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

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ABSTRACT. *We analyze 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 coupled with water conservation strategies or soil conservation strategies, but not when implemented in isolation.* (JEL Q54, Q56)

## 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 who 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, 51). 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, 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 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,

[1] Countries at low latitudes are predicted to bear three to four times the 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).

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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 analyze 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 gauge 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, 2008b; Seo 2010; Kurukulasuriya 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 adopting water-related strategies such as water harvesting and water conservation. These adaptation measures account for more than 95% 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

[2] Di Falco, Veronesi, and Yesuf (2011) follow a similar approach; however, they focus on the binary choice of 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.

net revenues by a two-stage procedure that allows us 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 particularly 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, as opposed to strategies adopted in isolation.

## II. BACKGROUND

Ethiopia's GDP is closely associated with the performance of its rain-fed agriculture (Deressa and Hassan 2010). For instance, about 40% of national GDP, 90% of exports, and 85% of employment stem from the agricultural sector. The rain-fed production environment is characterized to a large extent by 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 smallholder farm households. They account for about 95% of the national agricultural output, of which about 75% is consumed at the household level (World Bank 2006). With a minimally 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 has been more erratic, with some areas becoming drier but others 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 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 and with the least capacity to respond (Orindi et al. 2006; Stige et al. 2006). The Nile basin is a very large area covering roughly one-third of the country. The sampling frame

[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.

considered the traditional typology of agroecological zones in the country (i.e., *Dega, Weina Dega, Kolla,* and *Bereha*), percent of cultivated land, average annual rainfall, rainfall variability, and vulnerability (number of food-aid dependent people in the 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 20 *woredas*. Random sampling was then used in selecting 50 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 45 annual crops were grown in the basin, the first five major annual crops (teff, maize, wheat, barley, and beans) cover 65% 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, using plough and yoke (animals' draught power). Labor is the major input in the production process during land preparation, planting, and postharvest 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 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's and children's labor are converted into adult male labor equivalents 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 adopting water strategies such as water harvesting and water conservation (Table 1).[6]

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:* Subsample of farm households that adapted at the plot level (sample size = 1,933).

The adaptation measures were implemented both in isolation and jointly. They are mainly yield related and account for more than 95% of the measures followed by the farm households that actually undertook an adaptation measure. The remaining adaptation strategies were much less frequently adopted. For instance, migration and finding off-farm jobs were considered viable adaptation strategies in less than 7% 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

[6] As a reviewer emphasized, there might be some significant effects on crop revenues depending on which 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.

TABLE 2
Descriptive Statistics

| | Total Sample | | Farm Households That Did Not Adapt | | Farm Households That Adapted | |
|---|---|---|---|---|---|---|
| Variable | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| Dependent | | | | | | |
| 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 | | | | | | |
| *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 |
| Labor | 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.

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 "nonadapting" as the reference category. Tables 2 and 3 show 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

