higher unit price than the initial price paid at the fertilizer distribution center[2]. An increasing price decreases the demand for fertilizer and therefore we expect a negative sign. See Larson and Frisvold (1996) and Agwe et al. (2007).

[2]Some farmers only use a small quantity of fertilizer (e.g. less than a full bag of 50 kg) on some specific small plots (e.g. vegetables), which they buy from other farmers. Others buy from colleagues to overcome small fertilizer shortages. Instead of buying a full-bag of fertilizer at full cost (which may not be used up), buying a small quantity of fertilizer for a slightly higher per unit price can be economical.

- *Land.* Farmers with large landholding are expected to have a higher chance of using fertilizer than farmers with small landholding because large farmers are usually richer than small farmers. On the other hand, in subsistence farming large landholders may have a higher probability of owning some fertile land. Owning more fertile land may imply that a farmer is well able to produce at least a subsistence level of food, decreasing the probability of using fertilizer. Small landholders may intensify their plots and maximize yield by applying fertilizer to secure food. This implies that the probability of applying fertilizer could also be higher for small landholders. So, the effect of total land on fertilizer use can be either positive or negative.
- *Labour.* The expected effect of labour on fertilizer use is negative. In traditional Ethiopian farming, farmers who have sufficient labour plough, weed, and clean their fields frequently. Farmers believe that ploughing a plot frequently increases the soil fertility, decreases weeds and hence increases yield. So fertilizer and labour can be substitutes, and the more labour used the lower the probability of using fertilizer. Zerfu and Larson (2011) found a negative but insignificant relationship between labour and fertilizer demand in Ethiopia.
- *Farm capital.* The number of oxen proxies for farm capital. Similar to labour, farmers with many oxen could plough their land more often to increase the soil fertility, which may lower the probability of using fertilizer. However, in contrast to this, farmers with more oxen are wealthier which increases the probability of fertilizer use so that the sign of this variable cannot be predicted prior.
- *Farming experience*. Good farm management increases the probability of using fertilizer. In this model we included the number of years of farming experience. More years of experience could increase the probability of using fertilizer compared to less years of experience. However, experience correlates with age and older farmers could be more conservative towards using fertilizer than younger farmers. Therefore, it is difficult to hypothesize on the direction of this effect.
- *Education*. Several studies found that the effect of education on fertilizer use in Ethiopia is positive and statistically significant (Zerfu and Larson, 2011; Fufa and Hassan, 2006) but Duflo et al. (2008) did not find any effect of education on fertilizer use. Given these mixed outcomes, we think it is relevant to investigate the effect of education on fertilizer use.
- *Distance to market.* Sadoulet and de Janvry (1995:76) listed road infrastructure as a major factor affecting input demand. In developing countries, the assumption of a perfect market is often invalid and markets frequently fail (Fafchamps, 2004: 7-12). The market distortion is usually measured by the transaction cost, and home to market distance proxies this transaction

cost. When transaction costs increase, it discourages the use of fertilizer (Duflo et al. 2008). In Ethiopia, the government invested substantial resources in rural road infrastructure and this decreased the average distance to market from 1.54 hour in 2005 to 1.22 hour in 2010. This could affect fertilizer use positively because many market centers correspond to fertilizer distribution centers. Therefore, distance to market is assumed to have a negative effect on fertilizer use.

- *Growing perennials.* Crop choice affects fertilizer use decisions. It is uncommon to use fertilizer for perennial crops. If most of the plots of the farmer are occupied with perennial crops, the probability of using fertilizer is assumed to decline.

- *Household size*. Based on microeconomic theory, when production and consumption decision are inseparable, household characteristics that affect consumption could affect input demand. In developing countries, households allocate financial resources to buy inputs after preserving a minimum level for household food, especially when there is a credit constraint. Some households exhaustively consume their harvest and later they are constrained to buy inputs such as fertilizer. This is particularly true for large family households. In addition, some households prefer paying school fees for their children instead of buying inputs and this could cause a financial constraint for purchasing inputs. The same argument is forwarded in Zerfu and Larson (2011). An additional effect of a large family is the availability of labour for work in the field and fertility management. This lowers the need for purchased inputs since labour acts as a substitute. Based on these two effects a negative relation is expected between household size and use of fertilizer.

- *Share of water used for livestock.* Water from water harvesting could be used for multiple purposes. For instance, in 2005 and in 2010, the users of WHT on average used 9.7% and 19.6% of their water for livestock respectively. Based on these figures, one can hypothesize that when households share the water from WHT to their livestock, the volume that is available for irrigation declines, which indirectly decreases the probability of fertilizer use. Using harvested water for livestock may occur if households can earn a higher income from livestock rearing than from crop growing (Tulu, 2006).

- *Soil fertility.* Farmers with fertile soils may not need to use fertilizer. Therefore, higher soil fertility is assumed to decrease fertilizer use.

- *Year dummy.* Data we use for empirical analysis is panel that was not collected over consecutive years. The data was collected in 2005 and in 2010; hence the socio-economic dynamics over these years may have changed implying that some unobserved variables could have an impact on fertilizer use. We try to capture the effect of such unobservables by including a dummy variable to distinguish 2005 from 2010.

- *Region dummy*. The sample households are surveyed from two regions, Oromia and SNNPR. To capture differences between these regions a regional dummy is included.

6.2.2 The effect of fertilizer and other factors on WHT adoption

As technology components, fertilizer and water harvesting differ in that fertilizer is a short-run input whereas water harvesting is a long-run investment that decreases risk of crop failure, which may stimulate the use of purchased inputs such as fertilizer as argued above. In turn, one could argue that the use of fertilizer causes the adoption of WHT. This is because farmers using nitrogen fertilizer try to minimize its losses by controlling the timing of application during the crop growth period (Lisson and Cotching, 2011; Shapiro and Sanders, 1998; Huang et al. 1993). This can be better controlled if there is a reliable supply of water, which may be provided by WHT. Fertilizer users may therefore improve fertilizer application by adopting WHT. A reverse causal relation like this is supported by the literature. For instance, Kim and Schaible (2000) estimated a demand function for irrigation water with fertilizer price as an explanatory variable and found that fertilizer price increases irrigation water demand. This suggests that fertilizer use may relate to investment in WHT. So, fertilizer and WHT use could have a two way causal relationship, which is worthwhile to investigate. Existence of this two-way causality supports the idea of joint technology adoption of WHT and fertilizer. Other empirical studies underline the possibility of two-way causality between using technologies (Zepeda, 1994; Foltz and Chiang, 2002).

To investigate the case of joint technology adoption of fertilizer and WHT we need to estimate the relationship between WHT adoption and variables that are assumed to affect it, including fertilizer use, in addition to reverse relation between fertilizer and WHT as discussed in section 6.2.1. This joint relation is investigated in the second part of the empirical analysis. Besides fertilizer the following variables are hypothesized to affect WHT adoption:

- *Landholding*. If smallholders have limited land, they may not have enough space to dig or to expand ponds. Studies such as Jara-Rojas et al. (2012) and Gedikoglu (2010) found that farmers with much land adopt and continue to use technologies more often than farmers with little land, whereas Wendland and Sills (2008) found the reverse for farmers in Togo and Benin. This shows the difficulty to hypothesize on the effect of land on WHT adoption.

-*Labour*. Irrigation activities are labour intensive and for successful use of irrigation, labour availability is a prior factor (Moser and Barrett, 2003; Noltze et al. 2012). The labour intensive activities in irrigation include watering, managing water schemes, cleaning and maintenance. These activities are difficult to do in a situation of limited labour. Therefore we expect a positive effect of the quantity of available labour on WHT adoption.

- *Education*. Foster and Rosenzweig (2010) discuss how education affects technology adoption and conclude that more educated farmers tend to acquire and process information about a new technology in a better way compared to less educated farmers, which leads to better returns for the former. Education is therefore expected to have a positive effect on water harvesting adoption.

- *Distance to market.* With access to markets, the cost of marketing is low. Low marketing costs increase the expected returns from investing in water harvesting. Therefore, if farmers are close to markets, the probability of WHT adoption is expected to increase.

- *Perennial crops*. Crop choice is assumed to affect adoption of WHT. Perennials often require less water because their roots grow deep and extract ground water. Perennials with deep roots such as mango, guava and coffee collect water and moisture from the ground, which suggest there is no strong need for WHT. Other perennials such as *chat (catha edulis*) require a relatively low quantity of water to give leaves multiple times per annum with a small but critical amount of water. Water harvesting may provide this required small but critical water quantities to *chat*.

- *Soil fertility.* Soil has an intrinsic contribution to output, and the variation in its fertility affects output. However, it is difficult to predetermine the effect that soil fertility has on the adoption of water harvesting. Some soils hold little moisture and the use of water harvesting could improve this. For instance, sandy soils have low water storage capacity and high infiltration rates and they require a larger amount of water than fertile loam, silt and clay soils to give the same yield. Lichtenberg and Zilberman (1986) found farmers adopt a land quality-augmenting technology primarily on lower quality land.

- *Age*.Age affects adoption through its effect on risk-taking and on human-capital formation (Feder et al. 1985). Older farmers tend to be risk averse and resistant to changes, and consequently adopt technologies less frequently. This is confirmed by several studies, e.g. Rahim et al. (2008) and Moser and Barrett (2006).

-*Gender.* Female headed households are hypothesized to have less information on WHT and be short on labour compared to male headed households and therefore a negative effect for female-headed households is expected.

- *Training***.** Farmers who took training on how to use and manage water harvesting are more skilled in selecting sites for WHT and selecting crops based on crop water-requirement than farmers who did not take training. Training is therefore expected to be positively related to WHT adoption. E.g. Noltze et al (2012) found that training increases the probability of adoption of system of rice intensification in East Timor.

- *Average distance from plots to natural water sources.* Plot distance to natural water sources such as rivers, lakes and marshy areas affects soil moisture. If most plots of a WHT user are located close to a natural water source, the quantity of water to be used from water harvesting is low due to better soil moisture. Moreover, schemes constructed close to natural water sources could replenish water and seepage in those areas could also be low, which motivates investment. On the contrary, farmers whose plots are far away from natural water sources pay more attention to water harvesting because water scarcity is relatively higher. In this case, an increase in plot distance from natural sources could stimulate adoption. So, it is difficult to hypothesize on the effect of plot distance on WHT adoption.

- *Altitude*. In Ethiopia, high areas are characterised by more rainfall than low areas. For farmers that adopted water harvesting it is expected that they harvest sufficient run-off and continue to use WHT when there is sufficient rainfall. In this case, we expect a positive relation between altitude and adoption. On the other hand, high altitude areas are often affected by floods and landslides. Ayalew (1999) concluded that in Ethiopia areas with altitudes exceeding 1750 meter above sea level are sometimes hit by heavy flood and landslides. Floods could fill ponds and shallow-wells and silt could wash them away. With landslides, ponds and shallow wells could collapse. Awareness of such possible events could make farmers decide not adopt WHT. Therefore, altitude can increase or decrease the probability of WHT adoption.

