Working Paper Series
Department of Economics
University of Verona

How Can African Agriculture Adapt to Climate Change? A Counterfactual Analysis from Ethiopia

Marcella Veronesi, Salvatore Di Falco

WP Number: 14 March 2012

ISSN: 2036-2919 (paper), 2036-4679 (online)

How Can African Agriculture Adapt to Climate Change?

A Counterfactual Analysis from Ethiopia

Salvatore Di Falco

Department of Economics, University of Geneva
Uni Mail, 40 Boulevard du Pont D'Arve CH-1211 Geneva
Switzerland
Email: salvatore.difalco@unige.ch
Phone: +41 22 3798279

and

Marcella Veronesi

University of Verona, Department of Economics, and
Institute for Environmental Decisions, ETH Zurich

CITATION: Di Falco, S. and M. Veronesi (2013), "How Can African Agriculture Adapt to Climate Change? A Counterfactual Analysis from Ethiopia," *Land Economics* 89(4):743-766.

ABSTRACT. We analyse the impact of different adaptation strategies on crop net revenues in the Nile Basin of Ethiopia. We estimate a multinomial endogenous switching regression model of climate change adaptation and crop net revenues and implement a counterfactual analysis. Households data are combined with spatial climate data. We find that adaptation to climate change based upon a portfolio of strategies significantly increases farm net revenues. Changing crop varieties has a positive and significant impact on net revenues when is coupled with water conservation strategies or soil conservation strategies but not when implemented in isolation.

Keywords: adaptation, climate change, endogenous switching, Ethiopia, net revenues, strategies.

JEL classification: Q54, Q56

Salvatore Di Falco (contact author) is Professor of Environmental Economics, Department of Economics, University of Geneva (Switzerland). Marcella Veronesi is Assistant Professor, University of Verona, Department of Economics, and ETH Zurich, Institute for Environmental Decisions.The authors are very grateful to the anonymous reviewers for their very useful comments and suggestions. The authors would also like to thank participants at the Workshop on Climate Change and Agriculture in Ethiopia held in Addis Ababa on 9 July 2012 organized by Environment for Development Initiative. We also would like to thank Jean-Marie Baland, Derek Eaton, Jeremy Laurent-Lucchetti, Tim Swanson, Vincenzo Verardi along with seminar participants at the University of Laval (Canada), University of Central Florida, University of Geneva, the Graduate Institute of International and Development Studies Geneva, the University of Namur, the 14th International BIOECON Conference held in Cambridge for comments. Data assistance by Xavier Vollenweider is gratefully acknowledged. The usual disclaimer applies.

I. INTRODUCTION

Effective adaptation of agriculture to climate change is crucial to achieve food security in Sub Saharan Africa (Lobell et al. 2011). This part of Africa is characterized by millions of small scale subsistence farmers that farm land and produce food in extremely challenging conditions. The production environment is characterized by a joint combination of low land productivity and harsh weather conditions (i.e., high average temperature, and scarce and erratic rainfall). These result in very low yields of food crops and food insecurity. Because of the low level of economic diversification and reliance on rain-fed agriculture, sub-Saharan Africa's development prospects have been closely associated with climate. Climate change is projected to further reduce food security (Rosenzweig and Parry 1994; Parry, Rosenzweig, and Livermore 2005; Cline 2007; Lobell et al. 2008; Schlenker and Lobell 2010). For instance, the fourth Intergovernmental Panel on Climate Change (IPCC) suggests that at lower latitudes, in tropical dry areas, crop productivity is expected to decrease "for even small local temperature increases (1 – 2° C)" (IPCC 2007). In many African countries access to food will be severely affected, "yields from rain fed agriculture could be reduced by up to 50% by 2020" (IPCC 2007, p.10). Future warming seems unavoidable. Current agreements to limit emissions, even if implemented, will not stabilize atmospheric concentrations of greenhouse gases and climate change. Farmers will thus still face a warmer production environment.

The identification of climate change adaptation strategies is therefore vital in sub Saharan Africa.[1] These strategies can indeed buffer against the implications of climate change and play an important role in reducing the food insecurity of farm households. While the importance of adaptation is widely accepted, our understanding on how to adapt (and its economic impact) is still quite weak. Adaptation is a complex phenomenon comprising of different strategies that may play an important role in supporting the welfare of farm households. There are different measures, that in principle, farmers can adopt to address climate change: For instance, switching crops, adopting water harvesting technologies, or adopting conservation measures to retain soil moisture. Farmers can implement these measures in isolation or in combination.

In this study, we analyse and compare the role of different adaptation strategies to answer the following research questions: What are the factors affecting the adoption of strategies in isolation or in combination? What are the "best" strategies that can be implemented to deal with climatic change in the field? In particular, what are the economic implications of different strategies? To answer these questions is important to make the adaptation process explicit. The basic premise of this paper is that a possible way to understand the role of adaptation is to study farmers mitigating responses to impacts of changes to date. Adaptation to changing climatic conditions is not, in fact, a new process. Farmers have constantly implemented adjustments to cope with the vagaries of climatic conditions. Thus, understanding the impacts of past adaptation can help us gauging the importance of these strategies in the face of future climate change. In addition, a farm level perspective can be particularly useful to inform us of the barriers and drivers behind the different adaptation strategies.

We contribute to the existing literature on climate change in agriculture in three ways. First, we disentangle the economic implications of different climate change adaptation strategies within a Ricardian framework.[2] This is within the spirit of the so called "structural Ricardian analysis" (pioneered by Seo and Mendelsohn 2008a and 2008b; Seo 2010; Kurukulasuruya and Mendelsohn 2008).[3] In particular, we investigate whether implementing these strategies in combination is more effective than implementing them individually. Second, we identify the most successful strategies by implementing a counterfactual analysis. This provides information on what farm households would have earned if they had not adapted a particular strategy. Third, we add some empirical evidence from Ethiopia on farmers' climate change adaptation strategies to a number of country specific studies (e.g., Seo and Mendelsohn 2008a, 2008b, 2008c, 2008d; Deressa et al. 2009; Kurukulasuriya, Kala and Mendelsohn 2011).

We have access to a unique database on Ethiopian agriculture to answer our research questions. One of the survey instruments was specifically designed to investigate farmers' climate change perception and adaptation. Specifically, farmers were asked what adjustments they made in response to long-term shifts in temperature and/or rainfall. Farmers in the study sites have undertaken a number of adaptation measures, including changing crop varieties, adopting soil conservation measures, and water related strategies such as water harvesting and water conservation. These adaptation measures account for more than 95 per cent of the measures followed by the farm households that actually undertook an adaptation measure.[4]

Farmers' decision to adapt and what strategy to adopt is voluntary and based on individual self-selection. Farm households that adopted a particular strategy are not a random sample of the original population, they may have systematically different characteristics from farm households that did not adapt or adopted a different strategy. Unobservable characteristics of farmers and their farm may affect both the adaptation strategy decision and net revenues, resulting in inconsistent estimates of the effect of adaptation on net revenues. For example, if only the most skilled or motivated farmers choose to adapt or choose the most profitable strategy then self-selection bias can affect the estimates. In addition, observable variables may have different marginal effects on net revenues within the context of different strategies.

We address these issues by estimating a multinomial endogenous switching regression model of climate change adaptation and crop net revenues by a two stage procedure which allows to produce selection-corrected net revenues. In the first stage, we use a selection model where a representative farm household chooses to implement a specific strategy, while in the second stage the information stemming from the first step is used in a Ricardian model (Mendelsohn, Nordhaus and Shaw 1994), where farm net revenues are regressed against climatic variables and other control variables.[5] Climatic variables such as rainfall and temperature at the household level were constructed via the *Thin Plate Spline* method of spatial interpolation. This method imputes the farm specific values using latitude, longitude, and elevation information of each farm household (see Wahba 1990 for details).

The inclusion of these climatic variables is essential to estimate the Ricardian model. The availability of climatic variables can also be useful to test whether the strategies were implemented in response to climate change. We use as selection instruments in the net revenue functions the variables related to past experience of extreme weather events (e.g., flood, drought, hailstorm) and past information sources (e.g., government extension, farmer-to-farmer extension, information from radio, and if received information in particular on climate). We establish the admissibility of these instruments by performing a simple falsification test: if a variable is a valid selection instrument, it will affect the decision of choosing an adaptation strategy but it will not affect the net revenue per hectare among farm households that did not adapt (Di Falco, Veronesi and Yesuf 2011).

We find that adaptation to climate change based upon a combination of strategies has a significant positive effect on farm net revenues opposed to strategies adopted in isolation.

II. BACKGROUND

Ethiopia's GDP is closely associated with the performance of its rainfed agriculture (Deressa and Hassan 2010). For instance, about 40 percent of national GDP, 90 percent of exports, and 85 percent of employment stem from agricultural sector. The rainfed production environment is characterized by large extent of land degradation and very erratic and variable climate. Historically, rainfall variability and associated droughts have been major causes of food shortage and famine in Ethiopia. The success of the agricultural sector is crucially determined by the productivity of small holder farm households. They account for about 95 percent of the national agricultural output, of which about 75 percent is consumed at the household level (World Bank 2006). With a low diversified economy and reliance on rain-fed agriculture, Ethiopia's development prospects have been thus associated with climate. For instance, the World Bank (2006) reported that catastrophic hydrological events such as droughts and floods have reduced its economic growth by more than a third.

The frequency of droughts has increased over the past few decades, especially in the lowlands (Lautze et al. 2003; NMS 2007). A study undertaken by the national meteorological service (NMS 2007) highlights that annual minimum temperature has been increasing by about 0.37 degrees Celsius every 10 years over the past 55 years. Rainfall have been more erratic with some areas becoming drier while other becoming relatively wetter. These findings point out that climatic variations have already happened. The prospect of further climate change can exacerbate this very difficult situation. Climate change is indeed projected to further reduce agricultural productivity (Rosenzweig and Parry 1994; Parry, Rosenzweig, and Livermore 2005; Cline 2007). Most of climate models converge in forecasting scenarios of increased temperatures for most of Ethiopia (Dinar et al. 2008).

III. SURVEY AND DATA DESCRIPTION

This study relies on a survey conducted in 2004 and 2005 on 1,000 farm households in the Nile Basin of Ethiopia (IFPRI 2010), one of the countries most vulnerable to climate change with least capacity to respond (Orindi et al. 2006; Stige et al. 2006). This is a very large area covering roughly one third of the country. The sampling frame considered traditional typology of agro-ecological zones in the country (namely, *Dega, Weina Dega, Kolla* and *Bereha*), percent of cultivated land, average annual rainfall, rainfall variability, and vulnerability (number of food aid dependent population). The sampling frame selected the *woredas* (an administrative division equivalent to a district) in such a way that each class in the sample matched to the proportions for each class in the entire Nile basin. The procedure resulted in the inclusion of twenty *woredas*. Random sampling was then used in selecting fifty households from each *woreda*.

Farmers reported their use of production input and output data at the plot level for two cropping seasons: *Meher* (long rainy season) and *Belg* (the short rainy season). Although a total of forty-eight annual crops were grown in the basin, the first five major annual crops (teff, maize, wheat, barley, and beans) cover 65 per cent of the plots. These are also the crops that are the cornerstone of the local diet. We limit the analysis to these primary crops. The final sample includes 941 farm households, and 2,802 plots. The scale of the analysis is at the plot level. The farming system in the survey sites is very traditional with plough and yoke (animals' draught power). Labor is the major input in the production process during land preparation, planting, and post-harvest processing. Labor inputs were disaggregated as adult male's labor, adult female's labor, and children's labor. This approach of collecting data (both inputs and outputs) at different stages of production and at different levels of disaggregation should reduce cognitive burden on the side of the respondents, and increase the likelihood of retrieving a better retrospective data. The three forms of labor were aggregated as one labor input using adult equivalents. We employed the standard conversion factor in the literature on developing countries where an adult female and children labor are converted into adult male labor equivalent at 0.8 and 0.3 rates, respectively.

