Climate and Development

ISSN: 1756-5529 (Print) 1756-5537 (Online) Journal homepage: www.tandfonline.com/journals/tcld20

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**To cite this article:** Hailemariam Teklewold, Alemu Mekonnen & Gunnar Kohlin (2019) Climate change adaptation: a study of multiple climate-smart practices in the Nile Basin of Ethiopia, Climate and Development, 11:2, 180-192, DOI: 10.1080/17565529.2018.1442801

**To link to this article:** https://doi.org/10.1080/17565529.2018.1442801



Published online: 05 Apr 2018.

*Climate and Development*, 2019
Vol. 11, No. 2, 180–192, https://doi.org/10.1080/17565529.2018.1442801

climate and development



RESEARCH ARTICLE

# Climate change adaptation: a study of multiple climate-smart practices in the Nile Basin of Ethiopia

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(*Received 11 July 2016; accepted 15 December 2017*)

Improving farm-level use of multiple climate change adaptation strategies is essential for improving household food security, particularly against a backdrop of a high risk of climatic shocks. However, the empirical foundation for understanding how farm households choose multiple climate-smart practices is far from being established. In this paper, the effects of household, farm and climatic factors on farmers' decisions to use multiple adaptation practices are analysed. A survey of 921 farm households and 4312 farm plots combined with historical climate data in the Nile Basin of Ethiopia is explored using multivariate and random effect ordered probit econometric models. Results show agricultural production can be characterized by complementarities between adaptation practices. This result is important to designing packages of adaptation practices. The econometric results confirm that social capital, tenure security and climatic shocks are important determinants of the choice of the type and number of adaptation practices. The results suggest the need for carefully designing combinations of adaptation strategies based on agro-ecological conditions.

**Keywords:** multiple adaptation practices; climate change; multivariate and ordered probit; Ethiopia

**JEL Classification:** Q01; Q12; Q16; Q18

## 1. Introduction

Despite the growing consensus that climate change is making agricultural development more challenging, there is little consensus on how agricultural practices should change in response (FAO, 2014; IPCC, 2007). In an era when climate change is salient for agricultural development, there is a need to identify various climate-smart practices as adaptation measures. Climate-smart practices include land and water management practices, which have the potential to build resilience to climate change and enhance productivity, while also result in lower greenhouse gas (GHG) emissions per unit of output (Campbell, Thornton, Zougmore, Asten, & Lipper, 2014).

In the Ethiopian context, climate-smart agricultural practices are generally understood to encompass inclusive and sustainably increased agricultural productivity while directing the agricultural sector to contribute to mitigation, adapt to existing and coming climate changes, plus building the resilience of the smallholder farmers that form the core of the agriculture sector in the country.

In accord with this, the Ethiopian government has recently launched a vision to build a Climate Resilient Green Economy by 2025 (FDRE, 2011). This is an economy that would be middle-income and resilient to the negative impacts of climate change and would be achieved with no net increase in GHG emissions relative to today. Accordingly, over the last few years, a range of climate-smart agriculture approaches have been recommended to build adaptive capacity that enhances resilience while at the same time increasing yields and lowering GHG emissions through soil, water and plant nutrient management (Campbell et al., 2014). Despite these efforts, adoption of adaptation practices has been low and uneven (Deressa, Hassan, Alemu, Yesuf, & Ringler, 2008; Shiferaw, Okello, & Reddy, 2009).

As a result, farmers' decisions to use climate-smart agricultural practices have been of continuing interest to researchers and policymakers. The main concern is that the design of policies to encourage the scaling up/out of practices requires an understanding of what factors

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induce farmers' choices among such practices. Moreover, because climate change adds several kinds of pressure to already stressed ecosystems, farmers can adopt multiple practices jointly so as to exploit the potential advantage of complements, substitutes or supplements to deal with their overlapping constraints. Hence, an analysis made without controlling for such interdependence in complex farming systems may underestimate or overestimate the influences of various factors on the decision to adopt the practices (Wu & Babcock, 1998).

Utilizing recent data in the Nile Basin of Ethiopia, we concentrate on the relative importance of various household, farm and location characteristics as they affect the probability and levels of adoption of multiple practices. Our study contributes to the growing literature on climate change adaptation in the following ways. First, we apply a system method of estimation that jointly determines the decision to adopt multiple climate-smart agricultural practices, such as agricultural water management, crop diversification, agro-forestry, soil conservation, modern crop varieties, fertilizer, minimum tillage and the use of manure. Second, we not only provide empirical evidence about whether farmers adopt certain practices but also analyse the number of climate-smart practices adopted per farm. Such knowledge is important to formulate specific policies to facilitate adoption of packages of adaptation practices. To the best of our knowledge, empirical evidence on the heterogeneous effects of climatic characteristics on the number of adaptation practices is scarce.

## 2. Study areas and sampling

The data used for this study are based on a farm household survey conducted in 2015 in five regional states of the Ethiopian part of the Nile Basin: Amhara, Oromia, Tigray, Benshangul-Gumuz and SNNP. The basin covers about two-thirds of the country's land mass (Erkossa, Haileslassie, & MacAliste, 2014). The farming system of the basin can be broadly categorized as a mixed crop-livestock farming system, where over 90% of the cultivated area is covered by cereal-based farming systems (Erkossa et al., 2014).

The sampling frame considered the traditional typology of agro-ecological zones in the country. These are *Dega* (cool, humid, highlands), *Weina-Dega* (temperate, cool sub-humid, highlands), *Kolla* (warm, semi-arid lowlands) and *Bereha* (hot and hyper-arid). First, 20 *woredas* (administrative districts) from the five regional states were selected (three from each of Tigray and Benshangul-Gumuz, six from Amhara, seven from Oromia, and one from SNNP). This resulted in a random selection of 50 farmers from each woreda, for a total of 1000 farm households with 4702 farming plots. After cleaning inconsistent responses, we kept data from 921 farm households and 4312 farming plots.

## 3. Descriptive statistics: dependent and explanatory variables

In this study, the portfolio of climate-smart agricultural practices is developed by allowing the respondent farmer to recount the type of practices used for each plot. Descriptive results of the adaptation practices are presented in Table 1.

The first adaptation practice is crop diversification. It is a strategy for growing more than one crop across space (that is intercropping) or time (that is crop rotation). This involves the exploitation of jointly beneficial interactions among individual crops, including reducing the incidence of weeds, pests and diseases; improving soil fertility and water-holding capacity; diversifying the seasonal requirements of resources and stabilizing farm income over time through evening out the impact of price fluctuations (Snapp, Blackie, Gilbert, Bezner-Kerr, & Kanyama-Phiri, 2010). In the study areas, crop diversification is used on only 22% of the plots.

The next practice is minimum tillage, defined as growing crops without disturbing the soil. It is either reduced tillage (only one plough pass) or zero tillage, combined with leaving crop residues on the soil surface. Minimum tillage can simultaneously achieve both adaptation and mitigation goals – through enhanced soil health, better soil aeration, carbon sequestration, and improved soil fertility and water-holding capacity (Arslan, McCarthy, Lipper, Asfaw, & Cattaneo, 2013). Minimum tillage is observed on only about 9% of the plots.