- *Number of months of rainfall shortage (severity of rainfall shortage).*Availability of rainfall is the basis of rain water harvesting. Farmers can harvest run-off from their catchment and preserve it when there is a rainfall. However, if there is a severe lack of rainfall, then there is no run-off to collect. In this case many months of rainfall shortage could decrease adoption. On the contrary, if the number of rainfall shortage months is high, water scarcity urges farmers to carefully collect rainfall (run-off). They may try to maximize the collected water by increasing their capacity to catch and accumulate the run-off. This means that a higher number of months of rainfall shortage could stimulate to adopt WHT. Therefore, it is difficult to hypothesize on this effect.

- *Region.* Regional differences may exist in institutional support to water harvesting, the attention paid to irrigation, culture and environmental differences. For instance, one region could assign more extension agents than the other, which causes a possible difference in adoption of water harvesting.

6.3 Data

This study uses a panel of 400 households for the empirical analysis. The data are obtained from a repeated survey on water harvesting conducted by the Ethiopian Development Research Institute in Ethiopia held in 2005 and 2010. In the 2005 survey, 30 sub-districts were selected at national level from four major regions based on the presence of ponds, shallow-wells and stream/river diversions. From 30 sub-districts with varying degrees of rainfall, a number of peasant associations (PAs; local administrative units) were randomly selected depending on the total number of PAs using WHT. From these PAs, 2082 households were randomly selected and interviewed in 2005. In 2010, from 7 of the 30 sub-districts, 400 of the 2082 households were randomly selected and interviewed again. Before selecting the sample households in 2010, we assessed the status of those households. From the assessment, we noticed that some households who used water harvesting in 2005 had abandoned it in 2010, whereas some non-users started to use WHT in 2010. In interviews, farmers mentioned the following reasons for disadoption: deterioration of the ponds and lack of materials to make repairs, labour shortage, and lack of conveyance equipment. Therefore, in selecting the 400 households for the 2010 survey, we took the status change into account and stratified the households interviewed in 2005 into users and non-users. Of the 400 panel households that are interviewed twice and used in this analysis, 332 used WHT in 2005 and 68 did not. In the 2010 sample, these numbers had changed to 235 users and 165 non-users of water harvesting (see table 6.1).

Table 6.1 Use of fertilizer by users and non-users of water harvesting in 2005 and 2010

Year	Users of fertilizer			Non-users of fertilizer	Total
	Only on irrigated plots	On both irrigated & rain-fed plots	Only on rain-fed plots		
2005					
Users of WHT	12	33	102	185	332
Non-users of WHT	-	-	15	53	68
Total	12	33	117	238	400

2010					
Users of WHT	6	51	119	59	235
Non-users of WHT	-	-	90	75	165
Total	6	51	209	134	400

Table 6.1 shows that in both 2005 and 2010 users of water harvesting systems used fertilizer more often. In 2005 out of 332 WHT users, 147 (44%) used fertilizer, whereas only 15 out of 68 (22%) non-users of water harvesting used fertilizer. In 2010, the percentage of farmers that used both water harvesting and fertilizer increased to 75% (176 out of 235). Although this percentage also increased for non-users of water harvesting to 55% (90 out of 165), this is still lower than the percentage for water harvesting users. To summarize, in both years users of water harvesting are more often using fertilizer compared to non-users of water harvesting. This may be due to the risk-reducing nature of water harvesting technologies that may have a positive impact on farmers' fertilizer purchasing decisions.

However, if we look more specifically at the type of plots fertilizer is applied, viz. irrigated or rain-fed plots, the relation between water harvesting and fertilizer use seems less strong. Because the quantity of harvested water is limited[3] and depends on the invested capacity, farmers often apply the harvested water on only part of their plots so that the remaining plots are rain fed. Table 6.1 summarizes on which type of plots fertilizer is applied and in both years farmers with WHT that apply fertilizer on their irrigated plots are a minority, although the corresponding percentage in 2010 was higher than in 2005. In other words, the use of WHT may not necessarily lead to the use of fertilizer on irrigated plots. This is because weather risk is not the only factor determining the use of fertilizer as hypothesized in the previous section.

The descriptive statistics of variables used in the empirical analysis such as variables affecting demand and supply of fertilizer, household characteristics, farm characteristics, prices, and others are summarized in table 6.2. Note that a higher soil fertility index indicates higher soil fertility.

[3] The quantity of water that a WHT scheme provides depends on the technology type and on the size. For instance, the average capacity of a pond in our sample is $65m^3$. For shallow-wells and run-off/stream diversions, it is difficult to estimate the quantity of water because of the unlimited size of the scheme and a possible recharge and flow to the accumulated water. Based on information from farmers, local extension agents estimate the quantity of water used for crops from these WHTs based on the frequency of watering (e.g. quantity of water used per week until crop harvesting) and the capacity of water lifting equipment (e.g. motor pump, bucket, traditional equipment).

Table 6.2 Descriptive statistics of the variables used for estimation

Variable	mean	std. dev.	min	max
Dependent variable:				
Fertilizer use (dummy)	0.535	0.499	0	1
Explanatory and other variables				
WHT use (dummy) , 1 if used	0.708	0.455	0	1
Price of fertilizer, ETB [a] per kg	5.465	2.538	0.600	20.000
Total land holding, hectare (ha.)	1.923	1.692	0.125	13.750
Labour, adult equivalent	5.073	2.216	0.720	12.240
Farm capital (proxy: number of oxen) [b]	1.675	1.894	0	16.600
Farming experience, years	21.170	11.302	0.000[c]	59.000
Education, 1 literate (dummy)	0.647	0.478	0	1
Distance to market, hour	1.384	0.941	0.000	6.000
Perennial crops (dummy), 1 yes	0.342	0.475	0	1
Household size	7.280	2.533	1	16.000
Share of water used for livestock, percent	0.098	0.177	0	1
Soil fertility index	12.69	12.55	0.25	97.25
Age	44.313	12.419	16.000[d]	86.000
Gender, 1= male	0.939	0.240	0	1
WHT training (dummy)	0.663	0.473	0	1
Average plot distance from natural water sources (minutes)	27.68	41.71	0.000	220
Altitude (in 1000m)	1.924	0.361	1	3.199
Number of months of water shortage	3.866	1.258	0	6
Region (dummy), Oromia = 1	0.700	0.460	0	1
Year dummy, 2010 = 1	0.500	0.500	0	1

a. ETB is the Ethiopian currency Birr. 1 ETB was 0.0741 USD in June 2010.

b. Probably, an orphan of 16 is a household head, as there are many such cases in Ethiopia.

c. A farmer that grew up in urban area could not have farm experience shared from parents.

d. Unlike an ox which serves a full-day for ploughing, a bull on average serves only a 0.6 day.

6.4 Methodology

This section describes the various steps taken in the empirical analysis. We first consider the potential causal effect of WHT on fertilizer use. However, before estimating an appropriate model to test for this effect a number of specification issues are considered. In the second part of this section we consider the joint adoption of fertilizer and WHT.

6.4.1 Empirical model for analyzing the effect of WHT on fertilizer use

To investigate whether the use of water harvesting systems has a causal positive effect on fertilizer use conditional on other explanatory variables that determine fertilizer use that were presented in section 6.2.1, a regression analysis is performed. The dependent variable for fertilizer use in this study is a binary indicator with value one if a farmer uses fertilizer and zero if not. Therefore, a binary choice model is used to estimate the relationship between fertilizer use and its determinants, including water harvesting. The panel nature of the data implies that a panel binary choice model should be estimated. However, the non-linearity of popular models like logit or probit makes it impossible to apply a within or first-difference transformation on the data to remove unobserved specific effects as applied in linear panel data models (Verbeek, 2012: 418). Although specific binary choice models with panel data are possible under certain conditions, e.g. a random effects (RE) probit model and a conditional fixed effects (FE) logit model, the potential endogeneity of the explanatory water harvesting variable creates a potential barrier in estimating these models since it is difficult to correct for endogeneity using instrumental variable techniques in these models (Wooldridge, 2002: 490).

The water harvesting indicator may be endogenous because unobservables that determine fertilizer use may also correlate with WHT use. Examples of such unobservables are wealth or attitude towards new technology. As a result the covariance between the residuals of the equation for fertilizer use and the WHT dummy is non-zero, leading to biased parameter estimates (Khandker et al. 2010: 25). So before specifying a binary choice model with panel data we first investigated whether there is an endogeneity problem with the WHT variable in explaining fertilizer use. Therefore, we followed a suggestion by Angrist (2001) and specified various Linear Probability Models with panel data using the same set of explanatory variables that we intend to include in our final model. Although Linear Probability Models are inferior in explaining choices compared to Probit and Logit models, they do allow for Instrumental Variable estimation and testing for endogeneity using Durbin-Wu-Hausman tests (Verbeek, 2012: 152), assuming either fixed effects (FE) or random effects (RE). From these Durbin-Wu-Hausman tests, it followed that in the Linear Probability model the WHT variable is not endogenous. Moreover, a standard panel data Hausman test indicated that the more efficient but potentially inconsistent estimator RE model is not rejected against the consistent estimator FE specification[4]. Based on these tests outcomes we proceed by specifying a random effects probit model to explain fertilizer use decisions:

$$P(fert_{it} = 1|X_{it}, WHT_{it}, \alpha_i, \beta) = \Phi\big((\alpha_i + X_{it}'\beta + \gamma WHT_{it})/\sqrt{1-\sigma_\alpha^2}\big) \quad (1)$$

where $fert_{it}$ is the dependent variable showing whether farmer i used fertilizer in year t,X_{it} a matrix of k explanatory variables, β are their coefficients; WHT_{it} is the dummy for the use of water harvesting technology with a coefficient γ; α_i are unit-specific error components that are $NID(0, \sigma_\alpha^2)$and $\Phi$is the cumulative density function of the standard normal distribution. For details on the estimation procedure see Verbeek (2012:421-422).