One of the survey instruments was specifically designed to analyze farmers' climate change perception and adaptation. Specific questions were included to investigate whether farmers have noticed changes in mean temperature and rainfall over the last two decades, and whether in response to these changes they made some adjustments in their farming by adopting some particular strategies. Farm households in the study sites have undertaken a number of adaptation measures, including changing crop varieties, adopting soil conservation measures, and water strategies such as water harvesting and water conservation (Table 1).[6]

[TABLE 1 HERE]

The adaptation measures were implemented both in isolation and jointly. They are mainly yield related and account for more than 95 percent of the measures followed by the farm households that actually undertook an adaptation measure. The remaining adaptation strategies were much less adopted. For instance, migration or finding off-farm jobs were considered viable adaptation strategies in less than seven percent of the sample. We identified eight main strategies: (1) changing crop varieties *only;* (2) implementing *only* water strategies such as water harvesting, irrigation or water conservation; (3) implementing *only* soil conservation; (4) implementing water strategies *and* changing crop varieties; (5) implementing soil conservation *and* changing crop varieties; (6) implementing water strategies *and* soil conservation; (7) implementing water strategies, soil conservation, *and* changing crop varieties; and (8) implementing other strategies. We set "non-adapting" as the reference category. Table 2 shows that implementing *only* soil conservation, and soil conservation *and* changing crop varieties are the most popular strategies (21% and 29% among the adapters).

Monthly rainfall and temperature data were collected from all the meteorological stations in the country. Then, the *Thin Plate Spline* method of spatial interpolation was used to impute the household specific rainfall and temperature values using latitude, longitude, and elevation information of each household.[7] This method is one of the most commonly used to create spatial climate data sets. Its strengths are that it is readily available, relatively easy to apply, and it accounts for spatially varying elevation relationships. However, it only simulates elevation relationship, and it has difficulty handling very sharp spatial gradients. This is typical of coastal areas. Given that the area of the study is characterized by significant terrain features, and no climatically important coastlines, the choice of the *Thin Spline method* is reasonable (for more details on the properties of this method in comparison to the other methods see Daly 2006). Variables' definition is presented in Table A1 of the appendix while the descriptive statistics in Table 2.

[TABLE 2 HERE]

IV. MODELLING CLIMATE CHANGE AND ADAPTATION STRATEGIES

In this section, we specify a model of climate change adaptation and net revenues in the setting of a two-stage framework. In the first stage, we assume that farm households face a choice of *M* mutually exclusive strategies to long term changes in mean temperature and rainfall. In the second stage, we outline an econometric model that is used to investigate the effects of different climate change adaptation strategies on net revenues. Particular functional forms are chosen to remain within the spirit of previous work in this area (e.g., Deressa and Hassan 2010).

Stage I – Selection Model of Climate Change Adaptation Strategies

In the first stage, let *A** be the latent variable that captures the expected net revenues from implementing strategy *j* (*j = 1 … M*) with respect to implementing any other strategy *k*. We specify the latent variable as

(1) $A_{ij}^{*} = \overline{V}_{ij} + \eta_{ij} = \mathbf{Z_i}\boldsymbol{\alpha}_\mathbf{j} + \eta_{ij}$

$$\text{with } A_i = \begin{cases} 1 \quad iff \quad A_{i1}^{*} > \max\limits_{k \neq 1}(A_{ik}^{*}) \text{ or } \varepsilon_{i1} < 0 \\ \vdots \qquad\qquad \vdots \qquad\qquad\qquad \vdots \\ M \; iff \quad A_{iM}^{*} > \max\limits_{k \neq M}(A_{ik}^{*}) \text{ or } \varepsilon_{iM} < 0 \end{cases}$$

that is, farm household *i* will choose strategy *j* in response to long term changes in mean temperature and rainfall if strategy *j* provides expected net revenues greater than any other strategy $k \neq j$, i.e., if $\varepsilon_{ij} = \max\limits_{k \neq j}(A_{ik}^{*} - A_{ij}^{*}) < 0$. Equation (1) includes a deterministic component ($\overline{V}_{ij} = \mathbf{Z_i}\boldsymbol{\alpha}_\mathbf{j}$), and an idiosyncratic unobserved stochastic component η_{ij}. The latter captures all the variables that are relevant to the farm household's decision maker but are unknown to the researcher such as skills or motivation. It can be interpreted as the unobserved individual propensity to adapt.

The deterministic component $\overline{V}_{ij}$ depends on factors $\mathbf{Z_i}$ that affect the likelihood of choosing strategy *j* such as farmer head's and farm household's characteristics (e.g., age, gender, education, marital status, and farm household size), the presence of assets such as animals, the characteristics of the operating farm (e.g., soil fertility and erosion), past climatic factors[8] (e.g., 1970 – 2000 mean rainfall and temperature), the agroecological zone of the farm household (*Dega*, *Kolla*, and *Weina Dega*), and the experience of previous extreme weather events such as droughts, floods, and hailstorms. Experience in farming is approximated by age and education.

Furthermore, farm households may have access to information on farming strategies before they can consider adopting them, as well as information about climate. Since extension services are one important source of information for farmers, we use access to government and farmer-to-farmer extensions as measures of access to information. We also control for tree planting. Besides providing agroecological benefits, trees provide a very important function: they are a proxy for land tenure security. This has been observed in previous research on sub-Saharan Africa. Perennial crops can be a way of strengthen claims to land and show to the rest of the community a continuous use of the resource (Sjaastad and Bromley 1997; Besley 1995). As Platteau (1992) noted “the best way of exercising control over land is to plant trees” (p. 166). This view is also documented in Ethiopia by Shiferaw and Holden (1998), Gebremedhin and Swinton (2003), Ayalneh, Taeb and Mitsugi (2006) and Mekonnen (2009).[9]

It is assumed that the covariate vector $\mathbf{Z_i}$ is uncorrelated with the idiosyncratic unobserved stochastic component η_{ij}, i.e., $E(\eta_{ij} | \mathbf{Z_i}) = 0$. Under the assumption that η_{ij} are independent and identically Gumbel distributed, that is under the Independence of Irrelevant Alternatives (IIA) hypothesis, selection model (1) leads to a multinomial logit model (McFadden 1973) where the probability of choosing strategy j (P_{ij}) is

$$(2)\quad P_{ij} = P(\varepsilon_{ij} < 0 | \mathbf{Z_i}) = \frac{\exp(\mathbf{Z_i}\boldsymbol{\alpha}_\mathbf{j})}{\sum_{k=1}^{M} \exp(\mathbf{Z_i}\boldsymbol{\alpha}_\mathbf{k})}.$$

Stage II – Multinomial Endogenous Switching Regression Model

In the second stage, we estimate a multinomial endogenous switching regression model to investigate the impact of each strategy on net revenues by applying Bourguignon, Fournier, and Gurgand (2007) selection bias correction model. Our model implies that farm households face a total of *M* regimes (one regime per strategy, where *j=1* is the reference category "non-adapting"). We have a net revenue equation for each possible regime *j* defined as:

$$
\begin{array}{lll}
(3a) & \text{Regime 1:} & y_{i1} = \mathbf{X_i}\boldsymbol{\beta_1} + u_{i1} \quad \text{if } A_i = 1 \\
\vdots & \vdots & \vdots \\
(3m) & \text{Regime M:} & y_{iM} = \mathbf{X_i}\boldsymbol{\beta_M} + u_{iM} \quad \text{if } A_i = M
\end{array}
$$

where y_{ij} is the net revenue per hectare of farm household *i* in regime *j*, ($j = 1, \dots, M$), and $\mathbf{X_i}$ represents a vector of inputs (e.g., seeds, fertilizers, manure, and labour), farmer head's and farm household's characteristics, soil's characteristics, and the past climatic factors included in $\mathbf{Z_i}$; u_{ij} represents the unobserved stochastic component, which verifies $E(u_{ij}|\mathbf{X_i}, \mathbf{Z_i}) = 0$ and $V(u_{ij}|\mathbf{X_i}, \mathbf{Z_i}) = \sigma_j^2$. For each sample observation only one among the *M* dependent variables (net revenues) is observed. When estimating an OLS model, the net revenues equations (3*a*)-(3*m*) are estimated separately. However, if the error terms of the selection model (1) η_{ij} are correlated with the error terms u_{ij} of the net revenue functions (3*a*)-(3*m*), the expected values of u_{ij} conditional on the sample selection are nonzero, and the OLS estimates will be inconsistent. To correct for the potential inconsistency, we employ the model by Bourguignon, Fournier and Gurgand (2007), which takes into account the correlation between the error terms η_{ij} from the multinomial logit model estimated in the first stage and the error terms from each net revenue equation u_{ij}. We refer to this model as a "multinomial endogenous switching regression model" following the terminology of Maddala and Nelson (1975) extended to the multinomial case.

Bourguignon, Fournier and Gurgand (2007, p. 179) show that consistent estimates of $\boldsymbol{\beta_j}$ in the outcome equations (3*a*)-(3*m*) can be obtained by estimating the following selection bias-corrected net revenues equations,

$$(4a)\quad \text{Regime 1:}\quad y_{i1} = \mathbf{X_i\beta_1} + \sigma_1\left[\rho_1 m(P_{i1}) + \sum_j \rho_j m(P_{ij})\frac{P_{ij}}{(P_{ij}-1)}\right] + \nu_{i1}\ \ if\ A_i = 1$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$(4m)\quad \text{Regime M:}\quad y_{iM} = \mathbf{X_i\beta_M} + \sigma_M\left[\rho_M m(P_{iM}) + \sum_j \rho_j m(P_{ij})\frac{P_{ij}}{(P_{ij}-1)}\right] + \nu_{iM}\ \ if\ A_i = M$$

where P_{ij} represents the probability that farm household i chooses strategy j as defined in (2), ρ_j is the correlation between u_{ij} and η_{ij}, and $m(P_{ij}) = \int J(\nu - \log P_j)g(\nu)d\nu$ with $J(.)$ being the inverse transformation for the normal distribution function, $g(.)$ the unconditional density for the Gumbel distribution, and $\nu_{ij} = \eta_{ij} + \log P_j$. This implies that the number of bias correction terms in each equation is equal to the number of multinomial logit choices M.

For the model to be identified it is important to use as exclusion restrictions, thus as selection instruments, not only those automatically generated by the nonlinearity of selection model (1) but also other variables that directly affect the selection variable but not the outcome variable. In our case study, we use as selection instruments in the net revenue functions the variables related to the past experience of extreme weather events[10] (e.g., droughts, floods, and hailstorms), and the information sources (e.g., government extension, farmer-to-farmer extension, information from radio, and if received information in particular on climate). We establish the admissibility of these instruments by performing a simple falsification test: if a variable is a valid selection instrument, it will affect the decision of choosing an adaptation strategy but it will not affect the net revenue per hectare among farm households that did not adapt (Di Falco, Veronesi and Yesuf 2011). Table 3 and Table A2 of the appendix show that the extreme weather events and the information sources can be considered as valid selection instruments: they are jointly statistically significant drivers of the decision to adapt strategy j but not of the net revenues per hectare by the farm households that did not adapt at the 1% and 5% statistical level. In addition, standard errors are bootstrapped to account for the heteroskedasticity arising from the two-stage estimation procedure.