Manure use refers to the application of livestock wastes on the farming plot. Manure use can have both climate change mitigation and adaptation effects. It is the major component of a sustainable agricultural system, with the potential benefits of long-term maintenance of soil fertility, by supplying nutrients, especially nitrogen (N), phosphorus (P), and potassium (K). The application of manure increases soil organic matter content, which leads to improved water infiltration and water-holding capacity, as well as removing atmospheric $CO_2$ and serving as a carbon sink (Marenya & Barrett, 2007).

Agro-forestry is an integrated system that combines trees with agricultural crops/livestock. It enhances farmers' ability to adapt to climate change because of the multiple benefits it delivers, including food provision, supplementary income and environmental services (Schoeneberger et al., 2012). Integrating trees and shrubs into food crop farming systems helps address food insecurity, increases $CO_2$ sequestration, and reduces the vulnerability of agricultural systems, which enhance the resilience of smallholders to current and future climate risks (Thorlakson, 2011).

Table 1. Description and descriptive statistics of the dependent and explanatory variables used in the analysis.

| Variable | Description | Mean | SD |
|---|---|---|---|
| **Dependent variables** | | | |
| Af | Agro-forestry | 15.82 | – |
| Sw | Soil conservation | 27.88 | – |
| Va | Improved variety | 23.48 | – |
| Fe | Inorganic fertilizer | 52.59 | – |
| Ma | Animal manure | 30.31 | |
| Mt | Minimum tillage | 9.11 | |
| Cd | Cropping diversification | 21.96 | – |
| Aw | Agricultural water management | 41.07 | – |
| **Household features** | | | |
| Gender | 1 = if male-headed household | 0.88 | – |
| Age | Age of the head, years | 51.86 | 12.70 |
| Education | 1 = if literate household head | 0.34 | – |
| Famlysize | Family size | 8.19 | 2.39 |
| **Resource constraints** | | | |
| Farmsize | Farm size, ha | 1.72 | 1.14 |
| Tlu | Livestock size | 4.80 | 3.48 |
| Credit | 1 = if credit constraint (credit is needed but unable to find it) | 0.44 | – |
| Asset | Value of household and farm assets, ‘000 Birr | 25.34 | 41.64 |
| Offarm | Off-farm income, Birr/month | 652.50 | 3790.88 |
| **Extension, information and market access** | | | |
| Teleph | 1 = if own telephone | 0.44 | – |
| Distoutmkt | Walking distance to output markets, minutes | 66.55 | 53.09 |
| Distinputmkt | Walking distance to input market, minutes | 55.71 | 37.66 |
| Totextcontact | Total number of topics that farmer received | 8.72 | 3.80 |
| Extconfd | 1 = if confident with the skill of extension agents | 0.86 | – |
| Infoclimate | 1 = if farmer is well informed about climate change | 0.79 | – |
| **Social capital network, social conformity and neighbourhoods effects** | | | |
| Relative | Number of relatives in the village | 21.12 | 30.31 |
| Agricmemb | 1 = if membership in at least one agriculture related group | 0.50 | – |
| Financmemb | 1 = if membership in at least one finance related group | 0.83 | – |
| Socalmemb | 1 = if membership in at least one social related group | 0.92 | – |
| Appreciation | If perceived appreciation by neighbour farmers on adoption of the practices (%) | 68.88 | – |
| Positive | If perceived positive effects on neighbour farms on adoption of the practices (%) | 41.60 | – |
| Negative | If perceived negative effects on neighbour farms on adoption of the practices (%) | 17.12 | – |
| **Shocks** | | | |
| Rainindex | Rainfall disturbance index (1 = best) | 0.70 | 0.28 |
| Plotindex | Plot-level disturbance index (1 = worst) | 0.19 | 0.18 |
| Relygovt | 1 = if the farmer relies on government support in case of crop failure | 0.42 | – |
| **Farm features** | | | |
| Plotdist | Walking distance of the plot from home, minutes | 15.33 | 18.98 |
| Tenure | 1 = if own the plot | 0.85 | – |
| Highfert[a] | 1 = if highly fertile soil plot | 0.36 | – |
| Midfert[a] | 1 = if medium fertile soil plot | 0.52 | – |
| Flatslop[b] | 1 = if flat slope plot | 0.60 | – |
| Midslop[b] | 1 = if medium slope plot | 0.37 | – |
| Depdepth[c] | 1 = if deep depth soil plot | 0.46 | – |
| Middepth[c] | 1 = if medium depth soil plot | 0.42 | – |
| Cereal | 1 = if cereal crops grown | 0.81 | – |
| Legume | 1 = if legume crops grown | 0.16 | – |
| **Climate** | | | |
| Rainfall | Amount of rainfall in the main season in mm (2000–2013) | 699.38 | 235.78 |
| PCI | Precipitation concentration index | 27.36 | 5.91 |
| Temperature | Average temperature in °C (2000–2013) | 19.92 | 2.59 |
| Elevation | Location of the household with respect to altitude, masl | 2223.86 | 416.34 |
| Number of observations (plots/households) | | 4312/921 | |

[a]Poor fertile soil is the reference category.
[b]Steep slope is the reference category.
[c]Shallow depth is the reference category.

Soil conservation includes grass strips, soil and stone bunds. These practices can improve household food security and reduce vulnerability by increasing soil water availability, decreasing soil erosion and ensuring that nutrients and inputs are maintained in the plot (Delgado et al., 2011). They also help increase groundwater recharge and protect the topsoil (FAO, 2014).

Agricultural water management practices offer one of the "best bet" strategies for adapting agricultural production to climate change and variability because they improve water balance, availability, infiltration and retention by the soil; reduce water loss due to runoff and evaporation; and improve the quality and availability of ground and surface water (Arslan et al., 2013).Water management (irrigation, drainage, and water conservation and control) achieves stability of crop production by maintaining soil conditions close to optimum for crop growth. Water management practices allow some water to seep into the soil (infiltration), improving the soil to allow more vegetation cover. This practice also increases groundwater recharge and protects the topsoil (FAO, 2014).

The other two technologies considered in this study are improved crop varieties and inorganic fertilizer. Adoption of improved crop varieties and the appropriate use of fertilizer can increase productivity, thus promoting food security and higher income for a rapidly growing population. Improved productivity increases resilience to climate variability and hence is an important strategy in adaptation to future climate change (Bryan et al., 2011).

## 4. Explanatory variables

The selection of our empirical specification is grounded on the technology adoption literature (Deressa et al., 2008; Kassie, Teklewold, Jaleta, Marenya, & Erenstein, 2015; Marenya & Barrett, 2007; Teklewold, Kassie, Shiferaw, & Köhlin, 2013; Wollni, Lee, & Janice, 2010; Yegbemey, Yabib, Tovignan, Gantoli, & Kokoye, 2013). Accordingly, detailed information on location, household and farm characteristics at the plot level for each individual farm household was collected and included in the model. Descriptions of the prospective explanatory variables and descriptive statistics are presented in Table 1.[1]

## 5. Econometric model specification

The econometric specification consists of two parts: the multivariate probit model (MVP) and the random-effects ordered probit model. The models can be augmented by Mundlak's (1978) approach, where the unobserved heterogeneities are parameterized by the mean value of plot-varying covariates.[2] This avoids bias by overcoming the possible correlation of plot-invariant unobserved heterogeneities with observed covariates.