TABLE 3
Descriptive Statistics by Adoption Strategy

| | 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 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| Dependent | | | | | | | | | | | | | | | | |
| Net revenues | 3,963.939 | 3,966.249 | 4,752.995 | 5,651.228 | 4,349.334 | 6,091.633 | 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 | | | | | | | | | | | | | | | | |
| *Belg* rainfall | 347.966 | 157.382 | 330.544 | 147.302 | 293.275 | 148.036 | 247.510 | 122.641 | 289.417 | 138.199 | 308.099 | 172.200 | 308.123 | 143.351 | 394.451 | 155.311 |
| *Meher* rainfall | 1,169.225 | 302.370 | 1,215.350 | 290.553 | 1,157.462 | 281.592 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 | 16.968 | 1.696 | 17.459 | 1.241 | 16.869 | 2.586 | 17.275 | 0.788 | 16.903 | 1.387 | 17.776 | 1.879 | 17.292 | 1.072 | 18.254 | 1.504 |
| Soil characteristics | | | | | | | | | | | | | | | | |
| Highly fertile | 0.209 | 0.407 | 0.333 | 0.476 | 0.251 | 0.434 | 0.216 | 0.414 | 0.340 | 0.474 | 0.255 | 0.438 | 0.201 | 0.401 | 0.138 | 0.346 |
| Infertile | 0.196 | 0.398 | 0.175 | 0.384 | 0.185 | 0.389 | 0.279 | 0.451 | 0.174 | 0.380 | 0.135 | 0.343 | 0.152 | 0.360 | 0.080 | 0.272 |
| No erosion | 0.448 | 0.498 | 0.684 | 0.469 | 0.397 | 0.490 | 0.495 | 0.502 | 0.487 | 0.500 | 0.539 | 0.500 | 0.488 | 0.501 | 0.464 | 0.501 |
| Severe erosion | 0.117 | 0.323 | 0.123 | 0.331 | 0.151 | 0.358 | 0.180 | 0.386 | 0.131 | 0.338 | 0.064 | 0.245 | 0.045 | 0.208 | 0.072 | 0.260 |
| Crop type | 3.350 | 1.293 | 3.048 | 1.349 | 3.246 | 1.527 | 3.061 | 1.410 | 3.288 | 1.351 | 3.018 | 1.459 | 2.915 | 1.579 | 3.163 | 1.476 |
| Tree planting | 0.000 | 0.000 | 0.326 | 0.470 | 0.351 | 0.481 | 0.353 | 0.478 | 0.468 | 0.501 | 0.531 | 0.500 | 0.525 | 0.501 | 0.536 | 0.500 |
| Labor | 113.545 | 131.221 | 106.727 | 135.718 | 101.945 | 125.071 | 94.372 | 114.142 | 112.802 | 159.835 | 127.478 | 144.102 | 89.241 | 79.195 | 99.067 | 135.289 |
| Seeds | 130.334 | 194.910 | 120.336 | 91.044 | 128.453 | 140.717 | 104.597 | 105.903 | 128.836 | 195.086 | 170.367 | 171.318 | 115.776 | 149.371 | 93.816 | 95.221 |
| Fertilizers | 73.159 | 171.875 | 62.933 | 111.958 | 52.951 | 127.914 | 38.986 | 64.249 | 75.932 | 266.837 | 49.169 | 86.172 | 42.779 | 111.020 | 86.999 | 121.555 |
| Manure | 222.720 | 850.262 | 820.221 | 2,052.245 | 298.849 | 1,135.466 | 161.506 | 519.779 | 199.403 | 693.824 | 552.640 | 1,604.505 | 206.183 | 642.273 | 41.444 | 186.226 |
| Animals | 0.935 | 0.247 | 0.754 | 0.434 | 0.893 | 0.310 | 0.838 | 0.370 | 0.890 | 0.313 | 0.887 | 0.318 | 0.865 | 0.342 | 0.919 | 0.275 |