A crucial assumption of the Bourguignon, Fournier and Gurgand (2007)'s model is that IIA holds. However, Bourguignon, Fournier and Gurgand (2007) show that "selection bias correction based on the multinomial logit model can provide fairly good correction for the outcome equation, even when the IIA hypothesis is violated" (p. 199). An alternative estimation method is provided by Dahl (2002), which corrects the outcome equation of endogenous selection semi-parametrically by adding a polynomial of choice probabilities to the covariate vector. However, Bourguignon, Fournier and Gurgand (2007) show that their method is more robust than the one proposed by Dahl (2002), which is more suitable when a large number of observations is available and the number of choices in the selection model is small otherwise "the identification of the covariance matrix between all model residuals becomes intractable" (p. 200), as it would be in our case.

In addition, we exploit plot level information to deal with the issue of farmers' unobservable characteristics such as their skills. Plot level information can be used to construct a panel data and control for farm specific effects (Udry 1996). Including standard fixed effects (where variables are transformed in deviations from their means) is, however, particularly complex in our multinomial switching regression approach. In addition, the alternative method of adding the inverse Mills ratio to the second step and using standard fixed effects does not lead to consistent estimates (Wooldridge 2002, p. 582-583). We follow Mundlak (1978) and Wooldridge (2002) to control for unobservable characteristics. We exploit the plot level information, and insert in the net revenues equations (4*a*)-(4*m*) the average of plot–variant variables $\bar{\mathbf{S}}_{\mathbf{i}}$ such as the inputs used (seeds, manure, fertilizer, and labor). This approach relies on the assumption that the unobservable characteristics v_i are a linear function of the averages of the plot-variant explanatory variables $\bar{\mathbf{S}}_{\mathbf{i}}$, that is $v_i = \bar{\mathbf{X}}_{\mathbf{i}}\boldsymbol{\pi} + \psi_i$ with $\psi_i \sim IIN(0, \sigma_{\psi}^2)$ and $E(\psi_i / \bar{\mathbf{X}}_{\mathbf{i}}) = 0$, where $\boldsymbol{\pi}$ is the corresponding vector of coefficients, and ψ_i is a normal error term uncorrelated with $\bar{\mathbf{S}}_{\mathbf{i}}$.

V. COUNTERFACTUAL ANALYSIS AND TREATMENT EFFECTS

In this section, we present the estimation of the treatment effects (Heckman, Tobias, and Vytlacil 2001), that is the effect of the treatment “adoption of strategy *j*” on the net revenues of the farm households that adopted strategy *j*. In absence of a self-selection problem, it would be appropriate to assign to farm households that adapted a counterfactual net revenue equal to the average net revenue of non-adapters with the same observable characteristics. However, unobserved heterogeneity in the propensity to choose an adaptation strategy affects also net revenues and creates a selection bias in the net revenue equation that cannot be ignored. The multinomial endogenous switching regression model can be applied to produce selection-corrected predictions of counterfactual net revenues.

In particular, we follow Bourguignon, Fournier and Gurgand (2007, p. 179 and pp. 201-203), and we first derive the expected net revenues of farm households that adapted, that in our study means $j = 2 \ldots M$ ($j = 1$ is the reference category “non-adapting”), as

$$(5a)\quad E(y_{i2} \mid A_i = 2) = \mathbf{X_i \beta_2} + \sigma_2 \left[\rho_2 m(P_{i2}) + \sum\nolimits_{k \neq 2}^{M} \rho_k m(P_{ik}) \frac{P_{ik}}{(P_{ik} - 1)} \right]$$

$$\vdots$$

$$(5m)\quad E(y_{iM} \mid A_i = M) = \mathbf{X_i \beta_M} + \sigma_M \left[\rho_M m(P_{iM}) + \sum_{k=1 \ldots M-1} \rho_k m(P_{ik}) \frac{P_{ik}}{(P_{ik} - 1)} \right]$$

Then, we derive the expected net revenues of farm households that adopted strategy *j* in the counterfactual hypothetical case that they did not adapt ($j = 1$) as

$$(6a)\quad E(y_{i1} \mid A_i = 2) = \mathbf{X_i \beta_1} + \sigma_1 \left[\rho_1 m(P_{i2}) + \rho_2 m(P_{i1}) \frac{P_{i1}}{(P_{i1} - 1)} + \sum_{k=3 \ldots M} \rho_k m(P_{ik}) \frac{P_{ik}}{(P_{ik} - 1)} \right]$$

$$\vdots$$

$$(6m)\quad E(y_{i1} \mid A_i = M) = \mathbf{X_i \beta_1} + \sigma_1 \left[\rho_1 m(P_{iM}) + \sum_{k=2 \ldots M} \rho_k m(P_{i,k-1}) \frac{P_{i,k-1}}{(P_{i,k-1} - 1)} \right]$$

This allows us to calculate the treatment effects (TT), as the difference between equations (5*a*) and (6*a*) or (5*m*) and (6*m*), for example.

VI. RESULTS

In this section, we first investigate the factors affecting the adoption of strategies in isolation or combination, and then, the implications of adopting a particular strategy on farm households' net revenues.

VI.I Drivers of climate change adaptation strategies

Table 3 presents parameter estimates of the multinomial logit model and allows us to answer the first research question on what are the main drivers of adopting a particular climate change strategy.

[TABLE 3 HERE]

Some covariates positively and significantly affect the adoption of a large number of strategies. This is the case for most of the climatic variables. Rainfall in the long rain period (Meher) and temperature are statistically significant drivers of the adoption of all strategies with the exception of (1) changing crop varieties in isolation and (8) other strategies.[11] The statistical significance of the majority of climatic variables on the probability of adaptation can provide some evidence that the adaptation strategies undertaken by farmers are indeed correlated with climate. It could in fact be argued that some of these strategies are part of standard farming practices rather than be related to climate adaptation per se. Below, in the next section, it is also shown that strategies that are indeed correlated with climatic variables also display a statistically significant treatment effect. This evidence can offer some reassurance that climate is indeed a key driver behind the adaptation strategies and that adaptation delivers an important payoff.

Soil conditions are found to be extremely important and consistent across the board. We indeed find evidence that farm households with highly fertile soils are less likely to adapt via changing crop varieties, soil conservation (both in isolation or jointly with water and crops). Farms characterized by very severe erosion, instead, are less likely to undertake more complex strategies that adopt a portfolio of responses such as jointly doing water, crop and conservation measures.

Interestingly, the role of planting trees is strongly positive and statistically significant. As reported earlier, this supports the hypothesis that trees are ways of securing property rights. The more tenure secure a farm household is and the more likely it is to undertake adaptation strategies. Compared with the existing literature on the determinants of adaptation this result is novel (e.g., Deressa et al. 2009; Kurukulasuriya and Mendelsohn 2008). Among the socio economic characteristics, both education and household size display a positive impact on some strategies. Past experience of extreme events also plays a role in adaptation. Events such as flood and hailstorm significantly increase the likelihood to choose soil conservation and crop-water strategies.

We explored the role of extension services on the probability to adopt the strategies. We find that both government extension and farmer-to-farmer extension have a positive and statistically significant effect on some of the strategies. Government extension services are positively correlated with the probability of adaptation via changing crops in isolation and in conjunction with soil conservation measures, while farmer-to-farmer extension increases the likelihood of adopting strategies only in combination. Those farmers that were approached by their peers were thus more likely to undertake a portfolio approach and implement the following combinations: water strategies *and* changing crop varieties, water strategies *and* soil conservation, water strategies *and* soil conservation *and* changing crop varieties. This latter most comprehensive strategy is also positively affected by the provision of information on climate change. In addition, information is positively and significantly correlated with other two strategies: soil conservation adopted in isolation, and changing crop varieties and water strategies adopted in combination. Our results on the role of extension and information are very consistent with the existing literature (Shiferaw and Holden, 1998; Bekele and Drake, 2003, Anley, Bogale and Haile-Gabriel 2007; Tesfaye and

Brower 2012). In the concluding section, we will further discuss our results, in particular, in light of their implications in terms of net revenues.

VI.II Economic implications of climate change adaptation strategies

We now turn on the economic implications of adopting a particular strategy on farm households' net revenues. What are the strategies yielding to the highest revenues? Two simple and standard approaches could be applied to identify the "best" adaptation strategy. First, we could compare actual mean net revenues per hectare by farm household adaptation strategy (Table 2, first row).[12] This naïve comparison would drive the researcher to conclude that farm households that adopted water strategies *and* soil conservation measures are those that earned the most, in particular, about 1,550 Etb/ha more than farm households that did not adapt (difference significant at the 1% level, t-stat.= -4.30). A second possible approach consists in estimating a linear regression model of net revenues that includes binary variables equal to 1 if the farm household adopted a particular strategy (Table A3 of the appendix). This approach would lead us to conclude that farm households implementing *only* water strategies would earn the most, about 1,680 Etb/ha more than farm households that did not adapt.

However, both approaches can be misleading, and should be avoided in evaluating the impact of adaptation strategies on net revenues. They both assume that adaptation to climate change is exogenously determined while it is a potentially endogenous variable. The difference in net revenues may be caused by unobservable characteristics of the farm households such as their skills. For instance, the apparently most successful farm households could also be the most skilled ones, and so, those that would have done better than the others even without adapting. We address this issue by estimating a multinomial endogenous switching regression model as described in section IV: in a first stage, we estimate the aforementioned multinomial logit model of choice between multiple combinations of strategies, and in a second stage, we estimate net revenue functions that account for the endogenous strategy decision.[13] Then, we plug the coefficients of the net revenue functions in equations (6*a*-6*m*) to produce selection-corrected predictions of counterfactual net revenues, that is what farm households would have earned if they had not adapted.

Table 4 presents net revenues per hectare under actual and counterfactual conditions. We compare expected net revenues under the actual case that the farm household adopted a particular strategy to adapt to climate change and the counterfactual case that did not. The last column of Table 4 presents the impact of each adaptation strategy on net revenues, which is the treatment effect, calculated as the difference between columns (1) and (2).

Importantly, we find no statistical evidence of the impact of strategies that are implemented in isolation. Thus, changing crops, water conservation, and soil conservation if implemented in isolation do not seem to significantly impact net revenues. We find that adaptation to climate change based upon a portfolio of strategies significantly increases farm households' net revenues, instead.

The counterfactual analysis allows us identifying the set of strategies that can deliver the highest payoff. As already identified by the existing literature, switching crops is one of the most remunerative strategies implemented by farmers (e.g., Kurukulasuriya and Mendelsohn 2007; Seo and Mendelsohn 2008c; Hassan and Nhemachena, 2008; Deressa et al. 2009; Wang et al. 2010). We find that the impact of changing crops on net revenues is highly significant (at the 1% statistical level) when is implemented along with water conservation or soil conservation, and not when it is implemented in isolation. In particular, the impact of strategy (4) changing crops combined with water conservation is equal to about 2,332 Etb/ha, and the impact of strategy (5) changing crops combined with soil conservation is about 2,193 Etb/ha. We also find that the adoption of the former or the latter strategy yields to payoffs not statistically different (p-value = 0.273). The combination of water and soil conservation has also a positive and statistically significant impact (about 1,730 Etb/ha), and even if lower, not statistically different from the previous strategies (4) and (5) (t-stat.

= 0.666 and 0.867, respectively). Interestingly, when all these three strategies (changing crops, water *and* soil conservation) are implemented as part of the same adaptation portfolio they deliver a payoff of 1,297 Etb/ha, which is lower and statistically different only from strategy (5) that entails the combination of changing crops and soil conservation (t-stat. = 2.753). In all the other cases, the impact of adopting three strategies combined is not statistically different from the impact of adopting two strategies. In other words, we find no statistical evidence that implementing a more comprehensive adaptation strategy that entails three strategies delivers higher net revenues than a less comprehensive strategies that uses the combination of two strategies. We will provide some interpretation of these results in the section below.