## 6. An MVP model

The MVP approach simultaneously models the influence of the set of explanatory variables on the choice of each of the practices, while allowing for potential correlation between unobserved disturbances of adoption equations (Belderbos, Carree, Diederen, Lokshin, & Veugelers, 2004). This approach models how the decision to adopt a particular practice may be conditional on the choice of another practice, due to either complementarities (positive correlation) or substitutability (negative correlation) between practices. Failure to capture interrelationships among adoption decisions leads to bias and inefficient estimates (Greene, 2008).

Consider the $i$th farm household ($i = 1, \ldots, N$) that is facing a decision on whether or not to adopt an available practice on plot ($p = 1, \ldots, P$). Let $U_0$ represents the benefits to the farmer from non-adoption, and let $U_k$ represents the benefit of adopting the $k$th practice, where $k$ denotes the choice of agricultural water management (Aw), agro-forestry (Af), conservation tillage (Mt), crop diversification (Cd), manure use (Ma), soil conservation (Sw), improved crop varieties (Va), and inorganic fertilizer (Fe). The farmer decides to adopt the $k$th practice on plot '$p$' if $Y^*_{ipk} = U^*_k - U_0 > 0$. The net benefit ($Y^*_{ipk}$) from adoption of the $k$th practice is a latent variable determined by observed household, plot, and location characteristics ($X_{ip}$) and the error term ($\varepsilon_{ip}$):

$$Y^*_{ipk} = X'_{ip}\beta_k + \varepsilon_{ip} \quad (k = \text{Aw, Af, Cd, Ma, Mt, Sw, Va, Fe}). \tag{1}$$

Using the indicator function, the unobserved preferences in Equation (1) translate into the observed binary outcome equation as follows:

$$\mathrm{Y_{ipk}} = \begin{cases} 1 & \text{if } \mathrm{Y^*_{ipk}} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (\mathrm{k} = \mathrm{Aw, Af, Cd, Ma, Mt, Sw, Va, Fe}). \tag{2}$$

In the multivariate model, where the adaptation of several practices is possible, the error terms jointly follow a multivariate normal distribution (MVN), with zero mean and variance normalized to unity:

where$(u_{Af}, u_{Sw}, u_{Va}, u_{Fe}, u_{Ma}, u_{Mt}, u_{Cd}, u_{Aw}) \tilde{} MVN\ (0, \Omega)$ and the symmetric covariance matrix $\Omega$ is given by

$$\Omega = \begin{bmatrix} 1 & \rho_{\mathrm{Af,Sw}} & \rho_{\mathrm{Af,Va}} & \rho_{\mathrm{Af,Fe}} & \rho_{\mathrm{Af,Ma}} & \rho_{\mathrm{Af,Mt}} & \rho_{\mathrm{Af,Cd}} & \rho_{\mathrm{Af,Aw}} \\ \rho_{\mathrm{Sw,Af}} & 1 & \rho_{Sw,Va} & \rho_{Sw,Fe} & \rho_{Sw,Ma} & \rho_{Sw,Mt} & \rho_{Sw,Cd} & \rho_{Sw,Aw} \\ \rho_{\mathrm{Va,Af}} & \rho_{\mathrm{Va,Sw}} & 1 & \rho_{Va,Fe} & \rho_{Va,Ma} & \rho_{Va,Mt} & \rho_{Va,Cd} & \rho_{Va,Aw} \\ \rho_{\mathrm{Fe,Af}} & \rho_{\mathrm{Fe,Sw}} & \rho_{Fe,Va} & 1 & \rho_{Fe,Ma} & \rho_{Fe,Mt} & \rho_{Fe,Cd} & \rho_{Fe,Aw} \\ \rho_{\mathrm{Ma,Af}} & \rho_{\mathrm{Ma,Sw}} & \rho_{,Va} & \rho_{Ma,Fe} & 1 & \rho_{Ma,Mt} & \rho_{Ma,Cd} & \rho_{Ma,Aw} \\ \rho_{\mathrm{Mt,Af}} & \rho_{\mathrm{Mt,Sw}} & \rho_{Mt,Va} & \rho_{Mt,Fe} & \rho_{Mt,Ma} & 1 & \rho_{Mt,Cd} & \rho_{Mt,Aw} \\ \rho_{\mathrm{Cd,Af}} & \rho_{\mathrm{Cd,Sw}} & \rho_{Cd,Va} & \rho_{Cd,Fe} & \rho_{Cd,Ma} & \rho_{Cd,Mt} & 1 & \rho_{Cd,Aw} \\ \rho_{\mathrm{Aw,Af}} & \rho_{\mathrm{Aw,Sw}} & \rho_{Aw,Va} & \rho_{Aw,Fe} & \rho_{Aw,Ma} & \rho_{Aw,Mt} & \rho_{Aw,Cd} & 1 \end{bmatrix}, \quad (3)$$

where ρ (rho) represents the pair-wise correlation-coefficient of the error terms to be estimated in the model.

## 7. A model of number of climate-smart practices

We also model the number of adaptation practices because the MVP model specified above only considered the probability of choice of adaptation practices, with no distinction made between, e.g. those who adapt one practice and those who combine multiple practices. In addition, the variables that affect the probability of adoption may affect the number of practices adopted differently. We follow Wollni et al. (2010) and Teklewold et al. (2013) and use the number of adaptation practices adopted as our dependent variable to model the number of adaptation practices. The information on the number of practices adopted could have been treated as a count variable. Count data are usually analysed using Poisson regression model, but the underlying assumption is that all events have the same probability of occurrence (Wollni et al., 2010). However, in our application, the probability of adopting the first practice could differ from the probability of adopting a second or third practice, given that in the latter case the farmer has already gained some experience and has been exposed to information about the practice. The number of practices adopted by farmers is an ordinal variable, hence the use of an ordered probit model in the estimations.

The ordered nature of the dependent variable ($C$) is a function of observed heterogeneity ($X$) with unknown weights (β) and other unobserved characteristics (u):

$$C_{ip} = X_{ip}\beta + u_{ip}. \quad (4)$$

Define the categorical outcome variable $C_{ip} \in \{1, \ldots, m\}$, indicating the number of adaptation strategies used by farmer $i$ on plot $p$. We employ the random effect ordered probit model to account for correlation in multiple plots within the same household.[3]

## 8. Results and discussion

### 8.1. *Interdependence of adaptation practices*

The sample conditional and unconditional probabilities presented in Table 2 highlight the existence of possible interdependence across the eight climate-smart practices. Inorganic fertilizer, agricultural water management and manure are used by 53%, 41% and 30% of the plots, respectively. This is followed by manure, soil and water conservation, improved seeds and crop diversification (adoption rate between 21% and 30% of the plots).