| Literacy | 0.426 | 0.496 | 0.509 | 0.504 | 0.591 | 0.492 | 0.631 | 0.485 | 0.505 | 0.500 | 0.674 | 0.471 | 0.446 | 0.498 | 0.486 | 0.502 |
| Male | 0.917 | 0.276 | 0.877 | 0.331 | 0.956 | 0.205 | 0.937 | 0.244 | 0.937 | 0.243 | 0.965 | 0.186 | 0.920 | 0.271 | 0.870 | 0.338 |
| Married | 0.917 | 0.276 | 0.912 | 0.285 | 0.981 | 0.138 | 0.955 | 0.208 | 0.923 | 0.267 | 0.972 | 0.167 | 0.900 | 0.301 | 0.848 | 0.360 |
| Age | 48.074 | 10.484 | 49.684 | 14.404 | 45.998 | 11.652 | 45.856 | 14.984 | 46.209 | 11.913 | 47.199 | 11.630 | 45.239 | 10.759 | 44.420 | 13.148 |
| Household size | 6.809 | 1.984 | 6.649 | 2.074 | 6.839 | 2.163 | 6.622 | 2.072 | 7.029 | 2.351 | 6.887 | 2.473 | 6.519 | 1.716 | 5.957 | 1.620 |
| Off-farm job | 0.313 | 0.465 | 0.368 | 0.487 | 0.292 | 0.455 | 0.306 | 0.463 | 0.238 | 0.426 | 0.390 | 0.490 | 0.280 | 0.450 | 0.268 | 0.445 |
| Relatives | 12.762 | 14.721 | 15.895 | 22.417 | 22.384 | 27.168 | 11.569 | 10.908 | 24.658 | 87.162 | 20.355 | 20.199 | 20.225 | 31.761 | 7.068 | 7.741 |
| Highlands *(Dega)* | 0.359 | 0.480 | 0.152 | 0.360 | 0.351 | 0.481 | 0.197 | 0.398 | 0.315 | 0.467 | 0.270 | 0.444 | 0.426 | 0.496 | 0.384 | 0.487 |
| Midlands *(Weina Dega)* | 0.404 | 0.491 | 0.600 | 0.491 | 0.544 | 0.503 | 0.491 | 0.501 | 0.685 | 0.467 | 0.469 | 0.500 | 0.468 | 0.501 | 0.540 | 0.499 |
| Flood experience | 0.174 | 0.380 | 0.070 | 0.258 | 0.375 | 0.485 | 0.279 | 0.451 | 0.185 | 0.389 | 0.092 | 0.290 | 0.183 | 0.388 | 0.152 | 0.360 |
| Drought experience | 0.426 | 0.496 | 0.667 | 0.476 | 0.655 | 0.476 | 0.541 | 0.501 | 0.637 | 0.481 | 0.638 | 0.482 | 0.536 | 0.500 | 0.203 | 0.404 |
| Hailstorm experience | 0.132 | 0.339 | 0.257 | 0.438 | 0.298 | 0.462 | 0.336 | 0.473 | 0.459 | 0.501 | 0.290 | 0.454 | 0.170 | 0.377 | 0.194 | 0.396 |
| Government extension | 0.752 | 0.433 | 0.649 | 0.481 | 0.701 | 0.458 | 0.820 | 0.386 | 0.833 | 0.374 | 0.723 | 0.449 | 0.875 | 0.331 | 0.464 | 0.501 |
| Farmer-to-farmer extension | 0.630 | 0.484 | 0.474 | 0.504 | 0.623 | 0.485 | 0.811 | 0.393 | 0.674 | 0.469 | 0.709 | 0.456 | 0.817 | 0.388 | 0.326 | 0.470 |
| Radio information | 0.222 | 0.416 | 0.351 | 0.481 | 0.258 | 0.438 | 0.486 | 0.502 | 0.464 | 0.499 | 0.624 | 0.486 | 0.474 | 0.500 | 0.174 | 0.380 |
| Neighborhood information | 0.530 | 0.500 | 0.105 | 0.310 | 0.397 | 0.490 | 0.225 | 0.420 | 0.282 | 0.451 | 0.064 | 0.245 | 0.284 | 0.452 | 0.406 | 0.493 |
| Climate information | 0.409 | 0.493 | 0.509 | 0.504 | 0.547 | 0.498 | 0.631 | 0.485 | 0.605 | 0.489 | 0.504 | 0.502 | 0.767 | 0.423 | 0.297 | 0.459 |
| Sample size | 230 | | 57 | | 411 | | 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.