VII. CONCLUSIONS

This study investigates what are the best strategies to adjust to long term changes in temperature and rainfall by estimating the impact of engaging in various agricultural practices on net revenues in the Nile Basin of Ethiopia. We implement a counterfactual analysis, and estimate a multinomial endogenous switching regression model of climate change adaptation and crop net revenues to account for the heterogeneity in the decision to adopt or not a particular strategy, and for unobservable characteristics of farmers and their farm.

We find that the choice of what adaptation strategy to adopt is crucial to support farm revenues. We find that strategies adopted in combination with other strategies rather than in isolation are more effective. Adaptation is, therefore, more effective when it is composed by a portfolio of actions rather than one single action. More specifically, we find that the positive impact of changing crop is significant when is coupled with water conservation strategies or soil conservation strategies. This highlights the importance of not implementing water or soil conservation programs in isolation. Interestingly, when all three strategies are implemented the impact is significantly not different than when two strategies are implemented. There is, therefore, no statistical evidence that a more comprehensive adaptation strategy has a higher payoff. This result, while puzzling at the outset, is actually quite intuitive. We are in fact modelling net revenues. It may therefore simply reflect the higher cost of implementing a more complex adaptation strategy. Adaptation through more strategies has higher impact on the costs of adaptation, thus eroding net revenues. This result may also indicate the important role of the cost of adaptation in our setting.

These findings are crucial to design polices for effective adaptation strategies to cope with the potential impacts of climate change. Public policies can indeed play an important role in helping farm households to adapt. This combines both the identification of the "best" portfolio and the determinants of adaptation strategies. For instance, tenure security is found to be positively correlated with all the strategies. The dissemination of information on changing crops and implementing soil conservation strategies are very important. Extension services are, for instance, very important in determining the implementation of adaptation strategies, which could result in more food security for all farmers irrespective of their unobservable characteristics. The availability of information on climate change may raise farmers' awareness of the threats posed by the changing climatic conditions.

In particular, we find that extension services (either via government or farmers) are particularly effective in increasing farmers' propensity to implement more strategies in combination. For instance, farmer-to-farmer extension is positively correlated with the probability of adopting water strategies combined with changing crop varieties or soil conservation. The adoption of these portfolio strategies yields to significantly higher net revenues than if farm households did not adapt or adopted the same strategies in isolation. Same result is found when we analyse the role of climate change information.

It is important to stress that both the set of adaptation strategies and the drivers of adaptation (such as extension services) identified in this paper have been traditional components of rural development programs. Our results highlight the fact that facilitating adaptation to climate change may also address development and poverty reduction. Raising the awareness of farmers regarding climate change and increasing their capacity to adapt to climate change imply increasing the opportunity of development.

In conclusion, some caveats are important. The results reported in this paper rely on cross sectional and plot level data. More and better data (e.g., panel data with time dimension) should be made available to provide more robust evidence on both the role of adaptation and its implications for agriculture. The dynamic of the problem should be also explicated. Some adaptation strategies can be effective in the short run while others may be delivering a payoff in the long run. Future research should be allocated to address these issues as well as the behavioural dimension of adaptation, and the impact of other management practices such as livestock and agroforestry.

APPENDIX

TABLE A1. Variables' Definition

Variable name	*Definition*
Dependent variables	
net revenues	*net revenues per hectare in Ethiopian birr (Etb). 1 Etb= $0.0592.*
Adaptation strategies	
changing crop varieties only	*dummy = 1 if the farm household only changed crop varieties as adaptation strategy, 0 otherwise*
water strategies only	*dummy = 1 if the farm household adopted only water strategies (i.e., irrigation, water harvesting scheme, water conservation) as adaptation strategy, 0 otherwise*
soil conservation only	*dummy = 1 if the farm household adopted only soil conservation as adaptation strategy, 0 otherwise*
water strategies and changing crop varieties	*dummy = 1 if the farm household adopted water strategies and changed crop varieties as adaptation strategy, 0 otherwise*
soil conservation and changing crop varieties	*dummy = 1 if the farm household adopted soil conservation and changed crop varieties as adaptation strategy, 0 otherwise*
water strategies and soil conservation	*dummy = 1 if the farm household adopted water strategies and soil conservation as adaptation strategy, 0 otherwise*
water strategies, soil conservation, and changing crop varieties	*dummy = 1 if the farm household adopted water strategies, soil conservation and changed crop varieties as adaptation strategy, 0 otherwise*
other strategies	*dummy = 1 if the farm household did not change crop varieties and did not adopt water strategies and did not adopt soil conservation strategies but other strategies such as early-late planting, migrating, off-farm jobs etc. (see Table 1).*
Explanatory variables	
Belg rainfall	*rainfall rate in Belg, short rain season (mm) 1970 - 2000*
Meher rainfall	*rainfall rate in Meher, long rain season (mm) 1970 - 2000*
average temperature	*average temperature (^oC) 1970 - 2000*
high fertility	*dummy =1 if the soil has a high level of fertility, 0 otherwise*
infertile	*dummy =1 if the soil is infertile, 0 otherwise*
no erosion	*dummy=1 if the soil has no erosion, 0 otherwise*
severe erosion	*dummy=1 if the soil has severe erosion, 0 otherwise*
crop type	*=1 if farm household grows barley, =2 if beans, =3 if maize, =4 if teff, =5 if wheat*
tree planting	*=1 if farm household planted trees in the last 20 years, 0 otherwise*
animals	*dummy=1 if farm animal power is used, 0 otherwise*
labour	*logarithm of labour used per hectare (adult days)*
seeds	*logarithm of seeds used per hectare (kg)*
fertilizers	*logarithm of fertilizers used per hectare (kg)*
manure	*logarithm of manure used per hectare (kg)*
literacy	*dummy =1 if the household head is literate, 0 otherwise*
male	*dummy =1 if the household head is male, 0 otherwise*
married	*dummy =1 if the household head is married, 0 otherwise*
age	*age of the household head*
household size	*household size*
relatives	*number of relatives in the woreda*
highlands (*Dega*)	*dummy =1 if highlands, 0 otherwise*
midlands (*Weina Dega*)	*dummy =1 if midlands, 0 otherwise*
flood experience	*dummy =1 if the farm household experienced a flood in the last 5 years*
drought experience	*dummy =1 if the farm household experienced a drought in the last 5 years*
hailstorm experience	*dummy =1 if the farm household experienced a hailstorm in the last 5 years*
government extension	*dummy =1 if the household head got information/advice from government extension workers, 0 otherwise*
farmer-to-farmer extension	*dummy =1 if the household head got information/advice from farmer-to-farmer extension, 0 otherwise*
radio information	*dummy =1 if the household head got information from radio, 0 otherwise*
climate information	*dummy =1 if extension officers provided information on expected rainfall and temperature, 0 otherwise*

TABLE A2. Parameter Estimates – Test on the Validity of the Selection Instruments

	Net revenues by farm households that did not adapt
Belg rainfall	-0.807
	(13.724)
squared Belg rainfall/1000	-3.806
	(16.050)
Meher rainfall	-37.910***
	(10.657)
squared Meher rainfall/1000	17.135***
	(6.320)
average temperature	-2351.328
	(1880.632)
squared average temperature	45.114
	(47.814)
highly fertile	-33.293
	(208.454)
infertile	60.026
	(364.022)
no erosion	92.164
	(226.473)
severe erosion	88.183
	(506.223)
crop type	331.699***
	(70.366)
animals	892.451***
	(280.885)
labor	20.061***
	(4.965)
squared labor/100	-1.963***
	(0.557)
seeds	-2.640
	(4.293)
squared seeds/100	1.391
	(1.015)
fertilizers	4.802**
	(1.957)
squared fertilizers/100	-0.120***
	(0.044)
manure	-0.941
	(0.798)
squared manure/100	0.038***
	(0.014)
literacy	-750.618***
	(225.656)
male	1260.908**
	(528.284)
married	-395.005
	(573.544)
age	-14.248*
	(8.438)
household size	-64.777
	(46.182)
relatives	6.265

	(14.653)
highlands (*Dega*)	-11635.369***
	(2610.380)
midlands (*Weina Dega*)	-3534.400**
	(1703.526)
Mundlak's fixed effects	
mean fertilizers	-0.296
	(1.730)
mean seeds	5.578**
	(2.306)
mean manure	0.336
	(0.818)
mean labor	-7.058**
	(3.518)
Instrumental variables	
flood	-603.797
	(505.598)
drought	705.854
	(601.810)
hailstorm	-811.235***
	(291.642)
government extension	20.971
	(360.713)
farmer-to-farmer extension	181.929
	(508.597)
radio information	248.469
	(310.423)
climate information	593.726
	(537.932)
constant	53,157.410**
	(21,015.245)
Wald test on instrumental variables (F-stat.)	0.053
Sample size	868
Adjusted R^2	0.315

Note: Robust standard errors in parentheses. Fixed effects at the *woreda* level are included. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

TABLE A3. OLS Estimates of Net Revenue Equations on Pooled Sample

Dependent variable: net revenues per hectare (Etb/ha)	Coefficient (std. error)
changing crop varieties only	13.964
	(354.835)
water strategy only	1,679.714*
	(821.221)
soil conservation only	339.939
	(290.910)
water strategy and changing crop varieties	1162.555*
	(596.455)
soil conservation and changing crop varieties	538.244**
	(197.431)
water strategy and soil conservation	1373.732***
	(453.240)
water strategy, soil conservation, and changing crop varieties	871.620***
	(279.772)
other strategies	163.341
	(387.233)
average temperature	-356.040
	(1049.538)
squared average temperature	3.011
	(26.332)
Belg rainfall	-8.258
	(17.948)
squared Belg rainfall/1000	19.182
	(27.008)
Meher rainfall	4.691
	(10.554)
squared Meher rainfall/1000	-2.006
	(5.143)
highly fertile	52.190
	(190.956)
infertile	-439.546***
	(131.781)
no erosion	10.870
	(136.365)
severe erosion	386.157
	(565.327)
crop type	414.288***
	(102.810)
tree planting	-147.443
	(224.823)
animals	472.207**
	(180.629)
labor	15.294***
	(4.016)
squared labor/100	-0.341
	(0.290)
seeds	2.061
	(2.555)

squared seeds/100	0.593***
	(0.199)
fertilizers	2.911**
	(1.390)
squared fertilizers/100	-0.060
	(0.037)
manure	0.378**
	(0.171)
squared manure/100	-0.004*
	(0.002)
literacy	-404.567***
	(141.146)
male	677.445**
	(312.041)
married	51.726
	(336.372)
age	-24.338***
	(7.092)
household size	-32.218
	(34.247)
relatives	-0.059
	(0.782)
highlands (*Dega*)	-2,447.619*
	(1,408.037)
midlands (*Weina Dega*)	-2,890.051
	(2,098.895)
Mundlak's fixed effects	
mean fertilizers	-0.627
	(1.105)
mean seeds	4.546
	(2.687)
mean manure	-0.034
	(0.204)
mean labor	-8.221***
	(2.821)
constant	6,849.685
	(16,648.037)

Note: Robust standard errors clustered at the *woreda* level in parenthesis. Fixed effects at the *woreda* level are included. Adjusted R^2 = 0.345. Sample size: 2,802 plots. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

TABLE A4. Estimates of Net Revenue Equations by Multinomial Endogenous Switching Regression Model