The result of the joint probability distribution of practices reveals that, of the 4312 plot observations, about 88% of the plots received one or more than one adaptation practices and only 2% of the plots received more than five practices.[4] About 12% of the plots did not receive any of the adaptation practices and about 23% of the plots received only one practice. For instance, the unconditional adoption rate of inorganic fertilizer is about 53%, but it is used in isolation on only 6% of the plots. The results show that, although fertilizer inputs are singly important, better complementarities are derived from fertilizer and other adaptation practices. The lowest adoption probabilities are for the use of minimum tillage (9%) and agro-forestry (16%). However, the probability of using these adaptation practices is increased conditional on the use of the other adaptation practices, suggesting complementarity among these practices.

Although a more rigorous multivariate analysis is warranted, a non-parametric crop net income distribution analysis showed that all the adaptation practices considered in this study impact the net value of crop production. The cumulative distribution of the net value of crop production on plots with crop diversification, inorganic fertilizer, improved seeds, manure use, minimum tillage, agricultural water management, agro-forestry and soil conservation dominates the crop net income cumulative distribution on plots without these adaptation practices. This is shown by the cumulative density function of crop net income with adaptation practices being constantly below or equal to that of plots without these practices. Confirming the above result, the Kolmogorov–Smirnov statistics test for equality of net crop production value distribution function also showed that the crop net incomes across each practice do not have the same distribution function. This is an important economic incentive for farmers to use each of these adaptation practices. We also test the heterogeneous effect of adoption of these practices on income across gender and households with different wealth status. We found that male-headed households earn more income than female-headed households from adopting these practices. Similarly, the farm income impact from adoption of

Table 2. Conditional and unconditional probabilities of adaptation practices.

| | Agro-forestry | Soil conservation | Improved variety | Fertilizer | Manure | Minimum tillage | Crop diversification | Water management |
|---|---|---|---|---|---|---|---|---|
| $P(Y_k = 1)$ | 15.82 | 27.88 | 23.48 | 52.59 | 30.31 | 9.11 | 21.96 | 41.07 |
| $P(Y_k = 1 \| Y_{Af} = 1)$ | 100.00 | 38.29 | 33.72 | 59.85 | 50.66 | 9.17 | 21.81 | 46.68 |
| $P(Y_k = 1 \| Y_{Sw} = 1)$ | 21.97 | 100.00 | 27.20 | 66.75 | 37.24 | 5.81 | 17.03 | 60.12 |
| $P(Y_k = 1 \| Y_{Va} = 1)$ | 22.40 | 32.81 | 100.00 | 81.60 | 36.59 | 4.17 | 29.11 | 44.29 |
| $P(Y_k = 1 \| Y_{Fe} = 1)$ | 18.15 | 35.18 | 35.99 | 100.00 | 30.57 | 3.15 | 25.46 | 47.63 |
| $P(Y_k = 1 \| Y_{Ma} = 1)$ | 26.773 | 34.88 | 27.73 | 52.98 | 100.00 | 7.08 | 21.15 | 45.55 |
| $P(Y_k = 1 \| Y_{Mt} = 1)$ | 16.54 | 17.32 | 10.92 | 20.32 | 23.63 | 100.00 | 15.98 | 35.33 |
| $P(Y_k = 1 \| Y_{Cd} = 1)$ | 15.02 | 21.23 | 30.88 | 62.05 | 29.23 | 6.19 | 100.00 | 45.62 |
| $P(Y_k = 1 \| Y_{Aw} = 1)$ | 18.45 | 41.36 | 25.49 | 60.71 | 33.14 | 7.63 | 24.99 | 100.00 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Sw} = 1)$ | 100.00 | 100.00 | 36.00 | 77.09 | 51.64 | 4.00 | 13.82 | 53.45 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Va} = 1)$ | 100.00 | 43.04 | 100.00 | 80.43 | 61.30 | 3.04 | 30.87 | 49.57 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Fe} = 1)$ | 100.00 | 51.08 | 44.58 | 100.00 | 48.92 | 2.41 | 25.30 | 51.08 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Ma} = 1)$ | 100.00 | 43.16 | 42.86 | 61.70 | 100.00 | 5.17 | 24.01 | 44.68 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Mt} = 1)$ | 100.00 | 16.92 | 10.77 | 15.38 | 26.15 | 100.00 | 12.31 | 21.54 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Cd} = 1)$ | 100.00 | 25.00 | 46.71 | 69.08 | 51.97 | 5.26 | 100.00 | 48.02 |
| $P(Y_k = 1 \| Y_{Af} = 1, Y_{Aw} = 1)$ | 100.00 | 46.37 | 35.96 | 66.88 | 46.37 | 4.42 | 23.02 | 100.00 |
| $P(Y_k = 1 \| Y_{Sw} = 1, Y_{Va} = 1)$ | 29.38 | 100.00 | 100.00 | 89.61 | 43.03 | 3.56 | 22.85 | 64.09 |
| $P(Y_k = 1 \| Y_{Sw} = 1, Y_{Fe} = 1)$ | 25.63 | 100.00 | 36.52 | 100.00 | 35.07 | 2.66 | 18.74 | 58.77 |
| $P(Y_k = 1 \| Y_{Sw} = 1, Y_{Ma} = 1)$ | 31.63 | 100.00 | 32.29 | 64.59 | 100.00 | 6.46 | 18.04 | 62.14 |
| $P(Y_k = 1 \| Y_{Sw} = 1, Y_{Mt} = 1)$ | 15.28 | 100.00 | 16.67 | 30.56 | 40.28 | 100.00 | 11.11 | 62.50 |
| $P(Y_k = 1 \| Y_{Sw} = 1, Y_{Cd} = 1)$ | 18.01 | 100.00 | 36.49 | 73.46 | 38.39 | 3.79 | 100.00 | 63.98 |
| $P(Y_k = 1 \| Y_{Sw} = 1, Y_{Aw} = 1)$ | 19.37 | 100.00 | 28.99 | 65.23 | 37.45 | 6.04 | 18.12 | 100.00 |
| $P(Y_k = 1 \| Y_{Va} = 1, Y_{Fe} = 1)$ | 22.08 | 36.04 | 100.00 | 100.00 | 31.86 | 2.74 | 29.47 | 43.68 |
| $P(Y_k = 1 \| Y_{Va} = 1, Y_{Ma} = 1)$ | 40.87 | 42.03 | 100.00 | 77.39 | 100.00 | 3.48 | 30.43 | 46.95 |
| $P(Y_k = 1 \| Y_{Va} = 1, Y_{Mt} = 1)$ | 17.95 | 30.77 | 100.00 | 58.97 | 30.77 | 100.00 | 35.90 | 46.15 |
| $P(Y_k = 1 \| Y_{Va} = 1, Y_{Cd} = 1)$ | 23.75 | 25.75 | 100.00 | 82.61 | 35.12 | 4.68 | 100.00 | 42.81 |
| $P(Y_k = 1 \| Y_{Va} = 1, Y_{Aw} = 1)$ | 26.02 | 49.32 | 100.00 | 83.56 | 36.98 | 4.11 | 29.22 | 100.00 |
| $P(Y_k = 1 \| Y_{Fe} = 1, Y_{Ma} = 1)$ | 31.09 | 44.41 | 40.89 | 100.00 | 100.00 | 3.22 | 25.11 | 48.09 |

Note: $Y_k$ is a binary variable representing the adoption status with respect to practice $k$ ($k$ = agro-forestry (Af); Soil and stone bunds (Sw); Improved variety (Va); inorganic fertilizer (Fe); manure (Ma); minimum tillage (Mt); crop diversifications (Cd); water management (Aw)).