impute the household-specific rainfall and temperature values using latitude, longitude, and elevation information for 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 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). Variable definitions are presented in Appendix Table A1, and the descriptive statistics in Tables 2 and 3.

## IV. MODELING 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 cope with 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 $j$ ($j = 1 \ldots M$) with respect to implementing any other strategy $k$. We specify the latent variable as

$$A_{ij}^* = \bar{V}_{ij} + \eta_{ij} = \mathbf{Z}_i \boldsymbol{\alpha}_j + \eta_{ij}, \quad [1]$$

with

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

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 $k \neq j$, that is, if $\varepsilon_{ij} = \max\limits_{k \neq j}(A_{ik}^* - A_{ij}^*) < 0$. Equation [1] includes a deterministic component ($\bar{V}_{ij} = \mathbf{Z}_i \boldsymbol{\alpha}_j$), and an idiosyncratic unobserved stochastic component $\eta_{ij}$. 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 $\bar{V}_{ij}$ 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*

[7] By definition, the 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 is in order to capture nonlinearities 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.

*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, 166) noted "the best way of exercising control over land is to plant trees." This view is also documented in Ethiopia by Shiferaw and Holden (1998), Gebremedhin and Swinton (2003), Bogale, Taeb, and Endo (2006) and Mekonnen (2009).[9]

It is assumed that the covariate vector $\mathbf{Z}_i$ is uncorrelated with the idiosyncratic unobserved stochastic component $\eta_{ij}$, that is, $E(\eta_{ij}|\mathbf{Z}_i)=0$. Under the assumption that $\eta_{ij}$ 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

$$P_{ij}=P(\varepsilon_{ij}<0|\mathbf{Z}_i)=\frac{\exp(\mathbf{Z}_i\boldsymbol{\alpha}_j)}{\sum_{k=1}^{M}\exp(\mathbf{Z}_i\boldsymbol{\alpha}_k)}. \quad [2]$$

**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's (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 "nonadapting"). We have a net revenue equation for each possible regime $j$ defined as

$$\begin{aligned}&\text{Regime 1: } y_{i1}=\mathbf{X}_i\boldsymbol{\beta}_1+u_{i1} \text{ if } A_i=1 && [3a]\\ &\quad\vdots \qquad\qquad \vdots \qquad\qquad \vdots\\ &\text{Regime M: } y_{iM}=\mathbf{X}_i\boldsymbol{\beta}_M+u_{iM} \text{ if } A_i=M && [3m]\end{aligned}$$

where $y_{ij}$ is the net revenue per hectare of farm household $i$ in regime $j$, ($j=1,\ldots,M$), and $\mathbf{X}_i$ represents a vector of inputs (e.g., seeds, fertilizers, manure, and labor), farmer head's and farm household's characteristics, soil's characteristics, and the past climatic factors included in $\mathbf{Z}_i$; 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 ordinary least squares (OLS) model, the net revenues equations [3a]–[3m] are estimated separately. However, if the error terms of the selection model (1) $\eta_{ij}$ are correlated with the error terms $u_{ij}$ of the net revenue functions [3a]–[3m], 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 $\eta_{ij}$ 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, 179) show that consistent estimates of $\boldsymbol{\beta}_j$ in the outcome equations [3a]–[3m] can be obtained by estimating the following selection bias-corrected net revenues equations:

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

$$\text{Regime 1:} \quad y_{i1} = \mathbf{X}_i\boldsymbol{\beta}_1 + \sigma_1\left[\rho_1 m(P_{i1}) + \sum_j \rho_j m(P_{ij})\frac{P_{ij}}{(P_{ij}-1)}\right] + v_{i1} \text{ if } A_i = 1 \quad [4a]$$

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

$$\text{Regime M:} \quad y_{iM} = \mathbf{X}_i\boldsymbol{\beta}_M + \sigma_M\left[\rho_M m(P_{iM}) + \sum_j \rho_j m(P_{ij})\frac{P_{ij}}{(P_{ij}-1)}\right] + v_{iM} \text{ if } A_i = M \quad [4m]$$

where $P_{ij}$ represents the probability that farm household $i$ chooses strategy $j$ as defined in [2], $\rho_j$ is the correlation between $u_{ij}$ and $\eta_{ij}$, and $m(P_{ij}) = \int J(v - \log P_j)g(v)dv$ with $J(\cdot)$ being the inverse transformation for the normal distribution function, $g(\cdot)$ the unconditional density for the Gumbel distribution, and $v_{ij} = \eta_{ij} + \log P_j$. 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 particularly 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 4 and Appendix Table A2 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's (2007) model is that IIA holds. However, Bourguignon, Fournier, and Gurgand (2007, 199) 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." An alternative estimation method is provided by Dahl (2002), which corrects the outcome equation of endogenous selection semiparametrically 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 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, 582–83). 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 [4a]–

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

TABLE 4
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/ 1,000 | −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/ 1,000 | 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) |

*(table continued on following page)*

TABLE 4
Parameters Estimates of Climate Change Adaptation Strategies, Multinomial Logit Model *(continued)*

| | (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 |
|---|---|---|---|---|---|---|---|---|
| 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 ($\chi^2$) | 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.