Dependent variable	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Net revenues per hectare	No adaptation	Changing crop varieties only	Water strategies only	Soil conservation only	Water strategies and changing crop varieties	Soil conservation and changing crop varieties	Water strategies and soil conservation	Water strategies, soil conservation, and changing crop varieties	Other strategies
Belg rainfall	-34.239	-296.554	-537.296	-110.826	28,161.109	36.509	-868.739	39.819	-186.304
	(37.221)	(624.725)	(1,011,682.154)	(295.998)	(203,050.847)	(53.701)	(2,305.468)	(247.649)	(1,236.646)
squared Belg rainfall/1000	37.492	504.006	414.515	557.952	-47,686.033	-13.355	3,425.785	-86.886	176.947
	(68.965)	(906.037)	(2,751,497.399)	(974.212)	(373,374.408)	(83.941)	(5,506.394)	(479.923)	(3,551.666)
Meher rainfall	-45.047**	-11.778	-309.311	153.748*	-1,093.581	22.454	659.708	34.998	80.337
	(20.083)	(329.821)	(129,145.824)	(84.771)	(78,798.469)	(22.254)	(1,758.357)	(165.619)	(492.031)
squared Meher rainfall/1000	21.479**	9.728	233.781	-82.588*	-179.522	-9.116	-314.452	-21.436	-34.552
	(10.580)	(128.033)	(75,570.889)	(44.201)	(33,464.488)	(11.320)	(935.136)	(56.508)	(339.614)
average temperature	-3,343.499**	3,677.712	0.000	7,214.195	-852,134.607	-790.109	77,120.809	-4,792.739	-5,675.554
	(1,648.058)	(5,600.008)	(63,499.652)	(7,106.849)	(6,277,380.105)	(2,161.772)	(198,109.375)	(35,149.307)	(352,104.403)
squared average temperature	67.880*	-119.728	-49.791	-166.494	19,193.768	14.604	-2,078.035	141.095	155.598
	(41.213)	(120.024)	(100,554.963)	(175.012)	(146,142.620)	(49.080)	(5,302.852)	(985.420)	(12,230.932)
highly fertile	121.576	1,145.813	-22,420.870	-134.531	1,634.783	-424.816	-83.022	2,846.859***	2,215.609
	(333.610)	(1,023.573)	(10,088,204.558)	(835.148)	(92,550.247)	(528.872)	(5,392.658)	(931.869)	(5,829.430)
infertile	169.386	218.363	-14,335.898	-853.603	-3,749.842	-318.793	-955.837	741.681	1,872.068
	(393.614)	(1,171.937)	(5,472,991.896)	(1,253.578)	(87,416.031)	(502.907)	(3,675.490)	(1,507.268)	(70,005.498)
no erosion	46.779	396.105	-41,168.615	-302.846	-4,469.720	157.321	2,574.029	1,334.466	639.850
	(268.495)	(1,003.037)	(6,246,705.683)	(780.785)	(70,130.113)	(453.800)	(4,843.401)	(1,175.211)	(1,888.621)
severe erosion	-107.144	2,468.274	-51,311.676	725.357	-3,135.675	491.668	2,252.426	1,189.844	2,029.045
	(456.259)	(1,560.632)	(7,643,366.696)	(2,032.351)	(358,994.118)	(693.307)	(6,011.182)	(1,611.219)	(2,979.983)
crop type	332.060***	455.841*	-4,088.209	350.076	49.748	469.010**	880.146	574.845**	89.629
	(91.656)	(249.060)	(648,652.980)	(278.277)	(14,705.053)	(200.286)	(958.329)	(266.086)	(550.200)
tree planting	.	3,390.961*	0.000	-88.712	-15,028.669	257.108	-3,010.950	933.532	-4,762.645
		(1,746.940)	(23,194,022.876)	(1,917.424)	(154,848.365)	(674.607)	(4,460.297)	(2,877.874)	(9,752.630)
animals	602.136	-2,954.382	18,182.047	792.757	-3,448.406	353.627	-2,179.353	710.344	-2,154.855
	(483.913)	(2,391.323)	(10,74,932.004)	(1,421.457)	(192,404.807)	(754.703)	(9,714.815)	(1,445.539)	(62,219.710)
labor	20.136***	20.094**	11.031	10.219*	56.209***	8.975***	9.250	5.919	6.985
	(3.475)	(10.110)	(1,667.127)	(5.855)	(12.674)	(3.328)	(17.596)	(31.965)	(20.775)

squared labor/100	-2.025***	-0.466	-0.908	-0.600*	-4.222***	-0.306	2.079	6.766	-4.153
	(0.405)	(1.157)	(671.283)	(0.322)	(1.060)	(0.851)	(3.084)	(12.325)	(17.399)
seeds	-2.630	12.063	113.304	8.088	-1.068	-0.955	18.182**	6.203	16.369
	(2.988)	(8.878)	(880.084)	(11.211)	(39.273)	(4.224)	(9.087)	(8.974)	(19.823)
squared seeds/100	1.492***	-0.445	-17.258	-0.589	-0.021	1.040*	-0.651	-0.068	-3.438
	(0.488)	(1.234)	(743.359)	(2.476)	(14.612)	(0.576)	(1.188)	(1.070)	(5.200)
fertilizers	4.699***	-9.627	11.567	10.128	15.782	3.061	21.331	14.983	-30.605*
	(1.449)	(8.591)	(910.179)	(8.709)	(49.906)	(4.026)	(23.503)	(15.384)	(8.893)
squared fertilizers/100	-0.117***	2.298	-1.405	-0.891	-4.993	-0.034	-5.029	-3.397	11.581**
	(0.039)	(2.091)	(695.618)	(1.776)	(253.824)	(0.227)	(8.791)	(7.480)	(5.091)
manure	-1.120	-1.454	-5.569	0.889	-3.259	1.534	-0.487	0.934	-2.200
	(0.785)	(1.338)	(779.909)	(2.411)	(110.792)	(1.308)	(0.672)	(2.485)	(362.643)
squared manure/100	0.041**	0.009	0.086	-0.001	0.126	-0.017	0.002	-0.023	0.438
	(0.016)	(0.033)	(15.000)	(0.056)	(16.574)	(0.030)	(0.014)	(0.131)	(47.342)
literacy	-639.513**	-2,349.360**	28,793.965	-984.544	-7,157.463	193.011	-1,607.923	-1,739.528	-5,281.643
	(314.383)	(965.358)	(6,118,431.990)	(1,061.308)	(214,377.314)	(730.148)	(9,321.956)	(1,574.511)	(10,922.211)
male	1,397.288**	2,054.260	125,560.283	1,017.026	45,812.341	-148.396	3,840.323	1,004.925	-894.755
	(638.055)	(2,763.508)	(5,602,193.823)	(1,734.802)	(192,768.101)	(901.535)	(9,081.139)	(2,872.048)	(22,045.814)
married	-58.247	-2,692.334	50,601.794	1,412.468	463.307	146.645	5,950.262	-3,485.932	3,876.606
	(726.837)	(2,255.475)	(8,148,789.237)	(2,085.168)	(324,400.213)	(1,212.065)	(13,042.580)	(2,888.692)	(22,113.303)
age	-12.460	-101.120***	-837.359	-27.039	-152.122	-7.278	2.088	-52.704	-167.306
	(10.621)	(36.298)	(452,029.580)	(32.279)	(4,344.739)	(23.806)	(257.399)	(57.406)	(872.549)
household size	-67.849	237.990	-5,257.526	-312.435	2,264.360	-24.064	-63.817	-132.223	134.803
	(62.179)	(301.920)	(2,362,800.004)	(268.036)	(42,543.385)	(124.900)	(1,013.717)	(267.995)	(1,111.797)
relatives	2.697	184.723***	1,839.014	-18.659	-112.036	5.003	-7.064	11.814	214.832
	(9.255)	(42.313)	(864,264.717)	(30.494)	(13,966.239)	(8.596)	(96.496)	(15.577)	(1,274.788)
highlands (*Dega*)	-13,620.754***	8,386.670	40,430.833	8,471.934	-613,049.662	4,557.348	0.000	-8,563.516	0.000
	(4,443.015)	(18,444.570)	(7,318,575.455)	(22,649.361)	(11181710.145)	(6,622.335)	(285,862.910)	(64,734.818)	(49,819.006)
midlands (*Weina Dega*)	-7,495.961**	-10,096.697	0.000	-43,515.458	0.000	7,580.795	0.000	1,521.160	-26,631.247
	(3,066.756)	(82,907.067)	(12,414.803)	(49,263.922)	(3,339,263.217)	(7,463.056)	(197,117.435)	(21,439.009)	(93,476.728)
Mundlak's fixed effects									
mean fertilizers	0.758	-2.725	-507.044	-4.414	82.022	-1.409	14.628	-12.712	19.929
	(1.333)	(9.201)	(362,451.368)	(6.705)	(3,338.314)	(1.418)	(40.782)	(20.565)	(94.108)
mean seeds	5.221*	-17.334***	638.419	16.987**	-1.391	7.399*	-8.126	6.131	-0.115
	(2.857)	(5.441)	(184,823.427)	(12.929)	(4,235.645)	(4.233)	(23.138)	(13.073)	(63.478)
mean manure	0.580	1.755	-3.342	-0.690	-7.304	-1.153	0.590	0.044	-0.457
	(0.632)	(1.461)	(1,216.028)	(1.917)	(507.629)	(0.880)	(2.051)	(2.625)	(525.827)
mean labor	-6.759**	-0.061	-281.266	-5.600	45.398	-5.670	-9.564	14.191	-0.177
	(3.327)	(8.250)	(24,100.974)	(6.181)	(757.536)	(3.355)	(20.190)	(14.971)	(59.224)

Selection Bias Correction Terms									
$m(P_{i1})$	-847.499	-10,509.325	-99,231.465	-1,408.912	64,511.147	-5,032.878	11,986.039	-2,039.801	-6,011.535
	(2,067.260)	(9,265.223)	(6,213,736.736)	(11,903.633)	(1771516.321)	(4,762.596)	(62,291.319)	(6,744.209)	(16,704.543)
$m(P_{i2})$	-2,369.504	-2,471.464	165,879.330	-6,858.571	26,507.851	-3,087.194	11,360.827	-3,546.128	-11,688.947
	(3,437.775)	(2,834.705)	(29,209,415.028)	(10,519.358)	(258,867.900)	(4,830.208)	(35,965.224)	(10,677.946)	(21,683.163)
$m(P_{i3})$	-1,362.623	-309.872	-54,247.776	1,644.009	-14,013.957	685.111	32,800.328	-5,761.376	-11,671.806
	(7,736.037)	(15,184.600)	(10,192,167.781)	(10,670.187)	(463,569.984)	(5,725.648)	(36,532.098)	(7,955.634)	(153,700.509)
$m(P_{i4})$	-361.931	5,549.891	34,934.255	-464.424	205.588	-711.977	-1,130.168	-12,480.003**	-15,788.851
	(2,892.221)	(9,036.193)	(18,270,579.871)	(3,107.522)	(596,638.364)	(5,159.755)	(28,505.294)	(6,710.176)	(35,931.673)
$m(P_{i5})$	2,148.226	-7,914.981	-102,128.141	-7,323.765	-5,277.523	4,979.756	4,127.745	-5,248.807	-2,831.767
	(4,138.221)	(9,347.511)	(20,109,161.069)	(8,656.025)	(182,071.021)	(4,930.670)	(30,794.495)	(6,956.239)	(783,879.408)
$m(P_{i6})$	-2,640.096	1,159.243	-4,701.878	-7,094.369	52,690.591	-773.742	2,730.381	6,074.771	-4,613.176
	(2,908.856)	(10,941.857)	(72,458,272.993)	(7,642.276)	(293,938.405)	(1,992.470)	(24,763.927)	(6,142.110)	(17,001.631)
$m(P_{i7})$	442.628	-31,754.618**	285,597.968	-3,145.913	6,373.880	-7,982.322	487.508	-13,367.269**	-34,511.564
	(5,676.732)	(15,477.543)	(11,667,010.882)	(11,773.918)	(347,387.250)	(6,032.569)	(11,031.093)	(9,430.932)	(38,484.485)
$m(P_{i8})$	154.343	-11,777.089	174,789.925	-4,681.736	28,547.838	-4,388.654	15,044.566	-3,987.976**	-13,724.175
	(4,606.581)	(8,432.444)	(77,679,001.638)	(8,378.007)	(1216321.706)	(3,849.735)	(18,759.951)	(2,727.857)	(24,246.399)
$m(P_{i9})$	-2,801.913	-319.281	-194,538.419	-4,886.493	30,346.791	359.727	10,970.299	4,353.128	-5,661.512
	(3,337.082)	(6,336.739)	(23,790,987.070)	(14,341.030)	(82,122.222)	(4,865.817)	(153,093.146)	(15,505.196)	(10,502.062)
constant	70,533.349***	16,148.207	246,454.257	-144,325.949	7,853,510.881	-11,222.824	-895,478.236	36,734.392	52,028.307
	(24,981.271)	(121,856.727)	(18,197,577.136)	(94,137.579)	(62,854,009.454)	(25,599.674)	(2,712,784.906)	(416,565.917)	(1,785,766.517)

Note: $m(P_{ij})$ refers to the correction term described in equation (4a). Fixed effects at the *woreda* level are included. Bootstrapped standard errors in parentheses. Sample size: 2,802 plots. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

References

Ai, C. R., and E. C. Norton. 2003. "Interaction Terms in Logit and Probit Models." *Economics Letters* 80(1): 123-129.