6.4.2 Empirical model for analyzing the joint adoption of WHT and fertilizer

In section 6.2.2 we discussed the possibility of two-way causality between WHT and fertilizer use. This can be tested by specifying a bivariate probit model, a system of two probit equations. Similar to eq. (1) the probit equation for fertilizer use contains the WHT dummy variable and other explanatory variables. In turn, the additional probit equation for WHT use includes a fertilizer use dummy and the explanatory variables that are assumed to affect WHT use that were discussed in section 6.2.2. A problem in this model is, however, that if indeed fertilizer and WHT use are jointly determined and they share the same unobservables, which can be assessed by testing for correlation of the residuals of both equations, then both WHT and fertilizer are endogenous explanatory variables leading to biased parameter estimates. Fortunately, the availability of panel data provides a solution in this case. Since we have two years of data available we can use exogenous lagged values of fertilizer and WHT as explanatory variables in both equations. Additionally, it allows for testing the direction of causality. If lagged WHT use affects current fertilizer use it indicates that WHT adoption precedes fertilizer use and vice versa. A drawback of using lagged values is that only data of the second year can be used to estimate the bivariate probit model. The bivariate probit model is specified as:

$$\begin{aligned} fert_{it}^* &= \alpha_1 + X_{it}'\beta_1 + \gamma_1 WHT_{it-1} + \epsilon_{1i}\ , \quad fert_{it} = 1 \text{ if } fert_{it}^* > 0,\ 0 \text{ otherwise} \\ WHT_{it}^* &= \alpha_2 + Z_{it}'\beta_2 + \gamma_2 fert_{it-1} + \epsilon_{2i}, \quad WHT_{it} = 1 \text{ if } WHT_{it}^* > 0,\ 0 \text{ otherwise} \end{aligned} \quad (2)$$

[4]The estimation and test results of various Linear Probability Models are not reported here but are available from the authors upon request.

where $fert_{it}^*$ and WHT_{it}^* are latent variables; α_1 and α_2 are constant terms; X_{it} are exogenous variables affecting fertilizer use with parameters β_1; Z_{it} are exogenous variables affecting WHT use with parameters β_2; $\gamma_1$and $\gamma_2$are impact parameters of WHT_{it-1} and $fert_{it-1}$, respectively, and $\epsilon_{1i}$and ϵ_{2i} are independently normally distributed error terms with properties $E(\epsilon_{1i}|X_{it}, Z_{it}, WHT_{it-1}, fert_{it-1}) = E(\epsilon_{2i}|X_{it}, Z_{it}, WHT_{it-1}, fert_{it-1}) = 0$; $Var(\epsilon_{1i}|X_{it}, Z_{it}, WHT_{it-1}, fert_{it-1}) = Var(\epsilon_{2i}|X_{it}, Z_{it}, WHT_{it-1}, fert_{it-1}) = 1$ and cross-equation covariance $Cov(\epsilon_{1i}, \epsilon_{2i}|X_{it}, Z_{it}, WHT_{it-1}, fert_{it-1}) = \rho$. For details on estimation see Greene (2008: 817-826).

6.5 Results

6.5.1. Impact of water harvesting on fertilizer use

The first objective of this study is to investigate if using water harvesting induces fertilizer use. This was first analyzed using the RE model and the explanatory variables discussed in section 6.2.1. Parameter estimates of this model are presented in the first column of table 6.3.

Table 6.3 Parameter estimates for random effect probit model and bivariate probit model [a]

Explanatory variables	Random Effects Probit with WHT use dummy	Bivariate Probit model for 2010	
		Fertilizer use	*WHT use*
Constant	0.52 (0.30)*	0.92 (0.48)*	2.10 (1.05)**
WHT use dummy, 1 if used	0.44 (0.17)***		
Lagged WHT use dummy, 1 if used		0.46 (0.19)**	
Lagged fertilizer use dummy, 1 if used			-0.13 (0.21)
Price of fertilizer	-0.05 (0.03)*	-0.05 (0.04)	
Total landholding, hectare	0.21 (0.07)***	0.25 (0.09)***	0.002 (0.09)
Labour, adult equivalent	0.03 (0.05)	0.05 (0.06)	0.02 (0.05)
Farm capital (number of oxen)	0.08 (0.04)**	0.03 (0.05)	
Farming experience, years	-0.02 (0.01)***	-0.02 (0.01)***	
Education dummy, 1 if literate	0.26 (0.13)**	0.25 (0.17)	0.09 (0.24)
Distance to market, hour	-0.26 (0.07)***	-0.28 (0.10)***	-0.31 (0.12)**
Perennial crop dummy, 1 if yes	0.04 (0.14)	0.38 (0.16)**	2.82 (0.31)***

Household size	-0.06 (0.04)	-0.08 (0.05)	
Share of water used for livestock	0.09 (0.35)	0.55 (0.45)	
Soil fertility	-0.01 (0.01)	-0.002 (0.01)	-0.01 (0.01)
Dummy Region, Oromia= 1	-0.79 (0.16)***	-0.28 (0.20)	0.02 (0.28)
Year dummy, 2010=1	1.13 (0.19)***		
Age			-0.02 (0.01)**
Gender			-0.75 (0.44)*
Training, dummy			-0.02 (0.27)
Average plot distance from natural water sources			0.02 (0.003)***
Altitude (in 1000m)			-0.62 (0.28)**
Number of months of water shortage			0.02 (0.08)
Sigma_u	0.52(0.14)		
rho	0.21(0.09)	0.28(0.14)	
Wald test statistic	108.74***	176.27***	
Likelihood ratio test	5.03**	3.99**	

a. Numbers in parentheses are standard errors; *** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$

The parameter estimates confirm our hypothesis that the use of water harvesting induces fertilizer use among the sampled households. The corresponding parameter in the estimated RE probit model is positive and significantly different from zero at a 1% significance level. Since the probit model is a non-linear specification we cannot infer the marginal effects directly from the parameter values. Therefore, the marginal values calculated at the sample mean are presented in table 6.4.

Table 6.4 Marginal effects of variables in RE probit at the sample mean

Variables	Marginal effect(dy/dx)[a,b]
WHT dummy	0.18 (0.07)***
Price of fertilizer	-0.02 (0.01)*
Landholding size	0.08 (0.03)***
Labour	0.01 (0.02)
Number of oxen	0.03 (0.02)**

Management experience	-0.01 (0.002)***
Education	0.10 (0.05)**
Distance to market	-0.10 (0.02)***
Perennial dummy	0.02 (0.06)
Household size	-0.03 (0.02)
Share of water for livestock	0.04 (0.14)
Soil fertility	-0.003 (0.003)
Region dummy	-0.30 (0.05)***
Year dummy, 2010=1	0.42 (0.06)***

a. *** $p < 0.01$, ** $p < 0.05$ and * $p < 0.1$

b. Standard errors are in parentheses.

At the sample mean, the adoption of water harvesting increases the probability of using fertilizer by 0.18[5]. Apparently, the available harvested water convinces farmers that fertilizer can be applied effectively and at low risk, underling an additional benefit from WHT besides directly providing water for plant growth. Extension agents that want to stimulate the use of modern fertilizers may therefore advice farmers to adopt WHT too in order to increase the effectiveness of fertilizer. The finding that WHT increases fertilizer use among our Ethiopian farmers corresponds to the results by Gebregziabher and Holden (2011) for other irrigation sources in Ethiopia and Fox et al. (2005) in Burkina Faso and Kenya. The latter study particularly stresses the importance of WHT in stimulating fertilizer use.

The confirmed effect of WHT adoption on fertilizer used is found conditional on other factors that have an impact on fertilizer use. Variables affecting supply and demand of fertilizer are also important. The estimates show the price of fertilizer has a negative effect that is significant at a 10% significance level. A rise in the fertilizer price of 1 ETB per kg decreases the probability of using fertilizer by about 0.02, indicating only a small effect of the absolute fertilizer price. In developing countries fertilizer use is affected not only by the price of fertilizer but also by the transport cost of fertilizer. Whereas the transportation cost from the port to the distribution center is accounted for in the fertilizer price, the cost of transportation from the distribution center to the farm is approximated by the distance from the farm to the market center. The estimates confirm that farmers who live further away from market centers have a significantly lower probability of using fertilizer. Living one hour further away reduces the probability of using fertilizer by 0.1. Surprisingly, soil fertility

[5] Probabilities are expressed between 0 and 1; 0.18 is the absolute change in probability.

measured by the Soil Fertility Index, does not have a statistically significant effect in fertilizer use. Apparently, farmers do not take the soil fertility into account in their decisions on fertilizer use.

The estimation results further indicate that being educated, having more farm capital (oxen) and land increase the probability of fertilizer use. The finding that education increases the probability of fertilizer use is consistent to the finding of Fufa and Hassan (2006) and Zerfu and Larson (2011) in Ethiopia, and Olwande et al. (2009) in Kenya. Interestingly, farming experience has a significant negative impact on fertilizer use, in contrast to our expectations. This may be because experienced farmers are usually older farmers who may be more conservative towards modern technologies, decreasing the probability of using fertilizer. The positive effect of total landholding shows that large farmers have a higher probability of using fertilizer. Large landholders tend to use fertilizer because of their income source to buy fertilizer, as also indicated by the significant positive sign for the number of oxen. Although having multiple oxen allows for ploughing more often, which could reduce the need for fertilizer, this effect is not found. Comparing different regions, it is found that fertilizer use is lower in the Oromia region. The estimation results indicate that in general fertilizer use was substantially higher in 2010, which is in line with table 6.1.

Overall, the estimated RE probit model performs well. The Wald test statistic indicates that the null hypothesis of all slope parameters jointly equal to zero is rejected. Also the predictive power of the model is acceptable. Comparing predicted fertilizer use with observed fertilizer use shows that 73.8% of the predicted values are correct (Count R^2). This value should be considered against the observed percentage of fertilizer use in the dataset, which is 53.5%. In other words, the explanatory variables provide about 20% correct predictions compared to a model without explanatory variables but only a constant term. Finally, the Likelihood Ratio test indicates that the assumption of farm-specific error components (random effects) is valid, confirming the existence of unobserved farm heterogeneity and supporting the use of a random effects probit model.

6.5.2. Causality between water harvesting technology use and fertilizer use

In section 6.2.2 it was hypothesized that fertilizer and WHT could be jointly adopted, which would be reflected in two-way causality between the two technology components. The estimation results for the bivariate probit model using 2010 data to test this hypothesis are presented in the second and third column of table 6.3. As explained in section 6.4.2 we use lagged values of WHT and fertilizer to test the causal directions. The estimation results provide a clear picture of these causal directions. Lagged use of water harvesting has a positive and statistically significant impact on current fertilizer use, whereas lagged fertilizer use does not have an impact on current WHT use. This underlines our first hypothesis that WHT stimulates fertilizer use, but not the other way around. Fertilizer users do not adopt WHT to improve the effectiveness of fertilizer. Apparently farmers first adopt WHT and then later on may start using fertilizer. Note however that these results just underline the causal directions of adoption of both technology components as observed in the sample area. The indicated risk-reducing effects of WHT that have a positive effect on fertilizer application still indicate that it is worthwhile to use both technology components in conjunction.