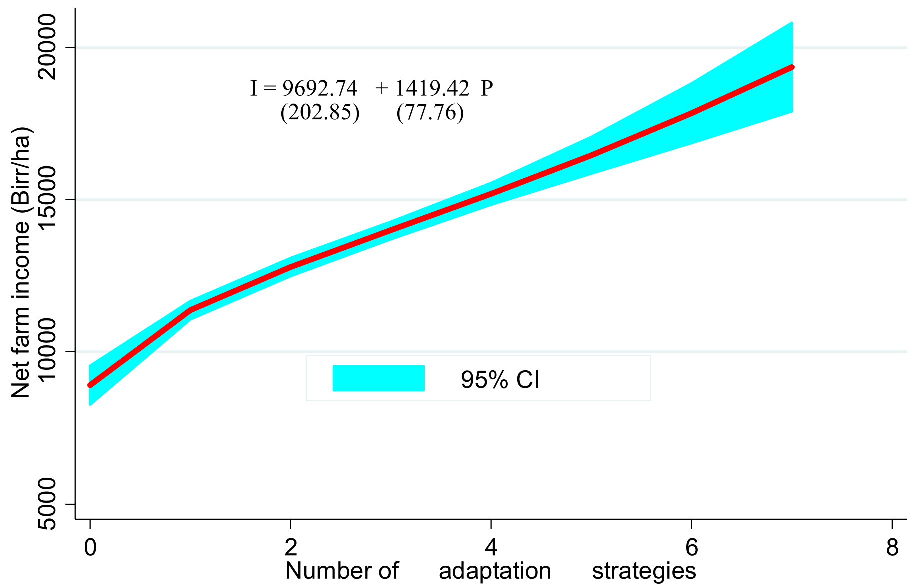


Figure 1. Average net crop income (Birr/ha) and the number of adaptation practices used.
Note: *P* is the number of practices used and *I* is crop net income. Numbers in parentheses are robust standard errors. All coefficient estimates are statistically significant at 1% level.

these adaptation practices is higher for non-poor households than poor households.[5]

The survey results also support a positive association between crop net income and the combination of practices used (Figure 1), suggesting a complementarity relationship among the practices that could lead to co-benefits. However, we observe heterogeneity among farm households on the number of adaptation practices used (Figure 2). Of the eight practices, the probability of using more than half of the practices jointly per plot (more than four practices) is lower than 10%. But the probability of using two to three practices jointly per plot is more than 50%.

## 8.2. *Regression results*

### 8.2.1. *MVP model results on adaptation decisions*

The result of the MVP regression is presented in Table 3. The likelihood ratio test [$\chi^2_{28} = 673$; $p = 0.000$)] of

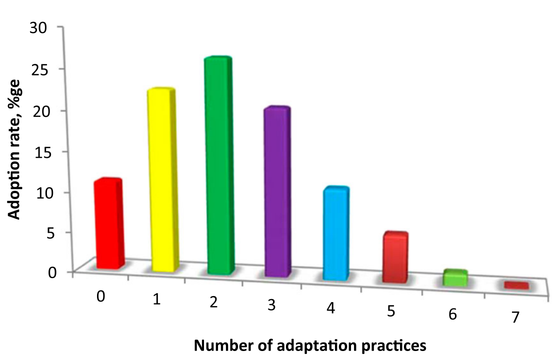


Figure 2. Intensity of adaptation practices used per plot.

independence confirmed the rejection of the null hypothesis that states the covariance of the error terms across equations are not correlated. These tests support estimation with MVP. Almost all the estimated correlation coefficients are statistically significant with positive signs, showing that the probability of adopting a practice is conditioned on whether or not a practice in the subset has been adopted.[6] These results also agree with the result reported in Table 2. This cross-correlation may have an implication in that a policy change that affects a given adaptation practice can have spillover effects on the other practices. The MVP regression results indicate heterogeneous factors influencing adoption of various practices. This implies there is no single solution to improve the adaptive capacities of farmers using climate-smart practices.

Results from Table 3 shows that households that own and use a mobile telephone are more likely to use an improved crop variety. This suggests that improving communication infrastructure and access to information is important to enhance the use of climate change adaptation practices through facilitating input and output transport, reducing the opportunity cost of farmers' time, and obtaining timely market information and other information about production and the changing climate. However, it is worthwhile to note that ownership of a mobile phone may also be picking up a wealth or liquidity effect, in the sense that those who own a mobile phone may also have more cash income to finance externally purchased agricultural inputs such as improved seeds.

In addition to the classical household characteristic and endowment variables, we also study the ways in which individuals relate to wider social networks and the effects

Table 3. Coefficient estimates of the MVP with Mundlak's approach.