[4m] the average of plot-variant variables $\bar{\mathbf{S}}_i$ 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 $\bar{\mathbf{S}}_i$; that is $v_i = \bar{\mathbf{X}}_i\boldsymbol{\pi} + \psi_i$ with $\psi_i \sim \text{INN}(0, \sigma^2_\psi)$ and $E(\psi_i/\bar{\mathbf{X}}_i) = 0\bar{\mathbf{S}}_i$, where $\boldsymbol{\pi}$ is the corresponding vector of coefficients, and $\psi_i$ is a normal error term uncorrelated with $\bar{\mathbf{S}}_i$.

## 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 nonadapters 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, 179 and 201–3), and we first derive the expected net revenues of farm households that adapted, which in our study means $j = 2 \ldots M$ ($j = 1$ is the reference category "nonadapting"), as

$$E(y_{i2} \mid A_i = 2) = \mathbf{X}_i\boldsymbol{\beta}_2 + \sigma_2\left[\rho_2 m(P_{i2}) + \sum_{k \neq 2}^{M} \rho_k m(P_{ik}) \frac{P_{ik}}{(P_{ik} - 1)}\right] \quad [5a]$$

$$\vdots \qquad \vdots$$

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

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

$$E(y_{i1} \mid A_i = 2) = \mathbf{X}_i\boldsymbol{\beta}_1 + \sigma_1\left[\rho_1 m(P_{i2}) + \rho_2 m(P_{i1}) \frac{P_{i1}}{(P_{i1} - 1)} + \sum_{k = 3 \ldots M}^{M} \rho_k m(P_{ik}) \frac{P_{ik}}{(P_{ik} - 1)}\right] \quad [6a]$$

$$\vdots \qquad \vdots$$

$$E(y_{i1} \mid A_i = M) = \mathbf{X}_i\boldsymbol{\beta}_1 + \sigma_1\left[\rho_1 m(P_{iM}) + \sum_{k = 2 \ldots M} \rho_k m(P_{i,k-1}) \frac{P_{i,k-1}}{(P_{i,k-1} - 1)}\right] \quad [6m]$$

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

### Drivers of Climate Change Adaptation Strategies

Table 4 presents parameter estimates of the multinomial logit model and allows us to answer the first research question: What are the main drivers of adopting a particular climate change strategy?

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 pe-

riod *(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 related to climate adaptation per se. In the next section, we show 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 and 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 implementing 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, 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 socioeconomic 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 choosing soil conservation and crop-water strategies.

We explored the role of extension services on the probability of adopting the strategies. We find that both government extension and farmer-to-farmer extension services 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 Brouwer 2012). In the concluding section, we further discuss our results, in particular, in light of their implications in terms of net revenues.

## Economic Implications of Climate Change Adaptation Strategies

We now turn to the economic implications of adopting a particular strategy on farm households' net revenues. What are the strategies that yield the highest revenues? Two simple and standard approaches could be applied to identify the "best" adaptation strategy. First, we could compare actual mean net rev-

[11] The significant coefficients of the linear and quadratic climatic terms could lead to the conclusion that temperature displays an inverted U–shaped behavior, while rainfall displays a U-shaped 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).

enues 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 ETB 1,550/ha more than farm households that did not adapt (difference significant at the 1% level, *t*-statistic = –4.30). A second possible approach consists of estimating a linear regression model of net revenues that includes binary variables equal to 1 if the farm household adopted a particular strategy (Appendix Table A3). This approach would lead us to conclude that farm households implementing *only* water strategies would earn the most, about ETB 1,680/ha more than farm households that did not adopt.

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, whereas 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, they are 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 into equations [6a]–[6m] to produce selection-corrected predictions of counterfactual net revenues, that is, what farm households would have earned if they had not adapted.

Table 5 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 5 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 instead that adaptation to climate change based upon a portfolio of strategies significantly increases farm households' net revenues.