Although the bivariate probit model only used observations from 2010 because of the inclusion of the lagged values, the results for the fertilizer use equation are remarkably robust. Parameters signs, size, and significance are very much in line with each other. Differences are the parameter for fertilizer price, farm capital, education and region that are now statistically insignificant, whereas the perennial crop dummy now has a significant parameter. This may be due to changes between years in fertilizer supply and demand. The RE probit model already showed a significant difference in fertilizer use between the two years. Apparently, the factors that explain fertilizer use have also changed.

Looking at variables that explain adoption of WHT we observe that farmers that are further away from markets are less inclined to adopt WHT. These farmers are more oriented on food production and less on cash crops, e.g. vegetables. The reason that these farmers have a lower probability of adoption could be that food crops need less water than cash-crops, but could also signal that they have less means to adopt WHT. Farmers that grow perennial crops have a higher probability of adopting WHT, which may be due to the nature of the perennials (e.g. *chat*). As expected, older farmers adopt WHT less, but interestingly female-headed households have a higher probability to adopt WHT. It should be noted however, that there are only a small number of female headed households in our sample (see table 6.2), so we should interpret this finding with care. Distance from natural water sources increases the probability of adopting WHT, which makes sense since they have fewer alternatives to obtain additional water. Finally, farmers farming at higher altitudes have a lower probability of using WHT systems.

The outcome of the Wald tests shows that the hypothesis that all parameters are jointly equal to zero is rejected. More interesting is the outcome of the Likelihood Ratio test that indicates that the correlation between residuals of both probit equations is significantly different from zero. This implies that both fertilizer use and WHT adoption have unobservables in common, justifying the estimation of a bivariate probit model. It also underlines that our choice of using lagged values of WHT and fertilizer instead of current values was a correct one, since current values would have correlated with the residuals leading to biased parameter estimates.

6.6 Discussion and conclusions

Whereas the use of modern inputs such as fertilizer is important in increasing agricultural productivity in developing countries, their application is often limited. For example, in Ethiopia fertilizer is only used on 39% of the cropped area. One reason for the limited use of fertilizer is risk of crop failure due to rainfall shortages (Alem et al. 2010). Fertilizer increases yields by enriching the soil with essential nutrients, but for the nutrients to function sufficient soil moisture is essential. Technologies that mitigate these water shortage risks may therefore stimulate the use of fertilizer. In smallholder agriculture, one of these technologies are water harvesting systems, small-scale water storage systems for supplementary irrigation in situations of moisture stress. Water harvesting technologies were introduced in Ethiopia during the early 2000s to reduce risks of water shortages, particularly during crop ripening periods. In this study we investigate whether the use of water harvesting technologies in crop production has a positive effect on fertilizer use. This issue is empirically analyzed using panel data and panel binary choice models. This study is therefore a valuable addition to the literature on fertilizer use in developing countries since most studies usually focus on demand and supply factors of fertilizer, ignoring the role of moisture availability as a precondition for the demand for fertilizer (Jayne et al. 2003; Olwande et al. 2009) or use cross-section (Gebregziabher and Holden, 2011) or experimental data (Fox et al. 2005) to investigate this issue.

Based on theoretical insights and existing literature, panel data analyses are performed to investigate whether water harvesting has a causal effect on fertilizer use. Two models are estimated using panel data on 400 Ethiopian households sampled from several districts in Ethiopia. First, a random effects probit model is estimated to test whether WHT have an effect on fertilizer use, conditional on other factors that explain fertilizer use. In this model we explicitly dealt with unobserved heterogeneity among farming households, which may arise from unobserved differences in farm attitudes, risk and time preferences, management skills, and environmental conditions. However, fertilizer and WHT may also be adopted jointly, suggesting two-way causality between fertilizer and WHT use. This is investigated using a bivariate probit model.

The findings strongly support the hypothesis that water harvesting induced the use of fertilizer in smallholder agriculture. First, conditional on other factors that have an impact on fertilizer use such as fertilizer price and landholding, we found that water harvesting increases the probability of using fertilizer by 0.18 in the estimated RE probit model. Moreover, the joint modeling of fertilizer and WHT use showed that WHT use precedes fertilizer use. These results support the view that water harvesting reduces production risk due to water shortages making it less risky for Ethiopian farmer to apply expensive fertilizer on their plots. Similarly, in line with agronomic principles, the reduction in water shortage improves soil moisture which is a basic condition for the functioning of the fertilizer nutrients to increase yield. Furthermore, in addition to the direct effect of inducing fertilizer use by reducing weather risk, the use of water harvesting may also indirectly induce fertilizer use through its income effect. Due to a rise in income from the use of water harvesting, farmers are able to buy fertilizer in subsequent years to apply not only on their irrigated plots but also on their rain-fed plots. This is in line with the finding that water harvesting technology use precedes fertilizer use.

In addition to water harvesting, fertilizer price, farming experience, and the distance between home and the market, decreased the probability of using fertilizer. The fact that the price of fertilizer significantly decreased fertilizer use shows that farmers in developing countries respond to price signals. In addition to input prices transaction cost factors such as distance between home and market have a substantial influence on fertilizer use.

The hypothesis of joint adoption of fertilizer and WHT is not supported by the results from the bivariate probit model. Whereas WHT induced fertilizer use, lagged fertilizer use did not affect adoption of water harvesting technology in 2010. Clearly, if farmers use both WHT and fertilizer it is WHT that precedes fertilizer use for reasons explained above. Factors that do stimulate adoption of WHT are proximity to market centers and growing perennials, suggesting that the types of crops grown provide an important explanation for the adoption of water harvesting technology. Natural conditions such as proximity to natural water sources and altitude also affect adoption of water harvesting technology as well as household characteristics age and gender.

Low agricultural productivity is a major problem in Ethiopian agriculture in the last three to four decades. Given that water harvesting increases the probability of fertilizer use underlines that encouraging these technologies may lift productivity of Ethiopian farmers, not only by reducing water shortages but also by improving the effectiveness of fertilizer and perhaps via a longer term effect on income that allows buying fertilizer and other yield improving inputs. The findings of this study imply that encouragement of water harvesting systems positively contributes to fertilizer use. Extension agents that want to stimulate the use of modern fertilizers may therefore advice farmers to adopt water harvesting technology too in order to increase the effectiveness of fertilizer.

CHAPTER 7

CONCLUSIONS AND DISCUSSION

7.1 Introduction

The overall objective of this thesis is to explore the economic aspects of water harvesting small-scale irrigation technology and its dynamics in Ethiopia using micro-econometric analysis. It embodies four specific objectives addressed in separate chapters. Each chapter provides specific conclusions. This chapter summarizes and synthesizes the main findings and conclusions in these chapters. With this target, the chapter is structured in the following way: Section 7.2 summarizes the main conclusions from chapter three to six and outlines implications. Section 7.3 provides a discussion on the major conclusions and discusses critical reflections. Finally, section 7.4 suggests further research.

7.2 Summary of main conclusions and implications

One of the objectives of this thesis was to estimate the marginal value of harvested water and see if the water is optimally allocated by Ethiopian farmers. The estimated value marginal products (VMPs) for onions and tomatoes are similar, indicating that on average Ethiopian farmers allocate the harvested water in an economically efficient way between these crops. However, this does not hold for green pepper, for which the value marginal product was not significantly different from zero. In other words, though the VMPs are estimated only for three crops, the evidence does not indicate economically inefficient water allocation for onions and tomatoes[1], but it does for green peppers. The positive and significant VMPs for onions and tomatoes also indicate that farmers earn positive returns from using harvested water for these crops, signalling the need to encourage non-users to adopt water harvesting with a sound crop choice and the need to take measures that reduce disadoption. The estimates provide insight into the economic efficiency of private small-scale irrigation in highland Ethiopia in contrast to cooperative-managed irrigation. In water harvesting irrigation, households individually decide on water allocation and crop choice, which contributed to the (economic) efficiency. Other studies also support the efficiency of private small-scale irrigation (Mwenge Kahinda et al. 2007; Fox et al. 2005). The results in this thesis also indicate the potential contribution of private small-scale irrigation to global water use

[1]This is consistent to the analysis of profitability (Gezaheng et al. 2006) and cost benefit analysis carried out in the past for investment in WHTs (e.g. Tesfay, 2008).

efficiency, a burning issue these days (Bogardi et al. 2012; de Fraiture et al. 2010; Strzepek and Boehlert, 2010; Tilman et al. 2002; Ruttan, 2002). It was also found that the estimated VMPs vary with the specific technology, indicating different marginal benefits of various systems, which also have different costs. For instance, reliability and flexibility of the water from shallow-wells have a positive contribution to onion output, indicating that the use of shallow-wells in suitable areas is beneficial for farmers and could lift the low proportion of land under irrigation.

The objective of the thesis in chapter four was to answer why the share of land irrigated with harvested water is smaller at large farms compared to smaller farms. The chapter concluded that financial, market and location constraints decrease the share of irrigated land with farm size. Normally, larger landholders have to invest more than smaller farmers to irrigate a larger proportion of their land. This means that they have to dig more ponds or shallow-wells and use more labour and motor pumps to harvest sufficient water to irrigate a large share of their land. To do this, larger farmers require more credit to invest compared to small landholders. Given that micro-credit provided by the microfinance centres in rural Ethiopia often has a maximum amount that can be borrowed and in view of the limited options to use this credit for investment in irrigation (see IFAD, 2009), the observed credit constraint is a likely one. For smaller farmers, micro-credit may be sufficient to construct a scheme and irrigate a large share of their land. Similarly, large farm-holders who are close to markets can irrigate more of their land unlike large farmers who are further away from markets. Institutional and local factors were also found to be relevant in examining the declining share. For instance, in areas where construction materials (e.g. plastic sheets) are equally distributed or sold to both large and small-farmers (e.g. by quota), the large farmers construct a pond or ponds equivalent to that of small-farmers. This indicates that setting the same credit-ceiling and construction material limit for both large and small farmers limits the share of the irrigated land of large farmers. Encouraging water harvesting irrigation technologies based on farm-size could increase the share of irrigated land of large farms and consequently increase the low share of irrigated land of the country at large.

Disadoption is part of the dynamics of water harvesting technologies and the fifth chapter investigated why disadoption of water harvesting technologies occurred. The chapter concludes that labour supply, credit and market access and plastic sheet constraint primarily caused disadoption. In addition, experience in water harvesting (learning), training and crop choice and regional diversity are also important. These factors determine the collection and use of harvested water. To decrease disadoption, an uninterrupted supply of plastic sheets is essential. Since plastic sheet is an imported construction material, providing the private sector with market information, putting a priority on imports and supporting the distribution could increase its supply. The estimated lifespan of plastic sheet is ten years and with the shortage of plastic sheets to substitute the deteriorated ones, disadoption occurs after ten years. Access to credit allows buying or renting in motor-pumps, which eases the labour constraints that cause disadoption. Training upgrades farmers' skills in using and maintaining water harvesting systems. Regional diversities including weather conditions, soil-fertility and institutional diversity influence disadoption. Geographical and institutional diversity (Wade, 1995) should be considered in stimulating the irrigation technologies to decrease disadoption. Previous encouragement of WHT adoption occurred throughout the country, ignoring regional diversities, which also explains disadoption.