| Variables | Agro-forestry | Soil conservation | Improved variety | Fertilizer | Manure | Minimum tillage | Crop diversification | Water management |
|---|---|---|---|---|---|---|---|---|
| **Household features** | | | | | | | | |
| Gender | 0.082 | 0.223 | 0.162* | 0.113 | −0.123 | −0.024 | −0.047 | 0.381** |
| Education | −0.045 | −0.061 | 0.115* | 0.056 | 0.042 | −0.001 | 0.119* | 0.057 |
| Famlysize | 0.013 | −0.001 | 0.032** | 0.004 | −0.010 | −0.000 | 0.002 | −0.010 |
| **Resource constraints** | | | | | | | | |
| Farmsize | −0.073 | −0.025 | 0.016 | 0.012 | −0.056* | 0.085* | −0.006 | −0.024 |
| Tlu | −0.006 | −0.005 | 0.015* | −0.000 | 0.017 | −0.008 | −0.015 | 0.003 |
| Credit | 0.032 | −0.218*** | −0.003 | −0.074 | −0.036 | −0.081 | −0.079 | −0.011 |
| Asset | −0.001 | 0.001 | 0.001 | 0.002*** | −0.002** | 0.000 | 0.001 | 0.001 |
| **Extension and market** | | | | | | | | |
| Teleph | 0.100 | −0.021 | 0.092 | 0.060 | −0.019 | −0.027 | 0.032 | 0.014 |
| Distoutmkt | 0.000 | 0.001* | −0.001* | 0.000 | 0.000 | 0.001 | 0.000 | 0.001 |
| Distinputmkt | −0.001 | −0.001 | −0.002** | −0.001 | −0.000 | −0.004*** | −0.003*** | −0.000 |
| Totextcontact | −0.071 | −0.081 | −0.005 | −0.010 | 0.026 | −0.029 | −0.029 | 0.180*** |
| Extconfdnt | −0.342 | −0.216 | −0.075 | 0.050 | 0.284** | −0.063 | 0.033 | 0.435*** |
| Infoclimate | 0.080 | −0.215** | −0.101 | 0.109 | 0.151* | −0.056 | 0.035 | 0.051 |
| **Social network, social conformity and neighbourhoods effects** | | | | | | | | |
| Relative | 0.006** | 0.001 | −0.001 | −0.0001 | 0.0001 | 0.0001 | 0.001 | −0.0001 |
| Agricmemb | 0.182* | 0.063 | 0.125* | 0.110 | −0.051 | −0.040 | −0.038 | 0.025 |
| Financmemb | −0.032 | −0.199* | 0.087 | 0.125 | −0.090 | −0.079 | 0.010 | −0.014 |
| Socalmemb | −0.033 | 0.093 | 0.220 | −0.002 | 0.158 | −0.104 | −0.049 | −0.116 |
| Appreciation | 0.476*** | 0.753*** | 0.296*** | 0.335*** | 0.161* | 0.338*** | 0.093 | 0.031 |
| Positive | 0.058 | 0.083 | 0.147* | −0.083 | 0.015 | −0.221* | −0.056 | 0.509*** |
| Negative | −0.086 | −0.234** | 0.290* | −0.024 | −0.105 | −0.033 | −0.244*** | 0.148* |
| **Shocks** | | | | | | | | |
| Rainindex | 0.081 | −0.251 | −0.154 | −0.079 | 0.270*** | 0.174* | −0.073 | −0.087 |
| Plotindex | 0.271** | 0.169 | −0.297 | −0.075 | −0.174 | −0.146 | −0.259 | −0.350* |
| Relygovt | 0.093 | 0.043 | 0.028 | 0.132** | −0.034 | −0.045 | 0.069 | −0.018 |
| **Climate** | | | | | | | | |
| Rainfall | 0.015** | 0.015** | −0.005 | 0.010* | −0.003 | −0.019** | −0.015** | 0.002 |
| Rainfall-squared | −0.0001* | −0.001* | 0.001* | −0.000 | 0.000 | 0.000 | 0.001*** | 0.000 |
| Temperature | 1.310 | 1.807** | 1.223** | 0.898 | 0.240 | −0.720 | 0.860 | 0.710 |
| Temperature-squared | −0.027 | −0.036* | −0.033** | −0.023 | −0.001 | 0.036 | −0.022 | −0.015 |
| PCI | 0.021*** | 0.015*** | −0.010** | −0.033*** | 0.008* | 0.006 | 0.009 | 0.091*** |
| Rainfall × PCI | −0.035** | −0.001 | −0.010* | −0.021* | −0.001 | 0.042** | 0.007 | −0.011 |
| Elevation | −0.000 | −0.0001 | −0.000 | −0.001* | 0.000 | −0.000 | 0.000 | −0.001** |
| **Farm features** | | | | | | | | |
| Plotdist | −0.013*** | 0.004* | −0.006*** | 0.002 | −0.049*** | 0.004* | 0.005*** | 0.001 |
| Tenure | 0.792*** | 0.416*** | 0.015 | −0.006 | 0.884*** | 0.037 | 0.276*** | 0.290*** |
| Higfert | −0.105 | −0.364*** | 0.046 | 0.061 | 0.199 | −0.083 | −0.043 | −0.134 |
| Medfert | −0.173 | −0.157 | 0.040 | 0.121 | −0.065 | −0.038 | −0.079 | −0.116 |
| Flatslp | 0.079 | −0.378** | −0.085 | −0.258 | 0.277 | 0.005 | −0.087 | −0.393** |

(*Continued*)

Table 3. Continued.

| Variables | Agro-forestry | Soil conservation | Improved variety | Fertilizer | Manure | Minimum tillage | Crop diversification | Water management |
|---|---|---|---|---|---|---|---|---|
| Medslp | 0.138 | −0.060 | −0.060 | −0.068 | 0.115 | 0.088 | −0.094 | −0.185 |
| Depdpth | 0.040 | −0.326** | 0.046 | 0.071 | −0.179 | −0.059 | 0.228 | 0.059 |
| Meddpth | −0.022 | −0.096 | 0.028 | 0.187* | −0.009 | 0.045 | 0.075 | 0.107 |
| Cereal | 0.048 | 0.241*** | 0.415*** | 0.528*** | −0.298*** | −0.394*** | 0.346*** | −0.241*** |
| Legume | −0.171* | 0.246** | −0.440*** | −0.634*** | −0.400*** | 0.693*** | −0.687*** | −0.415*** |
| **Constant** | −20.093 | −30.461*** | −9.426 | −10.000 | −6.465 | 4.291 | −4.043 | −7.906 |
| Joint significance of location variables, $\chi^2(13)$ | 65.90*** | 152.40*** | 163.02*** | 227.13*** | 41.68*** | 54.94*** | 137.17*** | 67.09*** |
| Joint significance of mean of plot-varying covariate, $\chi^2(8)$ | 14.71** | 23.59*** | 25.41*** | 9.93 | 85.39*** | 13.42* | 22.06*** | 29.44*** |

Note: Other non-significant variable include Age and Offarm.
*Statistical difference at the 10% level.
**Statistical difference at the 5% level.
***Statistical difference at the 1% level.

of these networks on the choice of climate-smart practices. We found that the kinship network (defined as the number of relatives living in the village) and membership in local institutions had a positive effect in explaining the choice of various climate-smart agricultural practices. Such networks can improve information flows about new opportunities and potential shocks and also can confer other benefits such as better access to finance and inputs. They also can serve as informal insurance mechanisms in times of crisis (Quisumbing, 2003).

We found a significant relationship between neighbourhood effects and social conformity and the decision to use climate-smart practices. Farmers who expect appreciation from their neighbours about the adoption of the particular adaptation practice are more likely to adopt that practice. We also found that the perception that adoption of climate-smart practices has positive productivity effects on neighbouring plots has mixed effects depending on the type of practice. Farmers are more likely to adopt agricultural water management and modern crop seeds on their plots if they believe there are positive productivity effects on their neighbours' plots. Adoption of water management techniques reduce soil erosion and increase soil moisture content, which might beneficially affect the neighbouring plots. The result corroborate Wolloni and Anderrson (2014) and Wydick, Hayes, and Kemp (2011), who respectively found a positive association between social conformity and neighbourhood effects in the adoption of organic agriculture in Honduras. However, farmers are less likely to adopt conservation tillage because they perceived that their adoption has beneficial effects that are captured by their neighbours and they experience disutility from the feeling that others free ride on their application of conservation tillage. The latter result is consistent with Wolloni and Andersson (2014), who suggest that farmers tend to forgo agricultural investments to prevent others from free riding on their efforts because not all the benefits accrue to the individual who adopts the practice.