Anley, Y., A. Bogale, and A. Haile-Gabriel. 2007. "Adoption Decision and Use Intensity of Soil and Water Conservation Measures by Smallholders Subsistence Farmers in Dedo District, Western Ethiopia." *Land Degradation and Development* 18: 289-302.

Ayalneh, B., M. Taeb, and E. Mitsugi. 2006. "Land Ownership and Conflicts over the Use of Resources: Implication for Household Vulnerability in Eastern Ethiopia." *Ecological Economics* 58: 134-145

Bekele, W., and L. Drake. 2003. "Soil and Water Conservation Decision Behavior of Subsistence Farmers in the Eastern Highlands of Ethiopia: A Case Study of Hunde-Lafto Area." *Ecological Economics* 46: 437-451.

Besley, T. 1995. "Property Rights and Investment Incentives: Theory and Evidence from Ghana." *Journal of Political Economy* 103(5): 903-937.

Bourguignon, F., M. Fournier, and M. Gurgand. 2007. "Selection Bias Corrections Based on the Multinomial Logit Model: Monte Carlo Comparisons." *Journal of Economic Surveys* 21(1): 174-205.

Cline, W.R. 2007. *Global Warming and Agriculture. Impact Estimates by Country*. Washington D. C.: Center for Global Development and Peter G. Peterson Institute for International Economics.

Dahl, G.B. 2002. "Mobility and the Returns to Education: Testing a Roy Model with Multiple Markets." *Econometrica* 52: 2367–2420.

Daly, C. 2006. "Guidelines for Assessing the Suitability of Spatial Climate Datasets." *International Journal of Climatology* 26: 707–721.

Deressa, T.T., and R.H. Hassan. 2010. “Economic Impact of Climate Change on Crop Production in Ethiopia: Evidence from Cross-Section Measures.” *Journal of African Economies* 18(4): 529-554.

Deressa, T., R. Hassen, T. Alemu, M. Yesuf, and C. Ringler. 2009. “Analyzing the Determinants of Farmers’ Choice of Adaptation Measures and Perceptions of Climate Change in the Nile Basin of Ethiopia.” International Food Policy Research Institute (IFPRI) Discussion Paper No. 00798, Washington, D.C.

Di Falco, S., M. Veronesi, and M. Yesuf. 2011. “Does Adaptation to Climate Change Provide Food Security? A Micro-perspective from Ethiopia.” *American Journal of Agricultural Economics* 93(3): 829-846.

Dinar, A., R. Hassan, R. Mendelsohn, J. Benhin, and others. 2008. *Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies*, London: EarthScan.

Gebremedhin, B., and M. Swinton. 2003. “Investment in Soil Conservation in Northern Ethiopia: The Role of Land Tenure Security and Public Programs.” *Agricultural Economics* 29: 69-84.

Hassan, R., and C. Nhemachena. 2008. “Determinants of Climate Adaptation Strategies of African Farmers: Multinomial Choice Analysis.” *African Journal of Agricultural and Resource Economics* 2(1): 83-104.

Heckman, J.J., J.L. Tobias, and E.J. Vytlacil. 2001. “Four Parameters of Interest in the Evaluation of Social Programs.” *Southern Economic Journal* 68(2): 210-233.

Holden, S.T., and H. Yohannes. 2002. “Land Redistribution, Tenure Insecurity and Input Intensity: A Study of Farm Households in Southern Ethiopia.” *Land Economics* 78(4): 573-590.

International Food Policy Research Institute (IFPRI). 2010. *Ethiopia Nile Basin Climate Change Adaptation dataset. Food and Water Security under Global Change: Developing Adaptive Capacity with a Focus on Rural Africa.* Washington, D.C.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Summary for Policymakers. Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to IPCC Fourth Assessment Report: Climate Change 2007, Geneva.

Kurukulasuriya, P., and R. Mendelsohn. 2007. "Crop Selection: Adapting to Climate Change in Africa." *Policy Research Working Paper Series*, World Bank.

Kurukulasuriya, P., and R. Mendelsohn. 2008. "Crop Switching as an Adaptation Strategy to Climate Change." *African Journal Agriculture and Resource Economics* 2: 105-125.

Kurukulasuriya, P., N. Kala, and R. Mendelsohn. 2011. "Adaptation and Climate Change Impacts: A Structural Ricardian Model of Irrigation and Farm Income in Africa." *Climate Change Economics* 2(2): 149-174.

Lautze S., Aklilu Y., A. Raven-Roberts, H. Young, G. Kebede, and J. Learning. 2003. *Risk and Vulnerability in Ethiopia: Learning from the Past, Responding to the Present, Preparing for the Future*. Report for the U.S. Agency for International Development. Addis Ababa, Ethiopia.

Lobell, D.B, M. Bänziger, C. Magorokosho, and B. Vivek. 2011. "Nonlinear Heat Effects on African Maize as Evidenced by Historical Yield Trials." *Nature Climate Change* 1: 42–45.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.M. Mastrandrea, W.P. Falcon, and R.L. Naylor. 2008. "Prioritizing Climate Change Adaptation Needs for Food Security in 2030." *Science* 319: 607-610.

Maddala, G.S., and F.D. Nelson. 1975. "Switching Regression Models with Exogenous and Endogenous Switching." *Proceeding of the American Statistical Association* (Business and Economics Section), pp. 423-426.

McCarthy N., L. Lipper, and G. Branca. 2011. *Climate Smart Agriculture: Smallholder Adoption and Implications for Climate Change Adaptation and Mitigation.* Mitigation of Climate Change in Agriculture (MICCA) Series 4. FAO, Rome. http://www.fao.org/docrep/015/i2575e/i2575e00.pdf (accessed on April 04, 2013).

McFadden, D.L. 1973. "Conditional Logit Analysis of Qualitative Choice Behavior." In P. Zarembka (ed.), *Frontiers in Econometrics* (pp. 105-142). New York. Academic Press.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *American Economic Review* 84: 753–71.

Mendelsohn, R., and A. Dinar. 2003. "Climate, Water, and Agriculture." *Land Economics* 79: 328-341.

Mendelsohn, R., A. Dinar, and L. Williams. 2006. "The Distributional Impact of Climate Change on Rich and Poor Countries." *Environment and Development Economics* 11(2): 159-178.

Mekonnen, A. 2009. "Tenure Security, Resource Endowments and Tree Growing: Evidence from Rural Households in the Amhara Region of Ethiopia." *Land Economics*, 85(2): 293-308.

Mundlak, Y. 1978. "On the Pooling of Time Series and Cross Section Data." *Econometrica* 46(1): 69-85.

NMS (National Meteorological Services). 2007. *Climate Change National Adaptation Program of Action (NAPA) of Ethiopia*. NMS, Addis Ababa, Ethiopia.

Orindi V., A. Ochieng, B. Otiende, S. Bhadwal, K. Anantram, S. Nair, V. Kumar, and U. Kelkar. 2006. "Mapping Climate Vulnerability and Poverty in Africa." In P.K. Thornton, P.G. Jones, T. Owiyo, R.L. Kruska, M. Herrero, P. Kristjanson, A. Notenbaert, N. Bekele, and A. Omolo. *Mapping Climate Vulnerability and Poverty in Africa*, Report to the Department for

International Development, International Livestock Research Institute (ILRI), Nairobi.

Parry, M., C. Rosenzweig, and M. Livermore. 2005. "Climate Change, Global Food Supply and Risk of Hunger." *Phil. Trans. Royal. Soc. B* 360: 2125-2138.

Platteau, J.-P. 1992. "Land Reform and Structural Adjustment in Sub-Saharan Africa: Controversies and Guidelines." FAO Economic and Social Development Paper 107.

Rosenzweig, C., and M.L. Parry. 1994. "Potential Impact of Climate Change on World Food Supply." *Nature,* 367: 133-138.

Schlenker, W. and D.B. Lobell. 2010. "Robust Negative Impacts of Climate Change on African Agriculture." *Environmental Research Letters* 5: 1-8.

Seo, S.N. 2010. "A Microeconometric Analysis of Adapting Portfolios to Climate Change: Adoption of Agricultural Systems in Latin America." *Applied Economic Perspectives and Policy* 32: 489-514.

Seo, S.N., and R. Mendelsohn. 2008a. "Measuring Impacts and Adaptations to Climate Change: A Structural Ricardian Model of African Livestock Management." *Agricultural Economics* 38(2): 151-165.

Seo, S. N., and R. Mendelsohn. 2008b. "A Ricardian Analysis of The Impact of Climate Change Impacts on South American Farms." *Chilean Journal of Agricultural Research* 68: 69-79.

Seo, S.N., and R. Mendelsohn. 2008c. "An Analysis of Crop Choice: Adapting to Climate Change in Latin American Farms." *Ecological Economics* 67: 109-116.

Seo, N., and R. Mendelsohn. 2008d. "Climate Change Impacts and Adaptations on Animal Husbandry in Africa." *African Journal Agriculture and Resource Economics* 2: 65-82.

Shiferaw, B., and S.T. Holden. 1999. "Soil Erosion and Small Holders Conservation Decision in the Highlands of Ethiopia." *World Development* 27(4): 739-752.

Shiferaw B., and S. T. Holden. 1998. "Resource Degradation and Adoption of Land Conservation Technologies by Smallholders in the Ethiopia Highlands: A Study in Andit Tid, Northern Shoa." *Agricultural Economics* 18: 233-247.

Sjaastad, E., and D. W. Bromley. 1997. "Indigenous Land Rights in Sub-Saharan Africa: Appropriation, Security and Investment Demand." *World Development* 25 (4): 549-562.

Stige, L.C., J. Stave, K. Chan, L. Ciannelli, N. Pattorelli, M. Glantz, H. Herren, and N. Stenseth. 2006. "The Effect of Climate Variation on Agro-Pastoral Production in Africa." *PNAS* 103: 3049-3053.

Tesfaye, A., and R. Brouwer. 2012. "Testing Participation Constraints in Contract Design for Sustainable Soil Conservation in Ethiopia." *Ecological Economics* 73: 168-178.