The last objective of the thesis was to investigate whether water harvesting induced fertilizer use. Based on the results, it is concluded that water harvesting induces fertilizer use in Ethiopia. Water harvesting reduces moisture constraint as a basic condition for fertilizer use, which is in line with the agronomic principles (de Wit, 1992; Paris, 1992) and with the risk-reducing effect of irrigation water (Rockstrom, 2000; Feder, 1980). To stimulate fertilizer use, the use of WHTs is an affordable option for smallholders. Without harvested water, drought risks undermine fertilizer use and this in turn undermines yields. It should be noted, however, that fertilizer use depends also on factors affecting the supply of fertilizer such as price and distribution. It is also interesting to find that past fertilizer use does not affect current water harvesting use, which indicates that those farmers who already use fertilizer do not care to adopt water harvesting for irrigation because in low weather-risk areas water harvesting is not so important. Investigating this kind of dynamics, in addition to analysing static effects (e.g. estimating VMPs), increases our understanding of WH irrigation. The availability of panel data helped to investigate this dynamic impact of water harvesting.

7.3 Discussion and critical reflection

Discussion

In this section, some lessons learnt from the thesis are discussed. The objective of introducing water harvesting in Ethiopia was to improve rural livelihoods (income and food security) by reducing the risk of rainfall shortage and variability especially during crop ripening periods. After adopting WHTs, though it was expected that farmers could use the harvested water to overcome moisture shortage in their common cropping, they shift to produce high-value crops rather than cereals. This is observed in the survey data of 2005 and 2010, which shows that more than 80% of the crops supplemented with harvested water are either fruits, vegetables or other perennials but not cereals. In fact, the choice of the relatively high-value crops is also not without a relatively lower weather risk. The evidence in this thesis indicates that in high-value crop production, on average farmers allocate the harvested water economically and earn a positive return. Other evidences also show farmers using WHTs are better off as a result of the income and the asset gain (IFAD, 2009; Wakeyo and Gezahegn, 2008; Hune, 2006), though this is not true for all farmers. On the other hand, although the ultimate goal of stimulating the technologies was to improve rural livelihood, to find out how WHT contributes to achieve the objectives (i.e. whether it is through increasing yields, increasing income by growing high-value crops or other ways of creating food availability),has not been precisely known (Moges et al. 2011).The evidence in this thesis indicates that the impact of harvested water use works through: 1) allocation of the harvested water to high-value crops,[2] a profitable and economically viable allocation; and, 2) the stimulating effect on fertilizer use that increases yields.

On the other hand, the estimated VMPs for various WHTs vary. For instance, using harvested water from shallow-wells for onion provides the highest VMP compared to that from ponds river/stream or flood diversions. The implication is that stimulating shallow-wells, a reliable and flexible water source (Playàn and Mateos, 2006; Rosegrant and Binswanger, 1994), could increase the low share of irrigated land of only 1.5% in Ethiopia (IFAD, 2009) and decrease the negative effect of rainfall shortage and variability. If the country wants to stimulate shallow-wells and increase the water storage capacity of small-holders, it is important to address the supply of water-lifting equipment and the corresponding energy sources (e.g. motor-pumps & petroleum) and paying attention to the negative environmental effects, especially if these schemes are located close to lakes and marshy-areas. In fact, returns from WHTs vary with geographical areas (You et al. 2011) and crop types and in areas where shallow-wells are not economical, other WHTs can be encouraged.

From the third chapter of the thesis, the conclusion does not indicate totally inefficient allocation of harvested water in vegetable production. At least in some of the vegetables, on average farmers allocate water efficiently. Documents also show estimated annual returns and long-run investments and those indicate benefits from the use of water harvesting. However, the risk-reducing effect (share of irrigated land) is limited by farm-specific, financial and

[2] In fact this should not overshadow the increases in cereal yields from flood diversions (also called spate irrigation) that farmers achieved in non-sample areas (e.g. van Steenbergen, 2011).

agro-ecology factors, as the fourth chapter indicated. In agro-ecologies that allow harvesting run-off, relaxing financial and other constraints increases the share of irrigated land. Efficient water allocation, if complemented with a reasonable share of irrigated land, increases high-value crop growing and this could enhance commercialization. The question of the scale of operation is often raised in connection with efficiency in the economic literature (Johnson and Ruttan, 1994). In this thesis, however, the issue of farm-size is raised from a perspective of the risk-reducing role of irrigation in a country where agriculture suffers from weather risk (Dercon and Christiaensen, 2011; Legesse, 2003). Unlike the conventional communal irrigation, where plots distance from irrigation scheme is a reason for a certain proportion of irrigated-land, in WH irrigation larger farmers could use more of the WHTs to increase the proportion of irrigated land if they are not constrained by shortage of plastics, motor-pumps, credit and market access. This conclusion is consistent to the literature on production and investment in developing countries (Sadoulet and de Janvry, 1995; Fafchamps, 1992) that imperfect and missing markets affect allocation decisions.

Importantly, market access positively influences the dynamics of water harvesting i.e. share of irrigated land, rate of disadoption and fertilizer use in smallholders. With market access, the share of irrigated land and probability of fertilizer use increase whereas disadoption of WHTs decreases. Other studies also underline the importance of market access in development (Gabremedhin et al. 2011; Diao et al. 2007; Oskam et al. 2004; Fafchamps, 2004). The importance of market access is underlined not only for small-scale water harvesting irrigation but also for large-scale irrigation in Africa (FAO, 2006). Therefore, investment in rural roads and communication in Ethiopia has to continue to improve and safeguard market access for Ethiopian smallholder farmers.

The thesis also stressed the importance of a reliable supply of construction materials and water-lifting equipment. Two of them have priority: supply of plastic sheets and motor-pumps, both of which are imported although WHT was presumed to depend on local materials. With experience, farmers started to favour the imported plastic-sheet ponds rather than ponds constructed from local materials (e.g. cement and clay). Supplying these inputs would provide business opportunities for the private sector (importers, distributors, and renters of motor-pumps) in Ethiopia. For the private sector to enter into and continue with this kind of business, however, market information, road networks, rural storage, distribution networks and facilities are vital. Not only the supply of materials but also the maintenance of plastic sheet and motor-pumps are essential. Lack of maintenance may also increase disadoption. Technical training on maintenance could prevent this, which again provides opportunities for the private sector. These points indicate that engaging the private sector is important for the success of WHTs. Contrary to this, government intervention is prevalent in Ethiopia instead of encouraging the private sector to play a role in the economy, which is a documented issue (IFAD, 2009).

The green revolution in Africa failed because lack of irrigation to overcome rainfall shortages is one of the major reasons (Movis et al. 2005). As the sixth chapter indicated, water harvesting induces fertilizer use. Fertilizer increases crop yields in a food deficit country. To reduce crop production risk and increase yields through modern input use, the use of small-scale water harvesting systems must be given a high priority in Africa. Even though high prices and weak distribution of fertilizer are also factors of low fertilizer use rate in Ethiopia (Zerfu and Larson, 2011; Fufa and Hassan, 2006), the thesis has gone a step further and explicitly tested the importance of supplementary water in fertilizer use. Theoretically, both the agronomic and economic principles support the notion that water is a precondition to fertilizer use. This study provides an evidence that irrigation (harvested water) lifts the persistent low fertilizer-use in Ethiopian (and the rest of African) agriculture and could improve food supply. The conclusion of the study gives insight into the path through which water use affects fertilizer use. So far it (the path) has been discussed from both agronomic and economic perspectives. However, from the economic perspective another likely path of the effect of WHTs on fertilizer use is that WHTs may increase farmers' income and the income could be used to buy fertilizer for rain-fed plots. This means that WHT induces fertilizer use not only directly on the irrigated plots due to the reduced risk but possibly also indirectly through its income improving effect.

Critical reflection

This section proceeds with the discussion of some critical reflection on the research done. In the third chapter, the estimated trans-log production function provided estimates of the elasticities and VMPs. The elasticities and VMPs change over time due to improved water use efficiency and prices. For instance vegetable prices in Ethiopia increased more than three-folds between 2007 and 2010. Similarly, water use efficiency improves over time with experience in the use of WHTs (Dinar, 1993). Therefore, the models estimated based on the 2005 data do not provide up-to-date information. In addition, farmers use the harvested water for expensive perennials such as *chat (catha edulis)* and apple. Estimating the VMPs for those crops is also interesting from a water allocation perspective. So, updating the estimation of VMPs is essential using recent price data and for several crops to see whether the allocation of harvested water is optimal and has improved over time. This involves the estimation of production functions.

In the fourth chapter, a Just and Pope (1978) production function is used to model land allocation decision between irrigation and rain-fed. In the modelling, it is assumed that farmers intend to decrease risk by increasing land under irrigation. However, farmers can also decide to use harvested water just on a small proportion of their land and maximize the return from the specific plot by intensifying production. In other words, intensification of production, more than extensive use of water, can also be a farmer's objective. This thesis, however, does not look into intensification which would require an independent study.

Disadoption was analysed using variables suggested by the theory of technology adoption. Even though this theory provides insight into the role of institutions, the top-down approach in stimulating technology adoption (Brugere and Lingard, 2003) could not be taken into account in the empirical analysis. Capturing those institutional issues in modelling would refine empirical studies. On the other hand, though it is a stylized fact that the low supply of a major investment material explains disadoption, adoption theory ignores the crucial role it plays in continuing with a technology.

Another critical reflection on this thesis involves the strong focus on the economic issues and economic behaviour related to WHTs. In a traditional rural society of Ethiopia, farmers also act based on non-economic behavioural grounds such as socio-cultural norms. For instance, in our field assessment of WHT in 2005, in SNNPR the team came across a story that a farmer abandoned his water harvesting scheme after he was socially isolated for selling water from his pond. The social norm in the locality prohibits the selling of water whatever the economic returns. Therefore, to consider non-economic behavioural data would give more insights into understanding the actions of farmers. Data is lacking not only on the non-behavioural variables. It is also lacking on some of the technical aspects. For instance technical data is lacking on site selection, design and slope. It is assumed that farmers could learn about their importance in training. However, these technical issues could influence several decisions on the use of WHTs which can better be assessed from an agro-engineering and hydrologic perspective. Obviously, they are not addressed in this study. In addition to these, there are limitations about the data used. First, there is a five-year gap between data collection in 2005 and 2010. Of course the five-year period is relatively reasonable to see the impact of a new technology such as WH. However, due to lack of data collected in between these two years, what happened in that period is not clear. Second, in addition to the time dimension, the regional coverage is also limited. Due to resource constraints, we include only two of the four regions in the 2010 panel data survey.