The MVP results underscore the importance of rainfall and plot-level shocks in determining the adoption of practices. We followed Quisumbing (2003) to construct the rainfall disturbance variable based on respondents' subjective rainfall satisfaction in terms of timeliness, amount and distribution in the preceding seasons, based on questions such as whether rainfall came late at the start of the growing season, whether there was a decrease in rainfall and whether there was erratic rainfall during the growing season, coded as unfavourable or favourable. By averaging over the number of questions asked, we constructed an index that provides a value close to zero for the unfavourable outcome and one for the best outcome. The other plot-level disturbance variable is captured by an index derived from the presence of the most common shocks, such as flooding, drought, hailstorms, and pest and disease pressures. The results indicate that in areas/years where rainfall is good in terms of timing, amount, and distribution, it is more likely that the household shifts to climate-smart agricultural practices (such as manure and minimum tillage). This finding also suggests that farmers who experienced other plot-level disturbance (such as pests, disease, flooding, and drought) are more likely to consider agro-forestry practices as adaptation strategies to ease the shocks. This is important evidence on the synergy between adaptation practices and climate change adaptation.

We merge the household data with climate variables based on geo-referenced historical temperature and precipitation data at household level for the period 2000–2013. 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 household-specific rainfall and temperature values using geo-referenced information. This method is one of those most commonly used to create spatial climate data sets (e.g. Di Falco, Yesfu, Köhlin, & Ringler, 2012). The generated climatic variables are included in our empirical model to capture whether differences in seasonal temperature and precipitation influence farmers' choice of practices. In order to identify the monthly pattern of rainfall heterogeneity, we used Oliver's (1980) Precipitation Concentration Index (PCI)[7] analysed at seasonal scale. The PCI value showed irregular distribution of rainfall, with values ranging from 22 to 33, indicating a very high concentration of rainfall.

The MVP results showed that changes in precipitation influence the choice to adopt agro-forestry, soil conservation, minimum tillage, and crop diversification. In high rainfall areas, climate change can contribute to land degradation. In this regard, agro-forestry and soil conservation are important adaptation practices due to their role in protecting the soil from water erosion. The positive first-degree and negative second-degree terms for growing season precipitation indicate a hill-shaped response to the likelihood of adoption of these climate-smart practices. On the other hand, the response of conservation tillage and crop diversification to rainfall is U-shaped, the linear coefficients are negative and the quadratic term coefficients are positive. However, the non-significance of the quadratic term coefficients of conservation tillage suggests that adoption of conservation tillage might be quite resilient to changes in precipitation. The result is consistent with Teklewold et al. (2013) and Asfaw et al. (2014), which showed that farmers adopted moisture conserving practices as a risk-decreasing strategy in response to declining rainfall, which strengthens farmers' resilience to climate change.

The results also show that soil conservation practices are important options for adapting agricultural production under warmer climatic conditions. As an adaptation strategy, soil conservation is key to ensuring agricultural production and reduction of risks, while at the same time improving resilience to drought and dry spells. Increasing rainfall variability significantly decreases the likelihood of adoption of fertilizer and modern seeds, thus reflecting the adverse effects of rainfall variability on adoption of risk-increasing inputs. In high rainfall variability conditions, agro-forestry, soil conservation, manure and agricultural water management are more responsive and considered as important adaptation strategies for smallholder farming systems. As risk-decreasing practices, the adoption of these climate-smart practices is considered as the most common response to rainfall variability and have the potential to strengthen farmers' resilience (Arslan et al., 2013).

Exposure to agricultural extension services positively influences the adoption of agricultural water management practices, suggesting that information exposed households are more likely to adopt knowledge-intensive management practices.[8] We also found that the decision to apply manure, crop diversification, water management, soil conservation, and agro-forestry are more common on owner-cultivated plots than on rented plots. The result is in agreement with previous work in Ethiopia by Asfaw et al. (2014) and Kassie et al. (2015). This may be due to tenure security. When land is accessed through a renting arrangement, it is often on a short-term basis. Given the fact that the benefits from investment in these adaptation practices accrue over time, this inter-temporal aspect suggests that secure land access will impact adoption decisions positively.

#### 8.2.2. *Number of adaptation practices*

We present estimation results of the random-effects ordered probit model with a Mundlak transformation in Table 4. There is enough variability between plots in the same household to favour random-effects ordered probit regression over a standard ordered probit regression.[9] Although the estimated parameters are not interpreted directly per se, the parameter estimates indicate that most of the socio-economic characteristics are statistically significant in explaining the number of adaptation practices.

The estimation results show that farmers who need credit but are unable to obtain it face financial constraints that limit the number of practices they adopt. Results from Table 4 also show the importance of social capital networks. Membership in various groups has a positive and significant effect in increasing the number of adaptation practices but with varying degrees of marginal probability. With membership in local institutions, a household increases the marginal probability of adopting more than two adaptation practices by 1.1%. Social capital can help farmers prepare for greater climate variability, provide contingency measures to deal with increasing risks, and alleviate the consequences of climate change. Wood, Jina, Jain,

Table 4. Coefficient estimates and marginal effects of the random-effects ordered probit model with Mundlak's approach.

| Variables | Coefficients | | Marginal effects | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Prob($Y=0\|X$) | Prob($Y=1\|X$) | Prob($Y=2\|X$) | Prob($Y=3\|X$) | Prob($Y=4\| X$) | Prob($Y=5\| X$) | Prob($Y>5\| X$) |
| Credit | −0.160*** | | 0.0195 | 0.0228 | 0.0048 | −0.0160 | −0.0160 | −0.0111 | −0.0030 |
| Socalmemb | 0.033** | | −0.0054 | −0.0048 | −0.0009 | 0.0049 | 0.0030 | 0.0020 | 0.0009 |
| Rainfall | 0.007 | | −0.0010 | −0.0013 | −0.0002 | 0.0009 | 0.0009 | 0.0006 | 0.0002 |
| Rainfall-squared | −0.0001 | | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 |
| Temperature | 2.223*** | | −0.3069 | −0.3728 | −0.0590 | 0.2546 | 0.2628 | 0.1740 | 0.0473 |
| Temperature-squared | −0.039*** | | 0.0074 | 0.0090 | 0.0014 | −0.0061 | −0.0063 | −0.0042 | −0.0011 |
| PCI | 0.018*** | | −0.0024 | −0.0029 | −0.0005 | 0.0020 | 0.0021 | 0.0014 | 0.0004 |
| Rainfall X PCI | −0.021* | | 0.0024 | 0.0029 | 0.0005 | −0.0020 | −0.0021 | −0.0014 | −0.0004 |
| Plotdist | −0.010*** | | 0.0014 | 0.0017 | 0.0003 | −0.0012 | −0.0012 | −0.0008 | −0.0002 |
| Tenure | 0.427*** | | −0.0719 | −0.0873 | −0.0138 | 0.0596 | 0.0616 | 0.0408 | 0.0111 |
| Higfert | −0.120 | | 0.0144 | 0.0174 | 0.0028 | −0.0119 | −0.0123 | −0.0081 | −0.0022 |
| Medfert | −0.098 | | 0.0139 | 0.0169 | 0.0027 | −0.0115 | −0.0119 | −0.0079 | −0.0021 |
| Flatslp | −0.279** | | 0.0373 | 0.0453 | 0.0072 | −0.0309 | −0.0319 | −0.0212 | −0.0057 |
| Medslp | −0.075 | | 0.0118 | 0.0143 | 0.0023 | −0.0098 | −0.0101 | −0.0067 | −0.0018 |
| Depdpth | −0.041 | | −0.0065 | −0.0079 | −0.0013 | 0.0054 | 0.0056 | 0.0037 | 0.0010 |
| Meddpth | 0.037 | | −0.0130 | −0.0158 | −0.0025 | 0.0108 | 0.0112 | 0.0074 | 0.0020 |
| Cereal | 0.712*** | | −0.0288 | −0.0350 | −0.0055 | 0.0239 | 0.0247 | 0.0163 | 0.0044 |
| Threshold parameters | | | | | | | | | |
| $\mu_1$ | 26.285*** | | | | | | | | |
| $\mu_2$ | 27.318*** | | | | | | | | |
| $\mu_3$ | 28.185*** | | | | | | | | |
| $\mu_4$ | 28.887*** | | | | | | | | |
| $\mu_5$ | 29.500*** | | | | | | | | |
| $\mu_6$ | 30.523*** | | | | | | | | |
| Wald $\chi^2(60)$ | | 745.85*** | | | | | | | |
| Joint significance of location variables, $\chi^2(13)$ | | 184.75*** | | | | | | | |
| Joint significance of plot-varying covariate, $\chi^2(10)$ | | 29.27*** | | | | | | | |