Udry, C. 1996. "Gender, Agricultural Production, and the Theory of the Household." *Journal of Political Economy* 104(5): 1010-1046.

Wahba, G. 1990. *Spline Models for Observational Data*. Philadelphia: Society for Industrial and Applied Mathematics.

Wang, J., R. Mendelsohn, A. Dinar, and J. Huang. 2010. "How Chinese Farmers Change Crop Choice To Adapt To Climate Change." *Climate Change Economics* 1: 167-186.

Wooldridge, J.M. 2002. *Econometric Analysis of Cross Section and Panel Data.* Cambridge, MA: MIT Press.

World Bank. 2006. *Ethiopia: Managing Water Resources to Maximize Sustainable Growth. A World Bank Water Resources Assistance Strategy for Ethiopia*, BNPP Report TF050714, Washington D.C.

TABLE 1. Climate Change Adaptation Strategies

	Frequency	Percent
Soil conservation	1,397	72.27
Changing crop varieties	1,186	61.36
Water strategies		
Building water harvesting scheme	309	15.99
Water conservation	82	4.24
Irrigating more	279	14.43
Other strategies		
Early-late planting	176	9.11
Migrating to urban area	23	1.19
Finding off-farm job	132	6.83
Leasing the land	3	0.16
Changing from crop to livestock	71	3.67
Reduce number of livestock	121	6.26
Adoption of new technology	26	1.35

Note: sub-sample of farm households that adapted at the plot level (sample size: 1,933)

TABLE 2. Descriptive Statistics

Variable name	Total sample		Farm households that did not adapt		Farm households that adapted	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Dependent variables						
net revenues	4,167.203	4,901.327	3,661.458	3,295.894	4,394.567	5,457.213
Adaptation strategy j						
changing crop varieties only	0.082	0.275	-	-	0.119	0.324
water strategies only	0.020	0.141	-	-	0.029	0.169
soil conservation only	0.147	0.354	-	-	0.213	0.409
water strategies and changing crop varieties	0.040	0.195	-	-	0.057	0.233
soil conservation and changing crop varieties	0.198	0.399	-	-	0.288	0.453
water strategies and soil conservation	0.050	0.219	-	-	0.073	0.260
water strategies, soil conservation, and changing crop varieties	0.103	0.304	-	-	0.150	0.357
other strategies	0.049	0.216	-	-	0.071	0.258
Explanatory variables						
Belg rainfall	322.668	160.670	356.033	177.310	307.668	150.251
Meher rainfall	1,111.069	295.173	1,034.002	302.518	1145.715	285.180
average temperature	17.737	2.034	19.022	1.991	17.159	1.773
highly fertile	0.280	0.449	0.333	0.471	0.257	0.437
infertile	0.158	0.365	0.127	0.333	0.172	0.378
no erosion	0.484	0.500	0.510	0.500	0.472	0.499
severe erosion	0.104	0.306	0.082	0.274	0.114	0.318
labour	101.096	121.362	90.385	87.701	105.912	133.503
seeds	115.151	148.714	91.315	103.513	125.867	163.948
fertilizers	60.739	176.934	57.728	174.630	62.092	177.988
manure	198.572	832.187	73.009	438.860	254.955	952.355
animals	0.874	0.332	0.844	0.363	0.887	0.317
crop type	3.180	1.396	3.350	1.293	3.104	1.433
tree planting	0.312	0.463	-	-	0.452	0.498
literacy	0.489	0.500	0.413	0.493	0.524	0.500
male	0.926	0.262	0.914	0.281	0.932	0.252
married	0.928	0.259	0.922	0.269	0.931	0.254
age	45.738	12.546	44.560	13.782	46.267	11.914
household size	6.602	2.189	6.242	2.260	6.765	2.136
relatives	16.490	43.674	9.466	13.280	19.561	51.321
highlands (*Dega*)	0.304	0.460	0.359	0.480	0.520	0.500
midlands (*Weina Dega*)	0.484	0.500	0.404	0.491		
flood experience	0.172	0.378	0.207	0.405	0.217	0.412
drought experience	0.443	0.497	0.074	0.261	0.565	0.496
hailstorm experience	0.229	0.421	0.132	0.339	0.273	0.446
government extension	0.608	0.488	0.269	0.444	0.761	0.427
farmer-to-farmer extension	0.516	0.500	0.197	0.398	0.659	0.474
radio information	0.307	0.461	0.139	0.346	0.382	0.486
climate information	0.422	0.494	0.111	0.314	0.563	0.496
Sample size	2,802		869		1,933	

Note: The sample size refers to the total number of plots. The final total sample includes 20 *woredas*, 941 farm households, and 2,802 plots.

TABLE 2 (cont.). Descriptive Statistics

	Changing crop varieties only		Water strategies only		Soil conservation only	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Dependent variable						
net revenues	3,963.939	3,966.249	4,752.995	5,651.228	4,349.334	6,091.633
Explanatory variables						
Belg rainfall	347.966	157.382	330.544	147.302	293.275	148.036
Meher rainfall	1,169.225	302.370	1,215.350	290.553	1,157.462	281.592
average temperature	16.968	1.696	17.459	1.241	16.869	2.586
Soil characteristics						
highly fertile	0.209	0.407	0.333	0.476	0.251	0.434
infertile	0.196	0.398	0.175	0.384	0.185	0.389
no erosion	0.448	0.498	0.684	0.469	0.397	0.490
severe erosion	0.117	0.323	0.123	0.331	0.151	0.358
crop type	3.350	1.293	3.048	1.349	3.246	1.527
tree planting	0.000	0.000	0.326	0.470	0.351	0.481
labour	113.545	131.221	106.727	135.718	101.945	125.071
seeds	130.334	194.910	120.336	91.044	128.453	140.717
fertilizers	73.159	171.875	62.933	111.958	52.951	127.914
manure	222.720	850.262	820.221	2,052.245	298.849	1,135.466
animals	0.935	0.247	0.754	0.434	0.893	0.310
literacy	0.426	0.496	0.509	0.504	0.591	0.492
male	0.917	0.276	0.877	0.331	0.956	0.205
married	0.917	0.276	0.912	0.285	0.981	0.138
age	48.074	10.484	49.684	14.404	45.998	11.652
household size	6.809	1.984	6.649	2.074	6.839	2.163
off-farm job	0.313	0.465	0.368	0.487	0.292	0.455
relatives	12.762	14.721	15.895	22.417	22.384	27.168
highlands (*Dega*)	0.359	0.480	0.152	0.360	0.351	0.481
midlands (*Weina Dega*)	0.404	0.491	0.600	0.491	0.544	0.503
flood experience	0.174	0.380	0.070	0.258	0.375	0.485
drought experience	0.426	0.496	0.667	0.476	0.655	0.476
hailstorm experience	0.132	0.339	0.257	0.438	0.298	0.462
government extension	0.752	0.433	0.649	0.481	0.701	0.458
farmer-to-farmer extension	0.630	0.484	0.474	0.504	0.623	0.485
radio information	0.222	0.416	0.351	0.481	0.258	0.438
neighborhood information	0.530	0.500	0.105	0.310	0.397	0.490
climate information	0.409	0.493	0.509	0.504	0.547	0.498
Sample size	230		57		411	

Note: The sample size refers to the total number of plots. The final total sample includes 20 *woredas*, 941 farm households, and 2,802 plots.

TABLE 2 (cont.). Descriptive Statistics

	Water strategies and changing crop varieties		Soil conservation and changing crop varieties		Water strategies and soil conservation		Water strategies, soil conservation, and changing crop varieties		Other strategies	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Dependent variable										
net revenues	4,173.987	4,324.955	4,598.201	6,188.283	5,211.351	6,797.752	4,493.598	4,661.898	3,682.941	3,668.852
Explanatory variables										
Belg rainfall	247.510	122.641	289.417	138.199	308.099	172.200	308.123	143.351	394.451	155.311
Meher rainfall	1,019.399	287.027	1,165.197	271.078	1,173.223	248.530	1,110.076	307.276	1,112.417	272.801
average temperature	17.275	0.788	16.903	1.387	17.776	1.879	17.292	1.072	18.254	1.504
highly fertile	0.216	0.414	0.340	0.474	0.255	0.438	0.201	0.401	0.138	0.346
infertile	0.279	0.451	0.174	0.380	0.135	0.343	0.152	0.360	0.080	0.272
no erosion	0.495	0.502	0.487	0.500	0.539	0.500	0.488	0.501	0.464	0.501
severe erosion	0.180	0.386	0.131	0.338	0.064	0.245	0.045	0.208	0.072	0.260
crop type	3.061	1.410	3.288	1.351	3.018	1.459	2.915	1.579	3.163	1.476
tree planting	0.353	0.478	0.468	0.501	0.531	0.500	0.525	0.501	0.536	0.500
labour	94.372	114.142	112.802	159.835	127.478	144.102	89.241	79.195	99.067	135.289
seeds	104.597	105.903	128.836	195.086	170.367	171.318	115.776	149.371	93.816	95.221
fertilizers	38.986	64.249	75.932	266.837	49.169	86.172	42.779	111.020	86.999	121.555
manure	161.506	519.779	199.403	693.824	552.640	1,604.505	206.183	642.273	41.444	186.226
animals	0.838	0.370	0.890	0.313	0.887	0.318	0.865	0.342	0.919	0.275
literacy	0.631	0.485	0.505	0.500	0.674	0.471	0.446	0.498	0.486	0.502
male	0.937	0.244	0.937	0.243	0.965	0.186	0.920	0.271	0.870	0.338
married	0.955	0.208	0.923	0.267	0.972	0.167	0.900	0.301	0.848	0.360
age	45.856	14.984	46.209	11.913	47.199	11.630	45.239	10.759	44.420	13.148
household size	6.622	2.072	7.029	2.351	6.887	2.473	6.519	1.716	5.957	1.620
off-farm job	0.306	0.463	0.238	0.426	0.390	0.490	0.280	0.450	0.268	0.445
relatives	11.569	10.908	24.658	87.162	20.355	20.199	20.225	31.761	7.068	7.741
highlands (*Dega*)	0.197	0.398	0.315	0.467	0.270	0.444	0.426	0.496	0.384	0.487
midlands (*Weina Dega*)	0.491	0.501	0.685	0.467	0.469	0.500	0.468	0.501	0.540	0.499
flood experience	0.279	0.451	0.185	0.389	0.092	0.290	0.183	0.388	0.152	0.360
drought experience	0.541	0.501	0.637	0.481	0.638	0.482	0.536	0.500	0.203	0.404
hailstorm experience	0.336	0.473	0.459	0.501	0.290	0.454	0.170	0.377	0.194	0.396
government extension	0.820	0.386	0.833	0.374	0.723	0.449	0.875	0.331	0.464	0.501
farmer-to-farmer extension	0.811	0.393	0.674	0.469	0.709	0.456	0.817	0.388	0.326	0.470
radio information	0.486	0.502	0.464	0.499	0.624	0.486	0.474	0.500	0.174	0.380
neighborhood information	0.225	0.420	0.282	0.451	0.064	0.245	0.284	0.452	0.406	0.493
climate information	0.631	0.485	0.605	0.489	0.504	0.502	0.767	0.423	0.297	0.459
Sample size	111		556		141		289		138	

Note: The sample size refers to the total number of plots. The final total sample includes 20 *woredas*, 941 farm households, and 2,802 plots

TABLE 3. Parameters Estimates of Climate Change Adaptation Strategies – Multinomial Logit Model