Finally, it is unfair to end this section without providing a glance of the current status of WHTs in Ethiopia. Those technologies are successful not in all areas. In many areas, they are disadopted, because they were introduced widely even in areas of excess rainfall and low rainfall-variability. Some success areas serve as sources of useful experiences, however. For instance, experts and farmers from other regions and zones visit one of the sample sub-district best practices in Gursum sub-district, where the social saying of "*no-pond-no-wife*" illustrates the importance of WHTs (Gezahegn et al. 2006).The qualitative information obtained from the Bureau of Agriculture of Gursum indicates that the purpose of the visits is to collect experiences for adopting, which are important in the diffusion of the technologies. The diffusion of WHT technologies based on learning from best practice areas could interestingly lead to scaling-up and replicating them (IFAD, 2009) and further studies on the diffusion of the technologies (e.g. Adegbola and Gardebroek, 2007).

Another issue concerns who benefits and who does not from WHTs. Farmers who produce perennial and annual cash-crops such as papaya, apple, *chat*, coffee, tomato, onion, garlic, potato, intercrops (e.g. maize and *chat*; vegetables and maize) and forage, and who have market access, benefited. On average, water harvesting small-scale irrigation increased income, asset and consumption. For instance, IFAD (2009) indicated that yields in Ethiopian small-scale irrigation increased in a range of 75-100% compared to that of rain-fed (25-40%). Due to small-scale irrigation, the average number of hunger-months fell from 6 to 2 and variety of food intake improved as a result of the diversified production. In addition, similar to the findings of Huang et al. (2005), rich farmers who own motor-pumps earn income from renting them and from share-cropping agreements they enter with other farmers using their motor pumps. Furthermore, using harvested water, poultry activity and growing new crops such as apple became possible (Namara et al. 2010; van Koppen et al. 2009) and consequently individual household income increased. After all, the use of harvested water also contributes to the irrigated output in the national economy at large (Hagos et al. 2009).

Not only individual farmers, but the public also seems to indirectly benefit from positive environmental impacts of WHTs. Field observations showed that with water harvesting, dry areas became greener and more attractive due to the agro-forestry. For instance in the 2010 survey, Alaba and Gursum farmers grew perennials that provide attractive landscapes compared to the situation in 2005. Due to harvested water, diverse bio-species recovered.

Given those benefits, water harvesting can be a kind of localized green revolution (Collier and Gunning, 1999) and part of a “blue revolution” (Movik et al.2005) that Africa requires to increase productivity. Sustained use and benefits of water harvesting irrigation are observed in various areas of Ethiopia indicating that success is not limited to specific agro-ecologies and that they are replicable to other parts of the country (IFAD, 2009) and the continent.

7.4 Further research

This section discusses directions for further research based on results and insights obtained in individual chapters and the current situation of WHTs. It is possible that optimal allocation of the harvested water focuses on water use for competing crops and also among competing uses (e.g. crop-growing & livestock-rearing). Though the question of allocation among competing uses is equally important, only the issue concerning whether harvested water is optimally allocated among competing crops was investigated in chapter three. Similarly, chapter four assumed that the objective of water harvesting is to use it for crop production to decrease risk and maximize profit in crop production. However, farmers could use the water also for non-irrigation (e.g. livestock). The use of the water for purposes other than irrigation may bring better returns. So, further studies could consider the use of water for non-irrigation purposes e.g. for livestock and home use (e.g. cleaning& cooking) in addition to the use for irrigation.

Furthermore, rather than assuming that a high share of irrigated land reduces weather risk in chapter four, it can be assumed that farmers who use harvested water could follow intensive farming to maximize output from a plot. In that case, they apply water to maximize the output from a particular small plot, while producing low-risk crops on the rest of their plots because of water and other resource constraints. This means that farmers may not increase investment on water harvesting to irrigate more of their plots. This could provoke to study intensification of production vis-à-vis water harvesting.

In modelling investment in WHT, chapter four assumes that rainfall is uncertain and the investment is a long-run business (10 years for plastic and cement ponds). Investment in WHT also implicitly assumes that there is some rainfall to accumulate, that no other sectors compete for run-off around smallholders’ plots and population settlement patterns are stable. However, run-off distribution, environmental viability and run-off demand from other sectors (e.g. commercial large-scale irrigation), and the urban and industrial sectors change over time (de Fraiture et al. 2010; Strzepek and Boehlert, 2010). Climate change also affects the economic viabilities of water harvesting because aridity and rainfall shortage months (changes with time) affect the scale of operation and status of use of water harvesting. These issues suggest the need to consider historical rainfall data to gain insights into the possible effect of other sectors on the viability of investment in WHTs. The insight could also help in understanding where to encourage and where not to encourage water harvesting technologies.

In chapter five, the findings indicate that labour shortage is one of the causes of disadoption. An option to decrease disadoption could be to buy motor pumps. On the other hand, if farmers buy motor pumps, they may use them below full capacity due to land and also possibly water constraints. As a result farmers may opt to rent in motor pumps rather than to buy. Rental of motor pumps can be either from rich farmers or from local business-men. Therefore, it may be better to encourage renting in and renting out motor pumps because: 1)otherwise the money invested by individual farmers on motor pumps is tied up causing resource use inefficiency; 2) the opportunity cost of motor pumps could be higher in other districts. Therefore, a mechanism that works better to encourage investment or rental in motor pumps requires future study.

In relation to chapter six, a further step could deal with the issue of whether fertilizer use due to water harvesting increased yields. This hypothesis is not tested in this study but one objective of WHT is to increase yields. So, a study can be conducted similar to the experiment conducted in semi-arid China (Li et al. 2004) to learn if WHT increased yields. In addition, in chapter six, it is assumed that water harvesting and fertilizer use have a direct relationship either from the perspective of law of the minimum (de Wit, 1992) or from risk-reducing effects of irrigation (Smith, 2004). Further study on the indirect relationship could identify this indirect impact of water harvesting. The indirect relationship could be due to the income effect of water harvesting.

Finally, the impacts on environment (e.g. bio-diversity, water resource) and agro-forestry also invite further research. For instance, though the public seems to benefit from the positive environmental impacts of WHTs (discussed in the end of section 7-3), the use of WHTs is also a source of concern. This is because if ponds, shallow-wells and stream diversions are extensively used, the natural environment could remain at low water share. In that case, the volume of rivers could decline; forests, lakes, natural marshy areas, grazing lands, wild animals, etc. could lose their natural share, which could create an imbalance in the natural environment. Therefore, the environmental aspects related to water harvesting require attention and could lead to follow-up studies.

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SUMMARY

In many African countries, food production is predominantly rain-fed and production cannot fully support a growing population. This is because rainfall shortage and variability undermine yields directly by reducing the water available for crop-growth and indirectly by decreasing the use of modern inputs such as fertilizer. In a subsistence economy with a growing population, the consequences of low yields are food shortage and poverty. To overcome these negative consequences of rainfall shortage and variability, an alternative is to invest in irrigation and water storage schemes. Dams, canals, reservoirs, ponds and shallow-wells are some of those schemes and can be classified as large- and small-scale schemes. African countries invested in large-scale irrigation in the 1970s and 80s to replicate the green revolution that increased yields in many Asian and Latin American countries. However, large-scale irrigation often failed due to several documented reasons: difficulties of ownership and maintenance of large-scale schemes, water use inefficiency, resource constraints for operation and maintenance, lack of market access, environmental problems and water conflicts. After the failures experienced with large-scale systems, small-scale irrigation technologies such as water harvesting were advocated. Many African countries launched programs to introduce them (e.g. Burkina Faso, Ethiopia, Kenya, Tanzania, etc.).

The weather risk that constrained yields in Ethiopia has been given attention by the government. In response to the food insecurity and poverty that prevailed, the government has stimulated water harvesting technologies (WHTs) since the early 2000s. These technologies include ponds, shallow-wells and river/stream or flood diversions. Even though they are not free of shortcomings, the advantages of these technologies compared to large-scale irrigation systems are that they are relatively inexpensive, they fit to smallholder land-tenure, could cause little water logging and trigger little conflict around water uses. Above all, to invest and allocate the harvested water is an individual household choice, unlike the conventional communal irrigation. The advantage is that individual choice in water allocation increases water use efficiency. Moreover, past experience has led Ethiopian farmers to have negative attitudes towards cooperatives, and individually owned irrigation schemes avoid problems of cooperative ownership.

The adoption of the technologies was stimulated by government institutes, taking into account several constraints suggested by households. After adoption, some households continued to use the technologies whereas others disadopted even though their use has positive impacts on income, food security, modern input use and asset holding. The individual

use of those technologies and their advantages in Ethiopia are the motivation for conducting this empirical micro-economic research. Chapter two of the thesis discusses the data used in the empirical analysis. The study uses data from a two-round survey and also field observations carried out several times during 2005 to 2010. A national survey was carried out by the Ethiopian Development Research Institute (EDRI) in 2005 in the major regional administrations of Tigray, Amhara, Oromia and SNNPR. During the 2005 survey, 2082 households were interviewed after random selection from 30 high- and low-moisture deficit sub-districts. In the second round of 2010, field assessments were carried out beforehand and the outcome of the assessments indicated that some households continued to use whereas others stopped using the technologies. The researcher stratified these user- and non-users households, randomly selected from seven sub-districts of Oromia and SNNPR and interviewed 400 households (235 users and 165 non-users) for a second time. Thus, this study uses both cross-section and panel data for the micro-econometric analysis carried out in individual chapters to answer research questions listed in the first chapter.

The general objective of the thesis is to study the economic aspects of water harvesting irrigation, its dynamics and impacts using micro-econometric analysis. Under this general objective, four specific objectives are set. Accordingly, the third chapter of the thesis investigated whether harvested water is optimally allocated among the three most frequently grown vegetables using water harvesting (onion, tomato and green pepper). Standard translog production functions and the alternative asymmetric production functions are estimated for each vegetable. After econometric tests are carried out, the translog production function is chosen and based on it, value marginal products (VMPs) are computed for the harvested water. The estimation results indicate that 1% of additional harvested water increased the output of onion and tomato by 0.12% and 0.23% respectively, but green pepper output would be reduced. The elasticity estimate of the green pepper is not very reliable and also implausible. In addition to this, the estimation result indicated that the VMPs of onion and tomato are almost equal. The equality of the two value marginal products indicates that on average the harvested water is economically allocated between these two crops. This gives a positive signal to non-users to use water harvesting with a sound crop choice. Another important conclusion of the chapter is that the estimated VMPs of the vegetables vary with the type of WHT. The difference in the VMP with the type of technology provides farmers a technology option because farmers face different economic conditions (e.g. availability of labour, market), weather conditions (e.g. rainfall), water resources and crop-growing conditions.