The counterfactual analysis allows us to identify 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 implemented along with water conservation or soil conservation, and not when implemented in isolation. In particular, the impact of strategy (4), changing crops combined with water conservation, is equal to about ETB 2,332/ha, and the impact of strategy (5), changing crops combined with soil conservation, is about ETB 2,193/ha. We also find that the adoption of the former or the latter strategy yields payoffs not statistically different (*p*-value = 0.273). The combination of water and soil conservation also has a positive and statistically significant impact (about ETB 1,730/ha), and even if lower, not statistically different from the previous strategies (4) and (5) (*t*-statistic = 0.666 and 0.867, respectively). Interestingly, when all three strategies

[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 Appendix Table A4 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.

TABLE 5
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 column (2) have been calculated following equations [6a]–[6m]. 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% level.

(changing crops *and* water conservation *and* soil conservation) are implemented as part of the same adaptation portfolio, they deliver a payoff of ETB 1,297/ha, which is lower and statistically different only from strategy (5), which entails the combination of changing crops and soil conservation ($t$-statistic = 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 approach that entails three strategies delivers higher net revenues than a less comprehensive approach that uses the combination of two strategies. We will provide some interpretation of these results in the next section.

## 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 adopt 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 of a portfolio of actions rather than one single action. More specifically, we find that the positive impact of changing crops is significant when 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 from when two strategies are implemented. There is, therefore, no statistical evidence that a more comprehensive adapta-

tion strategy has a higher payoff. This result, while puzzling at the outset, is actually quite intuitive. We are in fact modeling net revenues. It may therefore simply reflect the higher cost of implementing a more complex adaptation approach. 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 for designing 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 is 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 significantly higher net revenues than if farm households did not adapt or else adopted the same strategies in isolation. The same result is found when we analyze 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 a 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 deliver a payoff in the long run. Future research should be allocated to address these issues, as well as the behavioral dimension of adaptation, and the impact of other management practices such as livestock and agroforestry.

## APPENDIX

TABLE A1
Variable Definitions

| Variable | Definition |
|---|---|
| Dependent | |
| Net revenues | Net revenues per hectare in Ethiopian birr (ETB); ETB 1 = $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 | |
| *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 (°C) 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 |
| Labor | Logarithm of labor 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/1,000 | −3.806 (16.050) |
| *Meher* rainfall | −37.910*** (10.657) |
| Squared *Meher* rainfall/1,000 | 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 | 1,260.908** (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)* | −1,1635.369*** (2610.380) |
| Midlands *(Weina Dega)* | −3,534.400** (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*-statistic) | 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
Ordinary Least Squares Estimates of Net Revenue Equations on Pooled Sample

| Dependent Variable: Net Revenues per Hectare (ETB/ha) | Coefficient (Std. Err.) |
|---|---|
| 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 | 1,162.555* (596.455) |
| Soil conservation and changing crop varieties | 538.244** (197.431) |
| Water strategy and soil conservation | 1,373.732*** (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/1,000 | 19.182 (27.008) |
| *Meher* rainfall | 4.691 (10.554) |
| Squared *Meher* rainfall/1,000 | −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: Net Revenues per Hectare | (0) No Adaptation | (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 | −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/1,000 | 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/1,000 | 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) |

*(table continued on following page)*

TABLE A4

Estimates of Net Revenue Equations by Multinomial Endogenous Switching Regression Model *(continued)*

| Dependent Variable: Net Revenues per Hectare | (0) No Adaptation | (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 |
|---|---|---|---|---|---|---|---|---|---|
| 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 |
| a | (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) | (11,181,710.145) | (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) |

*(table continued on following page)*

TABLE A4
Estimates of Net Revenue Equations by Multinomial Endogenous Switching Regression Model *(continued)*

| Dependent Variable: Net Revenues per Hectare | (0) No Adaptation | (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 |
|---|---|---|---|---|---|---|---|---|---|
| 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) | (1,771,516.321) | (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 |
| | | (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) |
| | (4,138.221) | | | | | | | | |
| $m(P_{i6})$ | − 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) | (1,216,321.706) | (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.

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