	(1) Changing crop varieties only	(2) Water strategies only	(3) Soil conservation only	(4) Water strategies and changing crop varieties	(5) Soil conservation and changing crop varieties	(6) Water strategies and soil conservation	(7) Water strategies, soil conservation, and changing crop varieties	(8) Other strategies
Belg rainfall	-0.008	-0.030**	-0.010	-0.002	-0.021*	-0.027	-0.011	0.012
	(0.013)	(0.012)	(0.012)	(0.018)	(0.013)	(0.026)	(0.013)	(0.013)
squared Belg rainfall/1000	-0.007	0.031	-0.013	-0.018	0.020	-0.002	-0.007	-0.025
	(0.022)	(0.021)	(0.026)	(0.029)	(0.021)	(0.053)	(0.022)	(0.018)
Meher rainfall	-0.014	-0.024***	-0.003	-0.015*	-0.016**	-0.043***	-0.031***	-0.009
	(0.009)	(0.008)	(0.006)	(0.008)	(0.008)	(0.011)	(0.009)	(0.007)
squared Meher rainfall/1000	0.007	0.011***	0.0004	0.008*	0.008*	0.023***	0.016***	0.004
	(0.005)	(0.004)	(0.003)	(0.005)	(0.004)	(0.007)	(0.005)	(0.003)
average temperature	-0.021	4.029*	1.941**	4.143**	1.813*	-0.122	5.174**	0.125
	(0.757)	(2.346)	(0.793)	(1.911)	(1.099)	(2.443)	(2.364)	(0.677)
squared average temperature	-0.006	-0.100*	-0.048**	-0.102**	-0.049*	-0.006	-0.139**	-0.007
	(0.018)	(0.057)	(0.019)	(0.044)	(0.026)	(0.056)	(0.057)	(0.017)
highly fertile	-0.549*	-0.180	-0.454**	-0.546	-0.073	-0.520	-0.890**	-1.134***
	(0.297)	(0.725)	(0.226)	(0.500)	(0.213)	(0.491)	(0.365)	(0.373)
infertile	0.114	-0.066	-0.001	0.498	0.106	-0.580	-0.348	-0.761
	(0.328)	(0.728)	(0.330)	(0.399)	(0.285)	(0.515)	(0.408)	(0.470)
no erosion	0.046	0.614	-0.190	0.540	-0.015	-0.302	-0.405	0.099
	(0.270)	(0.593)	(0.276)	(0.452)	(0.235)	(0.448)	(0.324)	(0.362)
severe erosion	-0.358	0.087	-0.458	0.157	-0.307	-0.822*	-1.193**	-0.279
	(0.443)	(0.647)	(0.292)	(0.321)	(0.281)	(0.436)	(0.491)	(0.497)
crop type	-0.115**	0.116**	-0.011	0.031	-0.045	0.009	0.019	0.138
	(0.045)	(0.058)	(0.050)	(0.055)	(0.047)	(0.073)	(0.057)	(0.093)
tree planting	24.538***	24.802***	24.839***	24.998***	25.297***	25.629***	25.463***	25.401***
	(0.511)	(0.512)	(0.513)	(0.666)	(0.622)	(0.775)	(0.477)	(0.804)
animals	1.160*	-0.813	0.398	-0.298	0.177	0.382	0.250	1.346**
	(0.655)	(0.779)	(0.554)	(0.645)	(0.504)	(0.484)	(0.550)	(0.630)
literacy	-0.056	1.005**	0.694**	1.272**	0.205	1.397***	0.134	0.236
	(0.405)	(0.444)	(0.307)	(0.559)	(0.223)	(0.525)	(0.494)	(0.419)
male	0.425	-0.369	0.584	-0.544	0.940	0.598	0.427	0.042
	(0.903)	(1.410)	(0.969)	(1.342)	(0.700)	(1.189)	(0.908)	(0.798)
married	-0.557	0.322	0.008	0.588	-1.099	0.602	-0.414	-0.774
	(1.033)	(1.126)	(0.865)	(1.826)	(0.965)	(1.093)	(0.969)	(1.023)
age	0.010	0.020	0.005	0.028	-0.010	0.016	-0.001	-0.001
	(0.010)	(0.024)	(0.012)	(0.021)	(0.009)	(0.015)	(0.019)	(0.015)
household size	0.099	0.175**	0.033	0.105	0.183**	0.185*	0.135	-0.009

	(0.069)	(0.082)	(0.101)	(0.128)	(0.071)	(0.109)	(0.100)	(0.073)
relatives	0.007	0.007	0.012*	-0.006	0.015**	0.005	0.016**	-0.014
	(0.008)	(0.013)	(0.007)	(0.011)	(0.007)	(0.007)	(0.007)	(0.025)
highlands (*Dega*)	-1.839**	0.067	-0.533	21.394	-0.422	0.807	1.316**	-0.395
	(0.744)	(0.937)	(0.495)	(21.035)	(0.683)	(1.055)	(0.631)	(0.610)
midlands (*Weina Dega*)	0.650	0.975	-0.011	21.319	0.357	1.608*	2.275***	1.260**
	(0.650)	(0.989)	(0.473)	(21.282)	(0.498)	(0.860)	(0.644)	(0.594)
Instrumental variables								
flood	-0.055	-1.019	0.694*	0.596	-0.222	-0.597	0.172	0.310
	(0.494)	(1.174)	(0.412)	(0.392)	(0.603)	(1.004)	(0.429)	(0.637)
drought	-0.068	0.511	0.087	-0.149	0.572	0.539	-0.062	-0.453
	(0.439)	(0.529)	(0.400)	(0.461)	(0.468)	(0.419)	(0.595)	(0.495)
hailstorm	0.203	1.092*	0.808	1.142**	0.508	0.274	0.095	0.276
	(0.555)	(0.664)	(0.573)	(0.549)	(0.388)	(0.563)	(0.543)	(0.615)
government extension	1.267***	0.315	0.411	0.485	1.058***	0.289	0.538	0.328
	(0.414)	(0.508)	(0.389)	(0.385)	(0.192)	(0.515)	(0.444)	(0.470)
farmer-to-farmer extension	0.417	-0.068	0.262	1.768***	0.198	1.164**	1.062**	-1.018*
	(0.429)	(0.479)	(0.294)	(0.451)	(0.345)	(0.566)	(0.429)	(0.544)
radio information	-0.026	0.331	-0.437	0.936	0.780*	1.503**	1.008**	0.466
	(0.454)	(0.651)	(0.484)	(0.600)	(0.427)	(0.625)	(0.448)	(0.443)
climate information	0.145	0.396	0.632*	1.030*	0.655	-0.066	1.685**	1.219**
	(0.419)	(0.855)	(0.343)	(0.625)	(0.507)	(0.484)	(0.693)	(0.535)
constant	8.147	-30.698	-16.965*	-61.952***	-8.505	19.555	-37.371	-0.356
	(11.270)	(24.324)	(9.881)	(12.082)	(13.078)	(29.689)	(24.398)	(7.637)
Wald test on instrumental variables (χ^2)	23.26 ***	13.11 *	24.69 ***	53.54 ***	64.13 ***	28.28 ***	55.12 ***	55.26 ***

Note: The baseline is farm households that did not adapt to climate change. Pseudo-R^2: 0.351. Sample size: 2,802 plots. Robust standard errors clustered at the *woreda* level in parentheses. * Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.

TABLE 4. Impact on Net Revenues by Adaptation Strategy

	(1) Actual net revenues (Etb/ha)	(2) Counterfactual net revenues if farm households did not adapt (Etb/ha)	(3) Impact (treatment effect - Etb/ha)
(1) Changing crop varieties only	3,963.939	3,804.036	159.903
	(263.250)	(342.301)	(350.000)
(2) Water strategies only	4,752.995	3,325.668	1,427.327
	(748.523)	(774.360)	(939.035)
(3) Soil conservation only	4,349.334	3,689.859	659.475
	(306.116)	(305.365)	(361.593)
(4) Water strategies and changing crop varieties	4,173.987	1,842.288	2,331.700***
	(428.234)	(346.832)	(445.253)
(5) Soil conservation and changing crop varieties	4,598.201	2,404.897	2,193.304***
	(267.543)	(203.820)	(203.980)
(6) Water strategies and soil conservation	5,211.351	3,481.522	1,729.829***
	(449.527)	(582.655)	(601.024)
(7) Water strategies, soil conservation, and changing crop varieties	4,493.598	3,196.787	1,296.811***
	(281.635)	(337.170)	(349.426)
(8) Other strategies	3,682.941	2,689.196	993.745***
	(323.024)	(192.481)	(266.453)

Note: The final total sample includes 941 farm households and 2,802 plots. Values in columns (2) have been calculated following equations (6*a*)-(6*m*). Values in column (3) have been calculated as the difference between columns (1) and (2). Etb = Ethiopian birr, 1 Etb corresponds to $0.059. *** Significant at the 1% statistical level.

[1] Countries at low latitudes are predicted to bear three-fourth times climate change damages (Mendelsohn and Dinar 2003). The effect of warming on agricultural systems in temperate countries is instead projected to be positive. This identifies losers and winners as results of global warming (Mendelsohn, Dinar and Williams 2006).

[2] Di Falco, Veronesi and Yesuf (2011) follow a similar approach, however, they focus on the binary choice between adapting or not adapting to climate change without distinguishing the effect of different strategies.

[3] Differently from these studies we do not look at types of farms (specialized vs. mixed), livestock switching, or a specific technology adoption such as irrigation. We instead map the full set of actual adaptation strategies implemented by individual farms.

[4] It should be stressed that livestock and agroforestry practices can also be important in the context of adaptation to climate change. Future research should be devoted to the analysis of these other strategies.

[5] It should be stressed that the adoption of new practices may be driven by consumption preferences or risk management. We acknowledge this potential limitation in our study.

[6] As a reviewer emphasized, there might be some significant effects on crop revenues depending on what type of soil conservation measures are taken (e.g., soil bunds, fanya juu terracing). Unfortunately, our sample does not allow us to investigate these effects because of the very small sample size of these subgroups. Future research should be allocated to the estimation of the impact of different measures.

[7] By definition, *Thin Plate Spline* is a physically based two-dimensional interpolation scheme for arbitrarily spaced tabulated data. The Spline surface represents a thin metal sheet that is constrained not to move at the grid points, which ensures that the generated rainfall and temperature data at the weather stations are exactly the same as the data at the weather station sites that were used for the interpolation. In our case, the rainfall and temperature data at the weather stations are reproduced by the interpolation for those stations, which ensures the credibility of the method (see, Wahba 1990 for details).

[8] It is conventional in this body of literature to use quadratic terms for the climatic variables. This in order to capture non linearities and threshold effects in the relationship between revenues and climate (Mendelsohn, Nordhaus and Shaw 1994). Increasing temperature may have a positive impact on the growth of crops, however, up to a threshold level after which increased warming of the production environment may have detrimental effects on yields.

[9] Holden and Yohannes (2002) noted, however, that the direction of causality may be reversed. Farmers with more tenure security may plant more perennials.

[10] We thank the anonymous reviewer for suggesting these selection instruments.

[11] The significant coefficients of the linear and quadratic climatic terms could lead to conclude that temperature displays an inverted U-shape behavior while rainfall a U–shape behavior. This would highlight the existence of threshold levels in the climatic variables. It should be noted, however, that the standard interpretation of polynomials in a linear regression framework does not extend to nonlinear models where marginal effects could have different signs for different values of the independent variables (Ai and Norton 2003).

[12] It should be stressed that the use of net revenues in this context is not free from problems. A comprehensive determination of cost in this context can be indeed be problematic because of the

existence of some costs that are actually “hidden” (McCarthy, Lipper and Branca 2011). This caveat should be borne in mind.

[13] We present the coefficient estimates of the net revenue equations in Table A4 of the appendix for reasons of space, and because the paper focuses on selection-corrected predictions of counterfactual net revenues to measure the impact of climate change adaption strategies, and not on the factors affecting net revenues.