Chapter four looks into the problem of allocating land between fully rain-fed crops and crops irrigated with harvested water. The chapter assumes that the higher the share of irrigated land in total landholding of farmers, the higher the probability to manage rainfall-shortage risk. The preliminary data, however, showed that on average the share of irrigated land is lower for larger farms. The study investigates why the larger farms have relatively less irrigated land. It is necessary to investigate this issue, because a falling share of irrigated-land could suggest that the importance of WHTs decreases with commercialization. Moreover, a larger share of rain-fed land implies farmers could continue to grow low-value low-risk crops on a large part of their land, which may not change total yields much. The estimated random effect tobit model indicated that observed farm specific factors such as market access, credit per hectare, regional differences, the agro-ecological variables, and the institutional and cultural factors that are not observed by the researcher affect the share. Encouraging investment that takes into account farm-size, agro-ecological and regional diversities could therefore increase the share of irrigated-land of large farmers. Increasing the share of irrigated-land of large farms could also increase the proportion of nationally irrigated land, which is currently less than 1.5%.

Chapter five examines why some of the households prefer not to continue using WHTs though their use decreases weather risk and increases income and assets. To analyse disadoption, we consider a subset of farmers that initially adopted. Households that adopted in 2005 have either continued to use it or disadopted it. Exactly 332 panel households fulfilled this condition. For these 332 panel households, a Hausman-Taylor based (panel) linear probability model and a probit model on the changes in continuous explanatory variables and dummies are estimated. The estimation results in both models mainly indicate that plastic sheet shortage, number of rainfall-shortage months, labour availability, learning-by-doing (experience in water harvesting), market and credit accesses, growing perennials, and regional differences influence disadoption. To reduce disadoption, mainly increasing plastic-sheet supply has to be given a priority because shortage of plastic sheets to substitute the exhausted ponds (after the end of life span of the previously used one) escalates disadoption. In addition, increasing the availability of credit to buy motor pumps, which decrease labour shortage, encouraging water use for perennials, and investing in infrastructure to create market access also decrease disadoption. Importantly, taking into account agro-ecological diversity in encouraging water harvesting is fundamental. The study suggests that when government institutions stimulate a new technology, they better intervene to correct market failure instead of taking the role of the private sector. The private sector is better able to handle the supply of key construction materials (plastic-sheet), water-lifting equipment (e.g. motor pumps) and their maintenance. However, in the case of Ethiopia the actual involvement of the private sector is inadequate in small-scale irrigation technologies, including water harvesting which could affect the success of farmers in the use of the technologies.

In chapter six, the thesis explores the impact of WHT on fertilizer use. In 2008 fertilizer was only used on 39% of the cultivated land in Ethiopia. This average figure is too low to increase agricultural surplus and feed a large population. In this study, a panel probit and a bivariate probit model are estimated to investigate whether the use of WHT induces fertilizer use and if there is a joint relationship between fertilizer and WHT uses. To test the former, panel data is used. On the other hand, to test if the use of water harvesting affects current use of fertilizer and vice versa, dummy variables for lagged water harvesting use and lagged fertilizer use are included in the estimated model. The estimation results of both the panel probit and bivariate probit strongly support the hypothesis that WHTs induce fertilizer use in Ethiopia. This is because water availability is a basic condition for the use of fertilizer due to the agronomic principle of law of the minimum, but also due to the falling production risk. This conclusion indicates that the use of WHT could lift up the low rate of fertilizer use among smallholder farmers in Ethiopia if other fertilizer supply factors such as fertilizer price are also considered. The estimated bivariate model, on the other hand, indicates that past fertilizer use does not have a significant effect on current use of water harvesting. This could imply that in low weather risk areas water harvesting may not be so important. The conclusion indicates that small-scale WHTs induce fertilizer use and this could increase yields, which has a positive impact on the income and food security of Ethiopian farmers.

Finally, the seventh chapter of the thesis first summarizes the major conclusions of the core research chapters that dealt with each of the research objectives and provides policy implications. Next, the chapter discusses the major lessons learnt from the thesis and some caveats. And last, it suggests some areas of further research based on the assumptions, results, insights and current situation of water harvesting technologies.

SAMENVATTING (SUMMARY IN DUTCH)

In veel Afrikaanse landen is de voedselproductie in hoofdzaak regenafhankelijk en kan deze produktie de groeiende bevolking niet volledig van voedsel voorzien. Beperkte en varierende regenval leidt direct tot lagere gewasopbrengsten, maar indirect ook tot een geringer gebruik van moderne inputs zoals kunstmest. De gevolgen van lage opbrengsten in een zelfvoorzienende economie met een groeiende populatie zijn voedseltekorten en armoede. Een mogelijkheid om deze negatieve gevolgen van een tekort aan en variatie in de hoeveelheid regenwater tegen te gaan, is te investeren in irrigatie en wateropslag systemen. Voorbeelden hiervan zijn dammen, kanalen, waterreservoirs, vijvers en ondiepe putten. Hierin onderscheiden we groot- en kleinschalige irrigatiesystemen. Afrikaanse landen investeerden in grootschalige irrigatiesystemen om de Groene Revolutie, die de productieopbrengsten in veel Aziatische en Latijns-Amerikaanse landen liet stijgen, te kopiëren. Deze grootschalige irrigatiesystemen schoten echter vaak tekort om verschillende redenen: onduidelijkheden over eigendomsrechten en verantwoordelijkheid voor onderhoud, inefficiënt gebruik van water, beperkte middelen voor gebruik en onderhoud van de systemen, geen toegang tot markten, milieuproblemen, en conflicten rond watergebruik. Na het ondervinden van deze moeilijkheden in het gebruik van grootschalige irrigatiesystemen werden kleinschalige systemen voor verzamelen van water bepleit. Veel Afrikaanse landen lanceerden projecten om deze technieken te introduceren (bijvoorbeeld Burkina Faso, Ethiopië, Kenia en Tanzania).

Recentelijk hebben weerrisico's die productieopbrengsten in Ethiopië beperken, meer aandacht gekregen van de overheid. Als reactie op stijgende voedselonzekerheid en armoede, stimuleert de overheid sinds 2000 zogenaamde water opvang technologieën (*water harvesting technologies; WHT*). Deze technologieën omvatten vijvers, ondiepe putten en het omleiden van rivierstromen en overstromingen. Hoewel deze technologieën ook tekortkomingen hebben, zijn er belangrijke voordelen ten opzichte van grootschalige irrigatiesystemen. Voordelen zijn o.a. dat ze relatief goedkoop zijn, ze zijn geschikt zijn voor kleinschalige bedrijven, geven weinig vernatting en veroorzaken geen conflicten rondom watergebruik. Bovendien is het investeren in deze technologieën en het gebruik van het water gebaseerd op individuele beslissingen van een huishouden, in tegenstelling tot wat bij conventionele gemeenschappelijke irrigatiesystemen gebruikelijk is. Het voordeel van individuele beslissingen is dat water efficiënter gebruikt wordt. Daarnaast hebben eerdere ervaringen van boeren ertoe geleid dat ze een negatieve houding hebben ten opzichte van coöperaties.

Individueel eigendom van het irrigatiesysteem vermijdt problemen van gemeenschappelijk eigendom.

Het gebruik van deze technologieën werd gestimuleerd door overheidsinstanties, daarbij rekening houdend met beperkingen die door huishoudens werden aangedragen. Na de oorspronkelijke in gebruik name bleven sommige huishoudens de technologieën gebruiken, terwijl andere huishoudens ermee stopten, ondanks het feit dat ze een positieve invloed hadden op inkomen, voedselzekerheid, en gebruik van moderne productiemiddelen. De individuele aspecten van deze technologieën en de voor de hand liggende voordelen ervan in Ethiopië, zijn de aanleiding voor dit empirisch micro-economisch onderzoek. Hoofdstuk 2 van dit proefschrift bespreekt de data die gebruikt zijn in de empirische analyse. De studie is gebaseerd op data afkomstig uit enquêtes die in 2005 en 2010 gehouden zijn. Ook werden er meerdere keren veldobservaties gedaan tussen 2005 en 2010. Het *Ethiopian Development Research Institute* (EDRI) voerde de eerste nationale enquête uit in 2005 in de grootste administratieve regio's van Tigray, Amhara, Oromia en SNNPR. Gedurende deze enquête werden 2082 huishoudens ondervraagd via een random selectie uit 30 sub-districten met een groot of klein tekort aan water. In de tweede enquête-ronde in 2010 werd eerst vooronderzoek gedaan waaruit bleek dat niet alle huishoudens door waren gegaan met het gebruik van de technologieën. De onderzoeker stratificeerde deze gebruikers en niet-gebruikers, en selecteerde uit zeven sub-districten van Oromia en SNNPR willekeurig 400 huishoudens (235 gebruikers en 165 niet-gebruikers) voor een tweede interview. Deze studie gebruikt cross-sectie data en panel data voor de micro-econometrische analyses die worden beschreven in individuele hoofdstukken van dit proefschrift. Deze analyses zijn gebaseerd op de in hoofdstuk 1 geformuleerde doelstellingen en onderzoeksvragen.

De algemene doelstelling van dit proefschrift is het bestuderen van de economische aspecten, dynamiek en impact van water opvang systemen door middel van micro-econometrische analyses. Daarnaast zijn er vier specifieke doelstellingen geformuleerd. Overeenkomstig deze specifieke doelstellingen wordt in het derde hoofdstuk onderzocht of water optimaal wordt gebruikt bij de productie van de drie gewassen die het meest frequent gebruik maken van WHT, namelijk uien, tomaten en groene paprika. Standaard translog productiefuncties en alternatieve asymmetrische productiefuncties zijn geschat voor elk gewas. Nadat econometrische testen zijn uitgevoerd, is de translog productiefunctie gekozen, en gebaseerd op deze functie zijn de waardes van het marginale product berekend voor het verzamelde water dat gebruikt wordt om elk gewas te produceren. De geschatte resultaten laten zien dat een 1% toename van gebruik in water leidt tot een stijging in de productie van uien met 0.12% en tomaten met 0.23%, maar de productie van groene paprika daalt. De berekende elasticiteit van de groene paprika is niet erg betrouwbaar en ook onaannemelijk. Daarnaast laten de geschatte resultaten zien dat de marginale productiewaarde van water bij uien en tomaten bijna gelijk zijn. Deze gelijkheid geeft aan dat - gemiddeld gezien - het verzamelde water economisch wordt verdeeld over deze twee groenten. Dit geeft een positief signaal af naar de niet-gebruikers om water opvang technieken te gebruiken in combinatie met een solide productie keuze. Een andere belangrijke conclusie van dit hoofdstuk is dat de geschatte waardes van de marginale producten variëren met het type techniek. Dit verschil biedt boeren een technologie keuze omdat de boeren verschillen in hun economische situatie (bijvoorbeeld in de hoeveelheid arbeid en in hun afzetmarkt), weersomstandigheden (bijvoorbeeld regenval), watervoorraden en productieomstandigheden.