Note: Other non-significant variable include Gender, Age, Education, Famlysize, Farmsize, Tlu, Credit, Offarm, Distoutmkt, Distinputmkt, Extconfdnt, Relative, Agricmemb, Finmemb, Rainindex, Plotindex, Relygovt and Legume.
*Statistical difference at the 10% level.
**Statistical difference at the 5% level.
***Statistical difference at the 1% level.

Kristjanson, and De Fries (2014) also showed that farmers who participate in social institutions are more likely to make changes in farming practices than those who are not members of such groups.

We found a positive effect of temperature and rainfall variability on the number of adaptation practices, showing that climate change, through altering the weather, has a direct bio-physical effect on diversification of adaptation practices. Farmers generally diversify their production system by employing practices that are more compatible with variability in precipitation and temperature stresses and that take full advantage of beneficial climate conditions. The positive first-degree and negative second-degree terms for monthly temperature indicate a hill-shaped response to the number of practices adopted. In general, these results support the conclusion that farmers in developing countries have traditionally adapted to climate risk by diversifying across a number of adaptation practices (Shiferaw et al., 2009).

Tenure security influences the number of adaptation practices, with a greater number of practices on owner-cultivated plots than on rented-in plots. The result is consistent with earlier work on technology adoption in Ethiopia by Teklewold et al. (2013) and in Benin by Yegbemey et al. (2013). With tenure security, the probability of adopting more than two adaptation practices increases by more than 16%, linking the issues of property rights and climate change adaptation.

## 9. Conclusions

In this study, we analysed the probability and use of multiple adaptation practices (such as agro-forestry, water management, improved seeds, inorganic fertilizer, manure, crop diversification, soil conservation and conservation tillage) in the Nile Basin of Ethiopia, using household and plot-level observations coupled with spatial climate data. We used multivariate probit and random effect ordered probit models to identify the factors that facilitate or impede the adoption of such practices and the number of adaptation practices used.

The results show that there is a strong complementarity among adaptation practices. The cross-correlation among the adaptation practices may have important policy implications, in that a policy change that affects one practice can have spillover effects on the adoption of other practices. These interactions can help define appropriate packages of adaptation practices tailored to specific areas.

The farmer's decision to adopt a particular adaptation measure or combination of practices is affected by several policy-relevant factors. The significance of tenure security in influencing the probability and number of adaptation practices has called attention to the importance of securing property rights as an incentive in climate change adaptation. The significant role of social capital in adoption suggests the need for establishing and strengthening local institutions to quicken the adaptation process.

The relationship between climate variables and adaptation practices implies that climate change can offer new opportunities for productive and sustainable land management practices, such as agricultural water management, conservation agriculture, agro-forestry and application of modern inputs. We found that farm-level use of modern external inputs (fertilizer and improved seeds) is less probable under low rainfall condition. However, conservation tillage, crop diversification and other agricultural water management practices seem well suited to respond to the key agro-ecological constraints of low rainfall patterns and warmer climatic conditions. These different effects of climate variables on farm-level use of different adaptation practices suggest the need for careful designing and targeting of agro-ecological based adaptation strategies.

While lessons can be drawn from the interdependence of adaptation strategies, whether and how such complementarity can lead to co-benefits in terms of improving farm income and reducing the vulnerability of smallholder agriculture to climate change requires further empirical enquiry using panel data sets and will be an important avenue for future research.

## Acknowledgements

Logistical support for this study from the Environment and Climate Research Center (ECRC) at the Ethiopian Development Research Institute (EDRI) is gratefully acknowledged. Comments from the anonymous referees of this Journal, Bhim Adhikari and Cyndi Berck are also highly appreciated.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This study was financed by the International Development Research Centre (IDRC) under the project "Adaptation to Increase Resilience to Climate Change in Ethiopian Agriculture" [IDRC Project Number: 107745-001].

## Notes

1. See Teklewold, Mekonnen, Kohlin, and Di Falco (2017) for a detailed description of the explanatory variables.
2. Alternatively, a fixed-effects model could have been used. However, with this approach and the nature of our data, it would not be feasible to estimate plot-invariant covariates as the model relies on data transformation to remove unobserved heterogeneity.
3. Our analysis shows that the likelihood ratio test of the null hypothesis that the correlation between two successive error terms for plots (rho) belonging to the same household is significantly different from zero, justifying the application of the random effects model.
4. This result is not presented here for the sake of space.
5. The test results are not shown here for the sake of space.
6. The MVP regression correlation coefficients are not presented here for the sake of space.
7. The PCI is described as: $\text{PCI} = 50X\left[\sum r_m^2/\left(\sum r_m\right)^2\right]$, where $r_m$ is the amount of rainfall in the $m$th month. PCI values of less than 10 indicate uniform monthly distribution of rainfall (low precipitation concentration); values between 11 and 15 indicate moderate precipitation concentration; PCI between 16 and 20 indicates irregular distribution; and values above 21 indicate very high precipitation concentration (strong irregularity) (Oliver, 1980).
8. The variable agricultural extension exposure (number of topics the household is exposed) is potentially endogenous. Following Wooldridge (2002), we implemented a two-stage residual inclusion test for the endogeneity of the variable. We use walking distance to extension agent's office as the instrumental variable. The instrument significantly explains the exposure to extension service variable. The results suggest that endogeneity is not a problem. Results are available upon request. We thank the anonymous reviewer for pointing this out.
9. The null hypothesis that the inter-plot correlation coefficient $(\rho = \sigma_\eta/(\sigma_\eta + \sigma_e)$ is equal to zero is rejected $[\rho = 0.40(p = 0.000)]$. This result also suggests the plot variance component is not negligible and consequently the random effects model is justified.

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