Hoofdstuk 4 richt zich op het probleem van allocatie van land tussen volledig regen-afhankelijke productie en productie geïrrigeerd met opgeslagen water. De veronderstelling is dat hoe groter het deel geïrrigeerd land ten opzichte van het totale landoppervlakte, hoe groter de mogelijkheid om het risico van tekort aan regenval te hanteren is. Voorlopige onderzoeksresultaten laten echter zien dat het percentage geïrrigeerd land ten opzichte van het totale landoppervlak lager is voor een relatief groter bedrijf. Deze studie onderzoekt waarom dit het geval is. Een lager percentage van geïrrigeerd land ten opzichte van het totale landoppervlak kan immers de indruk wekken dat water opvang technieken minder relevant zijn voor grote landbouwbedrijven. Daarnaast zou een groter percentage regenafhankelijke productie betekenen dat boeren doorgaan met produceren van gewassen met een laag risico en lage opbrengst, wat groei van de totale landbouwproductie in de weg staat. Het geschatte random effect tobit model laat zien dat producent-specifieke factoren, zoals toegang tot de markt, krediet per hectare, regionale verschillen in landbouw-ecologische variabelen, en de institutionele en culturele factoren die niet door de onderzoeker worden geobserveerd, het percentage geïrrigeerd land beïnvloeden. Het aanmoedigen van investeringen die rekening houden met bedrijfsgrootte en verschillen tussen regio's en in landbouw-ecologische variabelen, zou kunnen leiden tot een hoger percentage geïrrigeerd land op grote bedrijven. Een stijging van dit percentage zou ook de proportie van geïrrigeerd land op nationaal niveau kunnen laten stijgen. Dit is momenteel minder dan 1.5%.

Hoofdstuk 5 onderzoekt waarom sommige huishoudens in de sub-districten stoppen met het gebruik van water opvang systemen terwijl het gebruik ervan leidt tot een reductie van het productierisico en het inkomen laat stijgen. In 2005 waren er 332 huishoudens uit het panel die een water opvang systeem gebruikten. Een deel van hen gebruikte in 2010 dit systeem nog steeds terwijl een ander deel hier mee gestopt was. Op basis van gegevens van deze 332 huishoudens zijn een Hausman-Taylor gebaseerd lineair kansmodel en een probit model geschat om te analyseren waarom huishoudens stopten of doorgingen met het gebruik van water opvang systemen. De schattingsresultaten van beide modellen laten voornamelijk zien dat een tekort aan plastic zeil, het aantal maanden met een tekort aan regenval, de beschikbaarheid van arbeid, ervaring in het gebruik van water opvang technieken, toegang tot de markt en krediet, het groeien van vaste planten, en regionale verschillen stoppen met gebruik beïnvloeden. Om dit terug te dringen moet voornamelijk het tekort aan plastic zeil worden opgelost. Daarnaast leiden het beschikbaar maken van krediet voor motorpompen, die een tekort aan arbeid oplossen, verbouwen van meerjarige gewassen, investeringen in infrastructuur voor een betere toegang tot de markt, tot een reductie van disadoptie. Ook is het belangrijk om rekening te houden met landbouw-ecologische verscheidenheid bij het promoten van water opslag systemen. De studie suggereert dat overheidsinstanties zich beter kunnen richten op het corrigeren van marktfalen dan dat ze de rol innemen van de private sector. De private sector kan zich dan richten op het aanbod van de belangrijkste constructiematerialen (plastic zeil) en pompen en het onderhoud daarvan. In Ethiopië is de betrokkenheid van de private sector in kleinschalige irrigatie technologieën beperkt. Dit geldt ook voor de betrokkenheid bij water opvang technieken. Dit kan ook een rol spelen bij het (beperkte) succes van deze technologieën onder kleine boeren.

In hoofdstuk 6 van het proefschrift wordt de invloed van water opvang systemen op het gebruik van kunstmest onderzocht. In 2008 werd slechts op 39% van het gecultiveerde land in Ethiopië kunstmest gebruikt. Dit percentage is te laag om de opbrengst te doen stijgen en een groeiende bevolking te voeden. In deze studie worden een panel probit model en een bivariate probit model geschat om te onderzoeken of het gebruik van water opvang systemen leidt tot het gebruik van kunstmest, en vice versa of er een verband bestaat tussen het gebruik van kunstmest en water opvang systemen. Om het eerste te testen is gebruikt gemaakt van panel data. Teneinde te testen of het gebruik van water verzamel technieken een effect heeft op het huidige gebruik van kunstmest en andersom, zijn indicator variabelen voor het gebruik in het verleden van zowel water verzamel technieken als kunstmest toegevoegd aan het model. De schattingsresultaten van zowel het panel probit model als het bivariate probit model geven sterk aan dat het gebruik van water opvang technieken leidt tot het gebruik van kunstmest in Ethiopië. Dit is zoals verwacht omdat de beschikbaarheid van water een basisvoorwaarde is voor het gebruik van kunstmest: het agronomisch principe van de wet van het minimum is hier debet aan, maar ook gaat met beschibaar water het productierisico omlaag. Deze conclusie geeft aan dat het gebruik van water opslag systemen het gebruik van kunstmest onder kleinschalige boeren in Ethiopië kan stimuleren, mits overige factoren die het aanbod van kunstmest bepalen, zoals de prijs, niet genegeerd worden. Aan de andere kant geeft het bivariate model aan dat het gebruik van kunstmest in het verleden geen significant effect heeft op het huidige gebruik van water opvang technieken. Dit zou kunnen betekenen dat in gebieden met lage regenval risico's water opvang technieken niet zo belangrijk zijn. De conclusie van dit hoofdstuk is dat kleinschalige water opvang technieken leiden tot het gebruik van kunstmest wat de opbrengstverhogend werkt, en wat een positief effect heeft op het inkomen en de voedselzekerheid van Ethiopische boeren.

In hoofdstuk 7 van dit proefschrift worden de belangrijkste conclusies van het onderzoek samengevat. Ook worden implicaties voor het beleid gegeven. Daarna geeft dit hoofdstuk de belangrijkste sterke punten en enkele valkuilen van dit proefschrift. Tot slot worden suggesties gedaan voor vervolgonderzoek gebaseerd op de veronderstellingen, resultaten en inzichten, en op de huidige situatie bij de water opvang technieken.

Completed Training and Supervision Plan (TSP)

Mekonnen Bekele Wakeyo
Wageningen School of Social Sciences (WASS)

Name of the course	**Department/ Institute**	**Year**	**ECTS***
Courses			
Mansholt Introductory course	MGS3,Mansholt Graduate School of Social Sciences Wageningen University	2008	1.5
Techniques for Writing and Presenting a Scientific Paper	MGS3, Wageningen University	2008	1.2
Scientific Writing	CENTA, Wageningen University Centre of Language Service	2008	1.5
Advanced Econometrics (AEP 50806)	MGS3, Wageningen University	2008	6.0
Economic Models (AEP 30806)	MGS3, Wageningen University	2008	6.0
Behavioural Economics	NAKE: Netherlands Network of Economics	2008	6.0
Economic Theory II	NAKE	2008	3.0
Spatial Econometrics	MGS3,Wageningen University	2008	1.5
Bayesian Econometrics	MGS3, Wageningen University	2008	1.5
Interpersonal communication for PhD Students	MGS3, Wageningen University	2008	0.6
Presentations at conferences			
Farm size and the share of irrigated land in total landholding: the case of water-harvesting irrigation in Ethiopia	XIII[th] EAAE 2011 Congress, Zurich, Switzerland	2011	1
The impact of water harvesting irrigation on fertilizer use in Ethiopia	AGRIMBA-AVA Congress II, Wageningen University, The Netherlands	2011	1
Farm size and the share of irrigated land in total landholding: the case of water-harvesting irrigation in Ethiopia	EAAE PhD Workshop, Nitra, Slovakia	2011	1
Farm size and the share of irrigated land in total landholding: the case of water-harvesting irrigation in Ethiopia	WASS Wageningen School of Social Sciences PhD Day, Wageningen University	2011	1
Disadoption of small-scale irrigation technologies: water harvesting irrigation in Ethiopia	WASS Cluster Seminar , Wageningen University	2011	1
Total			**33.8**

*One ECTS on average is equivalent to 28 hours of course work.

Curriculum vitae

Mekonnen Bekele Wakeyo was born on November 23, 1972 in Arsi in Ethiopia. Mekonnen attended primary, junior secondary and high school at Amigna Dinkiti, Amigna Gesgar (Adelle) and Didea Secondary School (Robe), respectively. He enrolled in the Addis Ababa University Social Science Faculty in 1988 and Department of Economics in 1989 and graduated with a Bachelor degree in Economics in 1992. He worked as a planning and research expert at Oromia Finance and economic development, Oromia Transport and Communication and Oromia Trade and Transport Bureaux, both in Harar (1993-1998) and Addis Ababa (1998-2002). He enrolled at Addis Ababa University School of Postgraduate in 1999and graduated with M.Sc. in Economic Policy Analysis in 2001. After graduation, he worked as a trade promotion expert in Oromia Trade and Transport Bureau in Addis Ababa and also engaged in a research project on technical vocational education in Ethiopia at the Ministry of Capacity Building in 2002. He was employed as an Associate Researcher at the Ethiopian Development Research Institute (EDRI) in January 2003. After four years of working in the Department of Agriculture, Rural Development and Environment at EDRI, he enrolled as a PhD Student in Agricultural Economics and Rural Policy Group (AEP) at Wageningen University. For some months, he conducted researches and shared experiences in agricultural water management in Japan at Japan International Research Centre for Agricultural Sciences/JIRCAS. Mekonnen is married to Ayantu Olana Wayessa and he is father of Milki and Hildana.

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- Front cover: unlined pond (Alaba special sub-district) and ponds lined by plastic-sheets (Gursum)
- Back cover: a cement pond in Alaba; a mango tree grown by the water from a pond (Alaba); a plastic-sheet lined pond constructed in a way that it allows access to the pond water

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